

Article

RAPTURE: Resilient Agricultural Practices for Transforming Uncertain and Resource-Scarce Environments Tool

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Abstract

The climate-smart agriculture (CSA) approach, a sustainable alternative to conventional practices in agriculture, supports three main pillars: increasing productivity, resilience, and greenhouse gas (GHG) mitigation through the adoption of climate-smart practices (CSPs). Effective CSA assessment tools are needed to evaluate the impact of and support the broader adoption of CSPs. This study addresses this need by developing the RAPTURE (Resilient Agricultural Practices for Transforming Uncertain and Resource-Scarce Environments) tool. The RAPTURE tool was developed through five steps, which included collecting data on CSA definitions, existing practices and classifications, climatic conditions of the study areas, and the mathematical equations used to assess CSPs—all of which were stored in databases. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was adopted to guide the selection and inclusion of 222 studies from the Web of Science database, forming the basis for the development of the RAPTURE tool. The first step of RAPTURE synthesizes simple and complex definitions of CSA from the database of 35 definitions. For the second and third steps, an updated classification of the CSPs was developed using a database with 78 CSPs, and a weather conditions database created from areas where CSPs have been studied and implemented was also provided, respectively. The fourth step of the RAPTURE tool includes a database containing the input and output variables necessary for the assessment of CSPs' impacts, which is essential for the selection of an assessment method. The fifth and last step of the tool contains the assessment methods available, including 24 mathematical methods documented and synthesized. An application of RAPTURE using agricultural data from Florida in 2022 and 2023, and considering an increase of 20% with the implementation of CSPs, showed better productivity and rain-use efficiency. While previous studies have shown that adopting CSPs in agriculture provides several benefits, such as better agricultural production, higher carbon sequestration, the application of the RAPTURE tool in assessing CSPs also demonstrates their ability to increase productivity and resource-use efficiency.

Keywords: RAPTURE; tool; CSA; CSPs; climate challenges; agriculture; productivity; resilience; mitigation



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1. Introduction

The world's population is projected to reach 9.7 billion by 2050, necessitating a 60% increase in food production to meet needs and limit food insecurity [1–4]. In addition, there is an increase in the severity of climatic events (e.g., floods, droughts, soil salinization, etc.) responsible for the inability of the agricultural sector to provide enough food for the population. Moreover, agricultural activities have contributed approximately one-third of all greenhouse gas (GHG) emissions while being highly vulnerable to the consequences of extreme climatic events, which intensify agricultural product loss and food insecurity worldwide [5,6]. Severe climatic events significantly impact agriculture through variations in weather patterns and their effects on water and land resources, leading to declining food production globally [7,8]. Therefore, there is a need for resilience through the use of adaptive agricultural practices that address growing challenges such as water scarcity and distribution, soil degradation, soil salinization, and pest and disease proliferation to ensure food security and sustainable resource management.

An approach introduced by the Food and Agriculture Organization (FAO) in 2010 as a sustainable alternative to traditional agricultural practices, climate-smart agriculture (CSA) aims to increase the resilience capability of the agricultural system through three main pillars: increasing productivity, building resilience to climate challenges, and enhancing GHG mitigation [1,2,9]. Therefore, CSA stands out as a triple-achievement strategy by simultaneously addressing food production and security, climate adaptation, and GHG emission reduction, making it a promising approach to sustainability in agriculture. In fact, it is necessary to document the scientific viewpoints and emerging definitions of the concept of CSA since its introduction by the FAO to highlight the main components necessary for its description.

To achieve the triple goal, CSA incorporates a set of environmentally friendly practices adopted globally [1,2]. The key features of these practices are mainly based on their specificity in addressing multiple functions such as resource conservation (soil, water, energy, crops, livestock, and nutrients), agricultural productivity enhancement, and environmental protection [10–12]. Examples of CSA practices include agroforestry, cover crops, mulching, crop rotation, and improved livestock management, and some benefits of their adoption are increased soil retention, runoff prevention, soil moisture, improved water infiltration, and enhanced nutrient availability [13,14]. There are existing gaps in the literature and insufficient information related to the classification of the agricultural practices employed under CSA, resulting in implementation failures in some regions [15,16]. In the literature, the term CSAPs is used to refer to practices implemented in agricultural activities to strengthen the resilience capacity of the sector and ensure harvest success. As a result, this concept automatically excludes non-agricultural practices adopted by people in their regular behavior that have positive impacts on climate mitigation and sustainable management of the agricultural sector. In fact, it is essential to refer to all such practices as climate-smart practices (CSPs), whether those implemented in agriculture or those adopted through human behavior, considering their ability to satisfy the objectives of the CSA approach. Therefore, there is a need to develop an updated classification of the practices used for CSA achievement to clearly distinguish the agricultural practices from the non-agricultural ones, while documenting their impact on agriculture and overall livelihoods as outcomes to highlight their effectiveness in meeting the three pillars of the CSA approach.

Previous studies have provided evidence of the effects of these practices on agriculture by evaluating their impacts on agricultural productivity, considering crop yield, household food security, and income [17–20]. In addition, studies have assessed the impacts of CSPs on building the resilience and adaptation capacity of the agricultural sector to climate challenges through resource-use efficiency in water, nutrient, and energy management, among

others [21,22]. The capacity of the CSPs to reduce GHG emissions from agricultural sources has also been assessed by evaluating their ability to sequester carbon (C) from the atmosphere and to reduce emissions produced by the agricultural sector [23,24]. Researchers have also examined the factors (e.g., farmers' characteristics, institutional interventions, land tenure and size, resource availability, etc.) that can either encourage or hinder the adoption of CSPs among farmers [15,25–28]. Moreover, there is a lack of studies that have synthesized the methods used to estimate CSP impacts and develop an assessment tool containing all these methods.

Tools play a crucial role in advancing CSA by enabling data-driven decisions, optimizing resource use, and enhancing resilience to climate variability. Despite their importance, there remains a significant gap in the availability and accessibility of practical, science-based tools tailored to CSP assessment. This lack hinders farmers, researchers, and policymakers from effectively implementing and scaling CSA strategies [16]. Developing user-friendly, context-specific tools is essential to bridge this gap and support sustainable agricultural systems. Innovative tools can help monitor soil health, manage nitrogen use, and adapt practices to changing climatic conditions, ultimately promoting food security and environmental sustainability.

The present study's main objective is to develop the RAPTURE tool and demonstrate its application to enable its use by stakeholders in assessing CSPs. Therefore, the development of the RAPTURE tool was carried out through five steps: (i) synthesizing CSA definitions while providing a comprehensive overview for a clear understanding of the approach; (ii) compiling CSPs collected from the literature to present an updated categorization specifying the area of implementation of the practices, either in agriculture or in people's daily lifestyles and behaviors; (iii) presenting the temperature and precipitation ranges in which the practices have been implemented and studied; (iv) investigating, documenting, and synthesizing the mathematical methods used for the evaluation and assessment of the CSPs; and (v) demonstrating the use of the RAPTURE tool through its application using real-world data.

2. Materials and Methods

2.1. RAPTURE Tool Development Process

The development and creation of the RAPTURE tool followed a scientific process divided into five phases. These phases included the formulation of the research topic, the selection of a database to collect studies for the literature review, the collection of data necessary for the creation of the tool and their subsequent analysis, and the conceptualization and finalization of the RAPTURE tool (Figure 1).

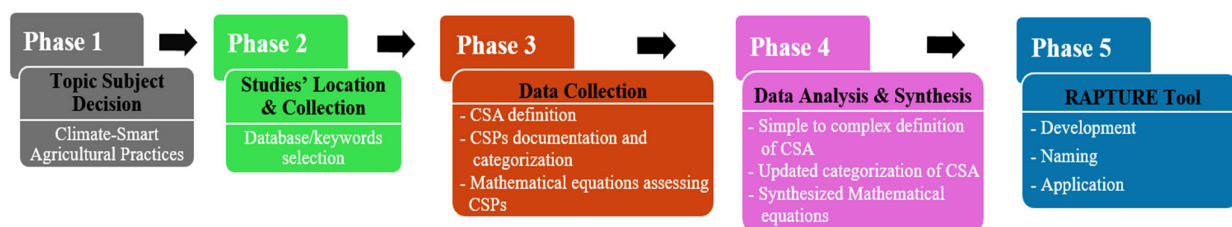


Figure 1. Framework of the development process leading to the RAPTURE tool conceptualization.

Multiple studies were utilized as data sources for the RAPTURE tool's database, with the selection process guided by the PRISMA framework. After analyzing and synthesizing the data, the RAPTURE tool was developed, named, and applied to test its usability by different stakeholders. Therefore, the RAPTURE tool is composed of five steps. The CSA definitions and descriptions from 35 articles were tabulated and presented as the

first step for the RAPTURE tool's database. For RAPTURE users who are not familiar with this approach, the definitions of CSA were synthesized from simple to complex, according to the level of detail provided and the scope of CSA's impact. For instance, a simple definition may cover the basic principles of CSA and present a single pillar as an expected outcome from the adoption of the CSPs, whereas a more complex one includes multiple pillars of CSA (e.g., productivity, resilience, and mitigation). Moreover, the definitions can be detailed to include multiple terms/concepts, such as (1) development goals [29]; (2) food security [30,31]; (3) ecosystem services [32,33]; (4) spatial and temporal scales [34,35]; (5) measures [36]; (6) technologies [36,37]; (7) trade-offs and synergies [36], and (8) techniques [38], which are necessary for the implementation of the CSPs. This step is crucial because the assessment process is highly dependent on the definitions chosen, as they frame the entire evaluation by clarifying the pillars that will be considered for assessment.

The second step of the tool's database concerns the classification of the CSPs and the selection of those that will be assessed. It is necessary to identify the specific category of practices in the assessment process, which involves the presentation of the selected CSPs, chosen either from the user's own list or from the one provided by the RAPTURE tool. Further, the tool requires checking the availability of the chosen CSPs and identifying the categories to which they belong, as presented in the collapsible trees. Verifying the appropriate category is necessary to ensure that the selected practice is aligned with the predefined categorization necessary for further analysis and comparison. This categorization of CSPs allows adopters to identify which practices to implement and adopt for their activities based on their objectives.

Step 3 of the tool's database prompts users to verify the optimum temperature and precipitation ranges for the selected CSPs, based on data collected from the literature for areas where these practices have been previously studied. The main idea is to determine whether CSPs are worth adopting; the comparison of weather conditions between the literature and new areas of adoption helps determine whether they fit. This step ensures that the practice is appropriate for the specific climatic conditions of the area, which is crucial for its effectiveness. This process helps adopters acquire usable knowledge of the outcomes that can be expected from CSPs, considering previous adopters' experiences.

In Step 4, the tool focuses on selecting the specific effects of the CSPs to assess, requiring users to identify the availability of both input and output variables. The identification of output variables (e.g., crop yield, water-use efficiency, GHG emissions, etc.) and their corresponding inputs (e.g., resources, technologies, etc.) is based on the data available in the database constructed by this study. Understanding the relationship between these variables is essential for accurately assessing the impact of the CSPs on agricultural performance. This process is crucial for stakeholders to select the appropriate assessment methods.

Step 5 is the final component of the tool, involving the selection of an appropriate mathematical method to evaluate the impacts of the CSPs on agriculture, their level of adoption in farming activities, and the factors that can influence their adoption by farmers. Depending on the selected CSPs and the available variables, various assessment methods, such as mathematical equations, statistical models, or simulation tools, can be chosen from the database provided by the RAPTURE tool to quantify the potential outcomes and effects. This ensures that the evaluation process is scientifically sound and that the results are reliable for decision-making. The selection of a mathematical assessment method to assess one or more CSPs considers the pillars defined in Step 1 and the expected outcomes. Overall, the RAPTURE tool contains a framework synthesizing the path of the five steps to follow when assessing CSPs. Additionally, the study provides a synthesis of how the operation and adaptation of the tool can be affected across different geographical,

economic, and cultural contexts. Also, it provides detailed information on two widely used assessment methods, the logit model and cost–benefit analysis (CBA), including the names attributed by different scientists, their effectiveness, and their requirements for assessing CSPs. Additional information on the data collected for the conceptualization of the tool can be found in the Supplementary Material.

2.2. RAPTURE Database Creation

2.2.1. PRISMA Framework: Selecting Items for the Databases

This paper reviews 222 studies on CSA and CSAPs published between 2014 and 2023. For this selection process, the PRISMA framework was used to select reference studies, following four principal steps (Figure 2). The steps include (1) Identification, which involved using the keywords “climate-smart agriculture practices” to search the Web of Science database on 11 May 2023; (2) Screening, which entailed reviewing the titles and abstracts of the 231 studies to identify the most relevant ones. Studies that did not focus on CSA and CSPs, lacked access to the full text, or were in languages other than English were excluded; (3) Eligibility, involving a thorough examination of the full texts of the remaining studies after screening, where those lacking substantial information on CSA and CSPs were excluded; and (4) Inclusion of 222 studies used to document useful information for RAPTURE tool development. This systematic approach ensures a comprehensive and unbiased selection of literature, focusing on the most relevant and informative sources on CSA and CSPs.

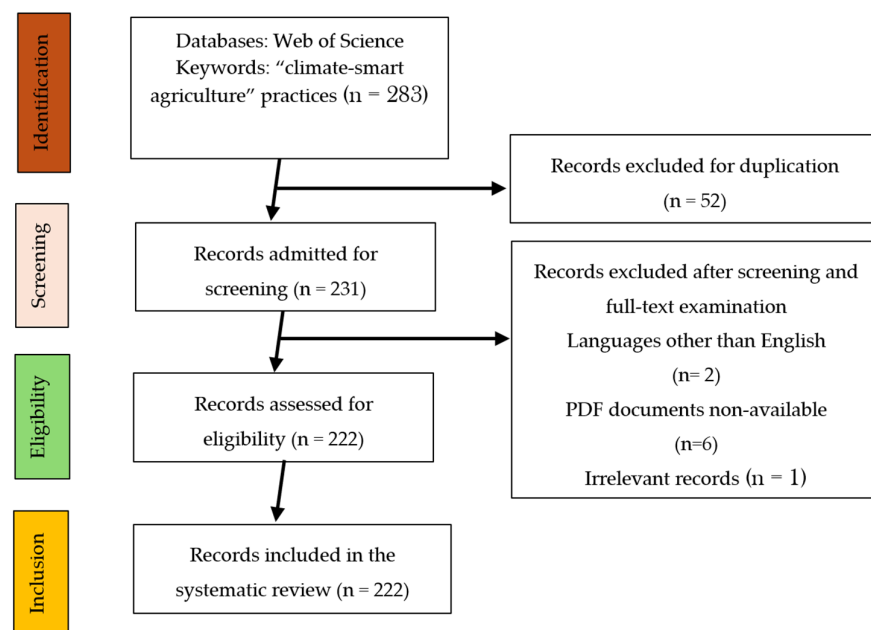


Figure 2. The PRISMA framework describing the selection process of items necessary for the conceptualization of the RAPTURE tool database.

2.2.2. Populating the Database

For the development of the RAPTURE tool’s database, the 222 studies were analyzed to extract information on the description of CSA, the CSPs studied and their classification, as well as data on climatic conditions (precipitation and temperature) for the study areas. Moreover, the equations used in the previous articles to assess CSPs were collected, synthesized, and classified based on the estimated outcomes as stated in the three main goals of the CSA approach. These equations are also presented along with information about each component regarding input (X) and output (Y) variables.

Information was gathered for RAPTURE on CSPs studied and the regions where the research was conducted. Therefore, background information necessary to show the importance of creating this assessment tool was provided through the collection of data on the geographic location of the studies, the number of publications at temporal and spatial scales, and an overview of review studies on the CSA approach. To conduct a bibliometric analysis and provide a background synthesis for the development of the RAPTURE tool, data were collected and compiled on the publication dates and study areas from the studies used in the literature. Moreover, information on the main areas of concern (the pillars of CSA) and how previous researchers have studied, analyzed, and assessed the CSA approach and related practices was also collected and synthesized. Additionally, the factors influencing the adoption of CSPs in the farming sector were also collected, analyzed, and synthesized into figures presenting eight groups of factors and detailed information on these factors that can promote and/or hinder the adoption of CSPs among farmers. Also, advantages and benefits experienced by CSP adopters were also synthesized in this study.

2.2.3. RAPTURE Tool Application

To facilitate the use of the RAPTURE tool and test its applicability by different stakeholders, two scenarios were developed using data on vegetable production, such as sweet corn, cabbage, cucumbers, bell peppers, squash, and watermelons, for Florida from 2021 to 2024, collected from the United States Department of Agriculture (USDA) National Agricultural Statistics Service, specifically from the USDA's National Agricultural Statistics Service Florida Field Office (part of the Southern Regional Field Office) https://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Crop_Releases/index.php (accessed on 28 October 2025) [39]. Also, data on average monthly and annual temperature and precipitation were collected for the state of Florida from 2021 to 2024 from the Florida Climate Center website (<https://climatecenter.fsu.edu/>, accessed on 28 October 2025). In the first scenario, a simple process was adopted, considering productivity as one pillar of CSA. In the second scenario, a more complex method was used, involving two pillars of CSA, productivity and adaptation. For a future scenario (2050), data on incremental changes in temperature and precipitation were collected from [40].

Microsoft 365 (Version 2509), including Excel, Word, and PowerPoint, was used in the realization of this document. Therefore, Microsoft Excel was used to organize the data. Also, PowerPoint, Microsoft Word, and R Studio (Version 2025.05.1+513) were applied to create the figures presented in this study.

3. Results

3.1. RAPTURE Tool Development

Developing the RAPTURE assessment tool is highly valuable to multiple stakeholders in the agricultural system. The tool accomplishes five main objectives to provide a structural pattern to CSP adopters, regardless of their level of knowledge about CSPs. This structured approach provides a comprehensive database and a clear pathway for stakeholders to evaluate and implement CSPs effectively, considering climatic conditions and assessment methodologies. To use the RAPTURE tool for raising awareness of CSPs, the following five steps need to be considered:

Step 1: Simple to Complex and Detailed Definitions of CSA

The first step of RAPTURE's database provides detailed definitions to enhance the understanding of CSA for different stakeholders (Figure 3a,b). Therefore, the tool contains different ways to define CSA, considering all the components necessary for its realization, making the approach both simple and complex to define.

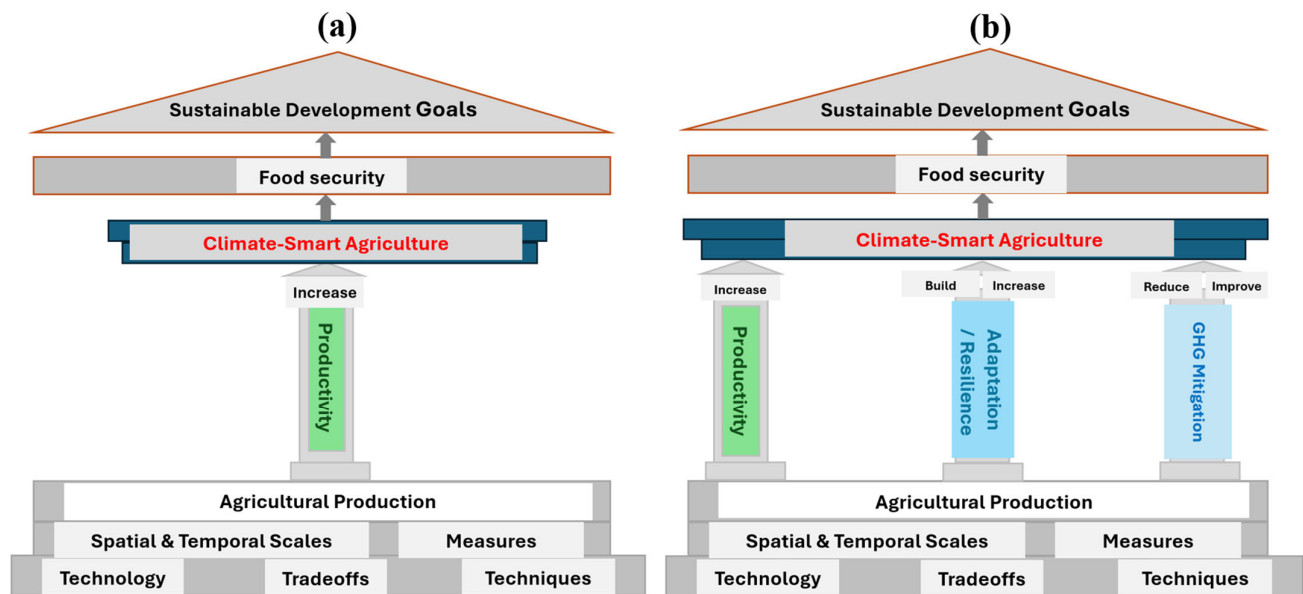


Figure 3. (a) CSA simple and detailed definition; (b) CSA complex and detailed definition.

This study synthesized 35 definitions of CSA and produced a simple to detailed and complex definition depending on the main concepts included, like the number of pillars, impacts, or outcomes (Figure 3a,b). A simple definition includes one pillar. For example, a simple definition of CSA is related to increasing productivity by adopting CSPs to meet food needs (Figure 3a). A complex definition includes more than one pillar, and CSA may be defined as the adoption of CSPs as sustainable practices to increase agricultural productivity, leading to higher farmers' income and household food security while mitigating GHG emissions (Figure 3b). Another complex definition of CSA refers to ensuring resilience in the agricultural system by sustainably coping with variability in weather events and minimizing their negative consequences for an increase in productivity and GHG mitigation through the reduction of gas emissions and increased C storage (Figure 3b).

Further, a detailed definition of CSA incorporates information on impacts, outcomes, scales, techniques, measures, technologies, and trade-offs, and it may include one (simple) to multiple (complex) pillars. For example, a complex detailed definition is the adoption of CSPs to (1) sustainably increase agricultural productivity and income to ensure food security among stakeholders; (2) enhance resilience to current climate challenges through the efficient use of resources such as water and land for maximum agricultural productivity; and (3) protect environmental ecosystems through the diminution of GHG emissions and reinforcement of C sequestration in soil and forests (Figure 3b), considering the characteristics of the technologies and techniques required, along with the trade-offs to consider for obtaining the expected outcomes. The approach of CSA, through these goals, contributes to a comprehensive strategy for sustainable agricultural systems, addressing immediate food security needs and long-term environmental sustainability. The details in the definition of CSA show that implementing CSA requires trade-offs based on priority needs for effective agricultural adaptation at spatial and temporal scales based on specific weather conditions and soil characteristics, which vary significantly by area and season [35,36]. Those details also document the technologies and techniques, i.e., the CSPs, required to enable sustainable agricultural production by efficiently conserving natural resources such as land, water, and nutrients [2]. The aim to address the difficulties of the agricultural system under varying climatic conditions shows CSA's capability to effectively ensure resilience to extreme weather events while maintaining environmental stability and providing necessary

ecosystem services. The definition selected for the application of the RAPTURE tool may include key aspects such as:

Pillars: The core areas (productivity, adaptation, mitigation) of impact that CSA aims to address (e.g., environmental, economic, social dimensions).

Outcomes: Expected results or benefits from adopting CSA, like improving crop yield, increasing income, ensuring food security, increasing resource-use efficiency, enhanced resilience to extreme weather events, reducing GHG emissions, and improving C sequestration.

Scales: The scales, which can be spatial (e.g., farm-level, regional, national) or temporal (e.g., rainy or dry season), at which the CSA is expected to be implemented.

Techniques and Measures: The specific practices or interventions (e.g., improved irrigation methods, soil conservation techniques, rainwater harvesting, legume tree planting, and so on) and how they are measured.

Technology and Trade-offs: The role of technology in CSA implementation, the requirements in terms of knowledge and expertise for the implementation of certain CSPs, and potential trade-offs (e.g., higher initial costs vs. long-term benefits) necessary for their adoption.

A more detailed CSA definition allows stakeholders to understand the multifaceted nature of CSA and makes the assessment process more robust, which is necessary for users who might be new to working with the CSA approach and require detailed information to clearly understand the approach, its goals, and requirements. Therefore, the tool's usability is enhanced by choosing either a simple, complex, or more detailed definition that provides a clearer framework for evaluating CSPs and their expected impacts.

Why This Step is Important: The accuracy of the definitions for an appropriate CSP selection is foundational to the assessment since many stakeholders do not have any knowledge of the CSA approach and will use the tool to learn about the approach and its related benefits. A well-chosen definition of CSA will ensure that the assessment process is aligned with the local context, available resources, and stakeholder goals. Additionally, a detailed and contextually relevant definition of CSA improves the precision and effectiveness of the evaluation, providing stakeholders with a clearer understanding of the potential benefits and impacts of adopting a particular CSP.

Step 2: Climate-Smart Practices and Their Classification

The second step of the RAPTURE tool's database collects and provides a comprehensive list of more than 70 CSPs and gives a holistic categorization, defining the main area of intervention of the CSPs (Figure 4). CSPs were described as agricultural practices with the ability to meet one to three pillars of CSA to ensure sustainable output stability, such as food security, limitation of agricultural land expansion and deforestation, adaptation to water scarcity and drought conditions, and mitigation of atmospheric pollution, among others [34,41]. Therefore, studies may be focused on single practices (e.g., crop rotation, zero tillage, agroforestry, crop diversification, irrigation) or groups of practices (e.g., conservation agriculture, which comprises minimum/zero tillage, mulching/soil cover, and crop diversification) [42,43]. The number of CSPs analyzed and/or assessed in previous studies ranges from one to fifteen [44–46]. Some of the practices had similar functions but were identified with different names. For instance, improved seed varieties and stress-tolerant varieties refer to seeds and cultivars that can resist adverse conditions like drought, salinity, heat/cold, and pest invasion [46–48]. Also, improved grazing and improved pasture practices refer to the sustainable utilization of resources for livestock feeding and management [22,49,50]. In addition, residue retention and mulching are both the use of soil cover systems to increase soil moisture retention, but they differ in that residue retention refers to keeping crop residues on the soil surface, while mulching can

use materials other than crop residues to preserve soil moisture [51–53]. Agroforestry and legume tree planting are CSPs that encourage the introduction of trees in agricultural systems to ensure water and soil conservation, as well as natural fertilization of the soil, but they differ in that several types of trees can be used by an agroforestry system, while legume trees refer to specific plants that facilitate the capture and transformation of nitrogen to naturally fertilize the soil [22,54,55].



Figure 4. List of CSPs collected from the literature; the frequency of each practice is indicated by size, where larger items appear more frequently in the studies.

Choosing a CSP to Assess: Stakeholders need to choose at least one CSP to assess. The tool offers two pathways for stakeholders:

Path 1: The Stakeholder Has a CSP from Their Own List: If the stakeholder already knows which CSP they want to assess, they can proceed by selecting that practice directly. This simplifies the process for those with a clear idea of the practice they want to evaluate.

Path 2: The Stakeholder Chooses CSPs from RAPTURE’s List: If the stakeholder is unsure or does not have enough knowledge of the CSPs, the tool provides an authoritative list of available CSPs (Figure 4). The list includes practices that align with the definitions of CSA and have been studied in different contexts.

When selecting the CSPs to assess, the stakeholder can proceed to the next step of the assessment process if the selected CSP is on the RAPTURE tool's list. However, if the chosen CSP is not on the list, the tool may not be immediately helpful, considering the requirements for the next steps, and additional information or research will be needed to see if the selected CSPs correspond to practices within RAPTURE's list under different names or to find suitable CSPs that fit the context of the tool.

In this study, an updated categorization was developed, and the practices have been classified based on their roles in sustainable farming, focusing on food production, resource-use efficiency, and environmental pollution mitigation. Previous classifications of the practices documented from the literature are primarily centered around soil conservation, water management, nutrient management, and atmospheric cleansing (reducing GHG emissions such as carbon (C), methane (CH₄), and nitrogen (N)) [56–58]. The practices are tailored to specific climate conditions and local agricultural needs, emphasizing their importance in managing resources like water, soil, crops, livestock, energy, and nutrients [57,59,60]. Additionally, some classifications include the type of technologies (both scientific and indigenous), institutional support (financial and educational), and access to information

and communication technologies for decision-making, including weather forecasts [61]. The practices have been further classified based on their impact on the three pillars of CSA: productivity, resilience/adaptation, and mitigation [62]. Other classifications focus on the ability of practices to enable agricultural practitioners to manage weather, knowledge, and other resources efficiently [53,63,64].

The updated classification presented in this study assembles 78 practices and emphasizes the importance of adopting climate-smart strategies to address the challenges faced by the agricultural system due to climatic variability (Figure 5). Therefore, this classification, named climate-smart practices (CSPs), is divided into two main groups (Figure 5a):

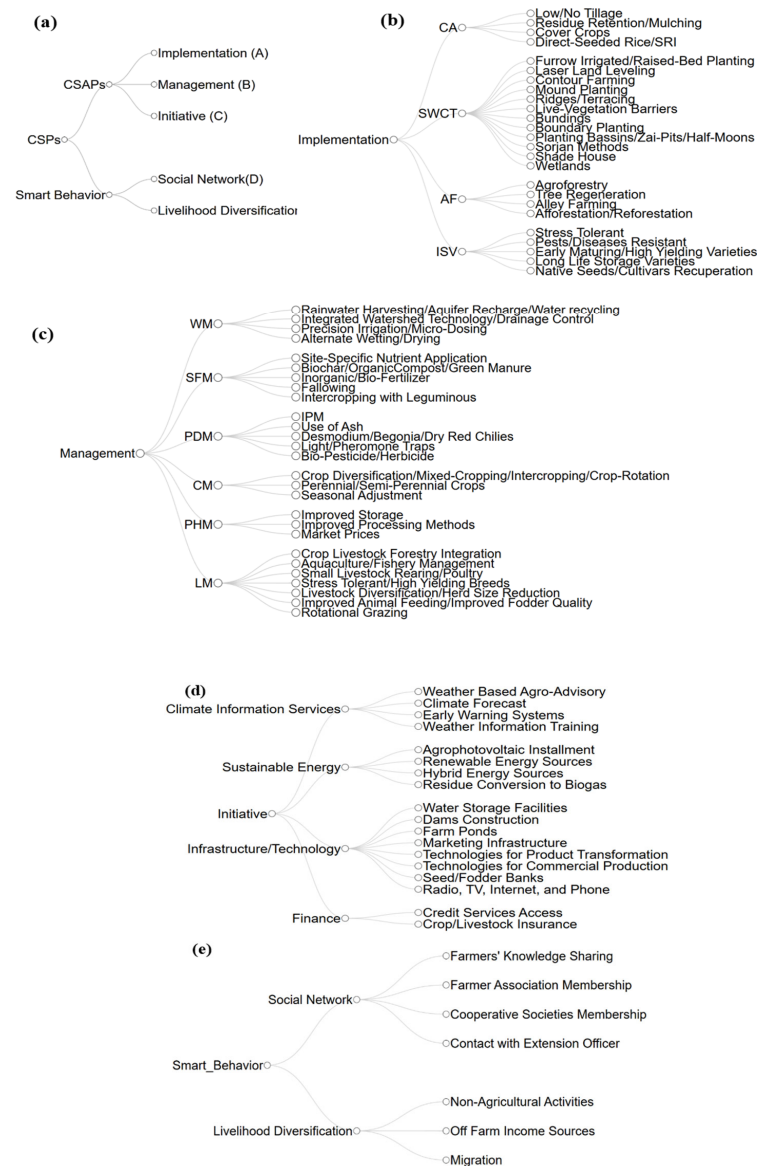


Figure 5. Updated categorization of climate-smart practices collected from previous studies. (a) Categorization of CSPs into two groups; (b) Implementation category; (c) Management category; (d) Initiatives category; (e) Smart Behavior group with Social Networks and Livelihood Diversification categories. CSPs: climate-smart practices; CSAPs: climate-smart agricultural practices; CA: conservation agriculture; SWCT: soil and water conservation techniques; AF: agroforestry; ISV: improved seed varieties; WM: water management; SFM: soil fertility management; PDM: pest and disease management; IPM: integrated pest management; CM: cropping management; PHM: post-harvest management; LM: livestock management.

Group one contains the CSAPs: it includes practices and technologies adopted within the agricultural system, further subdivided into the categories of Implementation (Figure 5b), Management (Figure 5c), and Initiatives (Figure 5d).

Group two refers to smart behavior: it focuses on people's daily actions and lifestyle choices, including the categories of Social Networks and Livelihood Diversification (Figure 5e), to cope with climate challenges.

Within the CSAPs group, Implementation involves farmers' actions to establish agricultural activities that adapt to climate challenges for successful production. Subcategories of practices in this category include conservation agriculture, soil and water conservation techniques, agroforestry, and improved seed varieties [45,58]. Next, the Management category focuses on the sustainable and optimal use of available resources for food production. It encompasses the subcategories of water management, soil fertility management, livestock management, pest and disease management, cropping management, and post-harvest management [57,61]. Additionally, the Initiatives category includes technologies and institutional interventions that enable farmers to operate and live in a climate-smart manner. It also comprises the subcategories of climate information services, infrastructure and technology, sustainable energy, and financial support [42,65].

The smart behavior group focuses on mitigating the impacts of climate challenges on overall living conditions through people's lifestyles and is divided into two categories. The first is Social Networks, involving networking events among farmers where they share knowledge and experience through associations and cooperative societies while maintaining contact with extension officers to obtain useful knowledge in the agricultural domain, enabling them to face climate challenges [53,66]. These organized activities aim to provide farmers with the skills necessary to enhance resilience to climate challenges within their farming activities through mutual support. The second category is Livelihood Diversification, which emphasizes the importance of engaging in activities other than agriculture or migrating to places with better opportunities to obtain income and sustain livelihood needs [45,62]. By diversifying income sources, households can reduce their dependence on agriculture, alleviating pressure on the sector.

Identification of the category to which the assessed CSP belongs: five collapsible trees are provided in Figure 5. The first tree is a detailed representation of the two groups (CSAPs and smart behavior) and five main categories of CSPs identified as Implementation, Management, Initiatives, Social Networks, and Livelihood Diversification. The other four trees represent the principal categories of CSPs, followed by their subcategories and the practices to assess, except for the tree representing the smart behavior group, which contains two categories followed by the corresponding CSPs without subcategories. To verify the category of the practice to assess, it is important to identify the collapsible trees to which the practices correspond (b, c, d, and e):

The position of the practice to assess: CSPs are normally positioned at the tree's last stage (b, c, d, and e).

The subcategory of the selected practice: This is the second stage of the collapsible trees (b, c, and d). The tree for smart behavior (e) does not have subcategories.

The category of the practice: The main category to which the selected practice belongs is in the first stage of the trees for Implementation, Management, and Initiatives, except for the smart behavior tree, where categories appear in the second stage.

The practice group: Practices belong to two main groups, which are CSAPs and smart behavior. To identify the group to which an assessed practice belongs, users should refer to the categories of the practices. Therefore, the categories Implementation, Management, and Initiatives belong to CSAPs, while Social Networks and Livelihood Diversification fall under smart behavior.

If the selected CSP to assess is not included in the categorization presented in this study, it must be compared to existing practices in search of similarities or replaced with one available in the provided list, in the case of a completely new practice with no similarity to those included in this study (Figure 4), for which a category is available (Figure 5). In conclusion, to identify the category in which a practice is found, it is important to note that all the trees have three stages. For Implementation, Management, and Initiatives trees, these stages are, from back to front, the practices, subcategories, and categories, except for Social Networks and Livelihood Diversification, which do not have subcategories; their stages are, from back to front, the practices, categories, and groups to which they belong. Selecting a practice with an available category is crucial to using the RAPTURE tool features.

Why This Step Is Important: Overall, this updated categorization provides a comprehensive framework for understanding and implementing CSPs in both agriculture and daily life, addressing the multifaceted challenges arising from weather events. It is also necessary to consider the complementarity that exists between the two groups of practices, where people's smart behavior will allow farmers to increase their chances of success in adopting CSPs. For instance, farmers who benefit from knowledge shared by other farmers through experience and extension officers while adopting CSPs ensure a higher likelihood of achieving improved productivity, adaptation, and GHG mitigation.

Step 3: Weather Condition Ranges Observed with CSPs

The RAPTURE tool's database provides synthesized data on the range of temperatures and precipitation observed in study areas where CSPs have been implemented. Knowing the climatic characteristics of places that have experienced success or failure in implementing CSPs remains crucial for decision-making when adopting and evaluating the CSA approach. This knowledge will enable stakeholders to adjust their technical management, increasing their chances of success in applying CSPs when aligning their activities with the weather conditions. Data on temperature and precipitation collected from previous studies were combined and plotted to present a range for the practices grouped into subcategories (Figure 6). For instance, the temperature ranges registered by subcategories of CSPs were 0–45 °C (agroforestry, cropping management, stress-tolerant varieties, and soil fertility management) [56,67], 4–45 °C (conservation agriculture, pest and disease management, and water management) [68,69]; 0–40 °C (soil and water conservation techniques) [70,71]; and −8.98–45 °C (livestock management) [72,73]. For the precipitation data collected, the ranges were 50–3000 mm (stress-tolerant varieties, conservation agriculture, and water management) [74,75]; 50–2200 mm (cropping management) [76,77]; 50–2500 mm (pest and disease management) [41,78]; 200–2500 mm (soil fertility management) [48,79]; 200–3800 mm (agroforestry and soil and water conservation techniques) [80,81]; and 300–2200 mm (livestock management) [49,63].

Identification of the optimum weather condition ranges: To find the temperature and precipitation ranges for a selected CSP to assess, it is necessary to:

Locate the related subcategory: Each plot in the figure represents a subcategory. Users must go to the collapsible trees and find the subcategory to which the selected practice belongs (Figure 5). Subcategories are positioned in the second stage of the Implementation, Management, and Initiatives trees, except for Social Networks and Livelihood Diversification, which do not have subcategories.

Find the range of temperature and precipitation from literature data: Refer to Figure 6 and locate the correct information about temperature and precipitation ranges for the selected CSP based on the subcategory.

Find and compare the range of temperature and precipitation for the area of concern with the data from literature: Data on weather conditions for the area considered for

the CSP implementation are necessary for comparison with weather data provided in the literature. Such data are often available on official climate information websites.

Why This Step is Important: Verifying the optimum ranges for temperature and precipitation collected from the literature for areas where CSPs have been studied and assessed is important for comparison with the climate conditions of places considered by users of the RAPTURE tool when assessing CSPs.

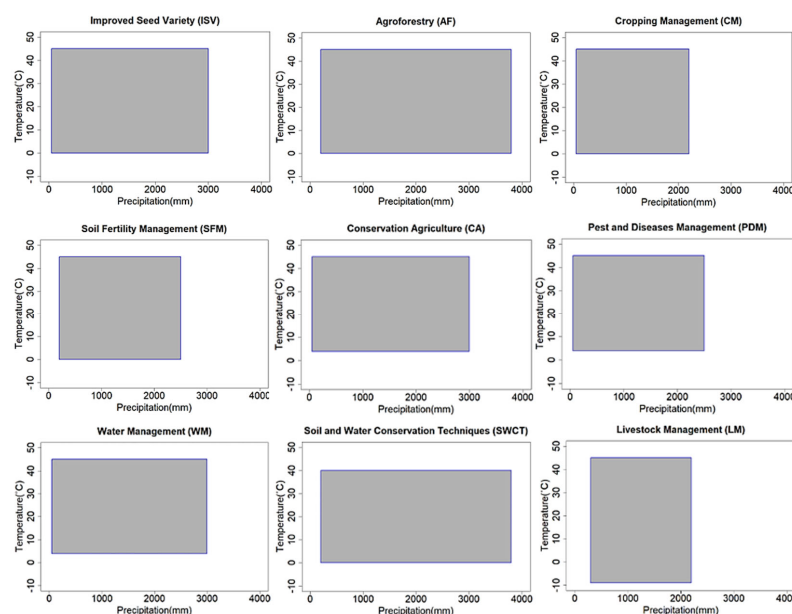


Figure 6. Synthesized optimum weather conditions for CSP implementation.

Step 4: Input and Output Variable Availability for CSP Assessment

In the fourth step of the database created to conceptualize the RAPTURE tool, the input and output variables necessary for the assessment process of CSPs were collected and provided (Table 1). According to the RAPTURE database, researchers have studied the adoption of CSPs among farmers while investigating their impacts on agriculture, considering the three pillars of CSA as outcomes.

Adoption of CSPs

The adoption of CSAPs in the agricultural system has been assessed using statistical methods such as the logit model and problem confrontation index (PCI) approaches. These methods used key variables such as the level of awareness of CSPs, acceptance level of CSPs, usage of CSPs, adoption decisions, determinants of adoption, and factors influencing CSP adoption in the assessment process [28,53,116]. Several variables have been assessed for their ability to affect CSP adoption and are known as characteristics of farmers, farms, and institutions involved in agricultural activities [54,85].

Productivity

The productivity pillar is assessed using outcome variables such as crop yield, farmers' income, and household food security through assessment methods such as statistical models (e.g., the logit model), food security models (e.g., food consumption score (FCS)), cost-benefit analysis (CBA) models [51,94,116]. Many input variables used in assessing productivity are capital input, labor, production input costs, water availability, household and farm characteristics, livestock ownership, distance to market, and institutional support, among others [38,80,87,88]. The crops studied include maize, rice, and wheat [51,80,100].

Table 1. List of equations synthesized for assessing CSPs.

Equations	Variable Description	Citations
Logit model $Y_i = \beta_0 + \sum_{i=1}^n \beta_i X_i + \varepsilon_i$ Endogenous switching regression (ESR) $Y_i = X_i \beta + \varepsilon$ Multinomial logit (MNL) model $CSA_{ijt}^* = \sum_{j=0}^J \beta_j M_{ijt} + \omega_i R_{ijt} + \alpha_i + \varepsilon_{ijt}$	Y: Crop production/Crop yield; Technical, economic, and water use efficiency; Productivity; Income; Area expanded into forests; Household food security status; Farmers adopting CSA/agroecology or conventional farming; Farming irrigation adoption decision; Smart agriculture adoption behavior; CSAF adoption X: Gender; Household size; Educational level; Religion; Migrant; Dependency ratio; On-farm income; Off-farm income; Farming experience; Access to farm credit; Household participation in farming; Tubewell ownership; Access to information; Farmers' cooperative society membership; Extension officers' contact; Family status; Arable land; Distance to market; Soil fertility; Storage; Area under CSA; Gross value of harvest capturing agricultural productivity; Adult equivalent measuring labor availability; Total landholding net of expanded area; Farm tenure; Application rates for seed and fertilizer; Prices for fertilizer and seeds; Recordkeeping of farm activities; Participation in farmer input subsidy program; Access to credit; Access to extension officers' advice; Land ownership; Farm distance from home; Certification; Livestock ownership; Agricultural wealth index; Cellphone ownership; Distance to paved road; Rainfall; Temperature; Flood incidence; Market availability; Auction place; Irrigation scheme; Agricultural collective action; Use of inorganic fertilizers; CSA adaptation level; Farm size; Number of farms; Residence status; Climate Field School (CFS) membership; Pond size; Market difficulty; Access to farm information; Perception of climate change; Membership in project; Farm mechanization; Hours worked per week; Crop species richness; Land title deed; Contact with agricultural extension and labor; Off-farm activities; Group membership; Farmer type; Annual turnover (TWD); Distance to district headquarters; Slope; Soil quality and soil type; Drought experience; Fertilizer; Seed; Labor; Organic fertilizer; Site; CSAF treatment; Season; Access to production and marketing information; Ownership of radio; Road condition; Group membership; Institutional support; Financial conditions; Asset index; Resource constraints and market access; CSAF information; Group membership; Rainfall shocks	[17,49,54,76,80,82–98]
$\Delta XCSA \text{ practice} = (XCSA \text{ practice} - Xcontrol)/XControl$	Y: Yield; Water use efficiency X: CSAFs; Control	[99]
$REY \text{ (Mg ha}^{-1}\text{)} = [\text{Yield of respective crop (Mg ha}^{-1}\text{)} \times \text{MSP of respective crop (INR Mg}^{-1}\text{)}]/[\text{MSP of rice (INR Mg}^{-1}\text{)}]$	Y: Rice equivalent yield (REY) X: Crop cycle; MSP: Minimum support price of crop; INR: India National Rupee	[21,51,100]
Productivity = Yield/ha/crop cycle Net income = gross income (from the sale of rice crops and alternative products) – total fixed and variable costs	Y: Productivity; Net income X: Yield; Gross income; Costs	[101]
FCS = w × f (cereals and or tubers) + w × f (pulse) + w × f (milk) + w × f (fruit) + w × f (meat and or fish) + w × f (sugar) + w × f (vegetables) + w × f (oil) + w × f (condiments) Regression model: $\ln(FCS_i) = \beta_0 + \beta_1 \ln T_Density_i + \beta_2 \ln T_Diversity_i + \sum_{i=3}^n \beta_i \ln X_i + \varepsilon_i$	Y: Income and food security X: Household (age, size, education, farming experience, dependency ratio) or farm characteristics (distance to market, size), livestock unit, tree density, tree diversity, extension services, access to farm credit	[44]
$\text{Income (I)} = \text{Gross Output Value (GOV)} - \text{Total Production Cost (TPC)}$	Y: Income X: Gross output value; Production cost	[83]
Cost-benefit analysis (CBA) $NPV = \sum_{t=1}^n \frac{B_{nt}}{(1+i)^t} - I_0$ $NPV = \sum_{t=1}^n \frac{B_t - C_t}{(1+r)^t}$ $NPV_{j}^{CSS-bau} = \sum_{t=1}^T \frac{1}{(1+r)^t} \left[\sum_{j=1}^j \left\{ P_{jt} * \left(\Delta Y_{jt}^{CSS-bau} - \Delta C_{jt}^{CSS-bau} \right) \right\} \right]$ $\Delta Net \text{ Benefit}_{tCSA}^{} = \left[\sum_i Price \text{ Product}, "i, ", *, Yield_1^{CSA}, -, Yield_1^{CP} \right]_t - \left[Cost_i^{CSA}, -, Cost_i^{CP} \right]_t$ $\frac{B}{C} = \sum_{t=0}^T \frac{B_t}{(1+r)^t} / \frac{C_t}{(1+r)^t}$ Benefit Cost Ratio (BCR) = $\frac{\text{Total Revenue (TR)}}{\text{Total Cost (TC)}}$ Payback Period (PP) = $\frac{\text{Initial Investment}}{\text{Net Cashflow Period}}$	Y: Discounted future net benefit; Relative profitability of CSPs adopted; Private profitability and relative risk indicators of CSP adoption X = CSAFs compared to the business as usual (BAU) practice BNt (net benefits per period), I0 (initial value of investment), and n (number of periods considered) Product price of the crop affected by the CSS adoption, incremental yield, change in the cost of implementing the CSS practice per year, discount rate (the cost of capital), lifecycle of the practice in consideration, maintenance cost (harvest threshing, labor for harvesting, machinery used for harvesting, storage facilities), and inputs (costs of seeds, fertilizers, pesticides, and storage bags). T: the lifecycle of the adaptation practice; r: relevant discount rate; B: benefits; C: costs; I0: initial value of investment; Pjt: product price of the crop affected by the CSS adoption; $\Delta Y_{jt}^{CSS-bau}$: the incremental yield $\Delta C_{jt}^{CSS-bau}$: the change in the cost of implementing the CSS practice per year	[29,55,56,102]
$\text{Soil moisture storage (SMS(\%))} = \left[SMC / \left(\rho_b \times d \right) \right] \times 100$	Y: Soil moisture storage X: Soil moisture content (SMC); soil bulk density (ρ_b); soil depth (d)	[99]
Evapotranspiration (ET) = P + ΔSWS Soil water storage (SWS) = $\bar{\theta} \times L$	Y: Evapotranspiration/water loss; Soil water storage (SWS) X: P = precipitation (mm); ΔSWS = difference in soil moisture storage (mm) between planting and harvesting stages; $\bar{\theta}$: volumetric available soil water content at a given depth (mm cm^{-1}); L: the rooting depth (cm)	[103]
$WUE = \text{Yield}/\text{ET (mm)}$	X: Water use efficiency (WUE) Y: Yield (kg ha^{-1}); ET: Evapotranspiration (mm)	[99,103,104]
$\text{Rainfall use efficiency (RUE)} = \text{Yield}/\text{Precipitation}$	Y: Rainfall Use Efficiency (RUE) X: Yield (kg/ha): mass (kg) of grain dry matter produced per hectare; Precipitation (mm): received during the rainy season	[105]
Water Productivity Irrigation (WPI) (kg m^{-1}) = Yield (kg ha^{-1})/Irrigation water used ($\text{m}^3 \text{ ha}^{-1}$) or Water Productivity (WP) = Yield/TWI WPI_{I+R} (kg m^{-1}) = Yield (kg ha^{-1})/Irrigation + Rainfall water used ($\text{m}^3 \text{ ha}^{-1}$)	Y: Water productivity X: Yield; Irrigation (I) and/or rainfall (R) water; Total water input (TWI) based on rainfall and irrigation	[21,51,106,107]

Table 1. Cont.

Equations	Variable Description	Citations
$A_{h,t} = \left(1 + K_j + \eta_j + \eta_d\right)A_{h,t-1}$	Y: Farm plot fertility X: K: discount (degradation) rate; η_1 : the CSA effect on soil fertility	[38]
Quantitative changes = the quantities of the current land use class minus the quantities of the past land use class Percentage on change = Area of observed change/Total area $\times$ 100	Y: CSAP effects on improved livelihoods X: Current land use; past land use	[108]
Problem confrontation index (PCI) $PCI = (P_{vh}X4) + (P_hX3) + (P_mX2) + (P_lX2) + (P_nX0)$	Y: Constraints to adopt CSP X: Pvh = Total number of farmers who expressed the problem as very high; Ph = Total number of farmers who expressed the problem as high; Pm = Total number of farmers who expressed the problem as medium; Pl = Total number of farmers who expressed the problem as low, and Pn = Total number of farmers who expressed the problem as not at all	[44]
Agro-IBIS agroecosystem model Albedo for ecosystem: $a_{eco} = f_{can}(1 - f_{snow})a_{can} + (1 - f_{snow})(1 - f_{can})a_{soil} + f_{snow}a_{snow}$	Y: Ecosystem albedo (α_{coco}) X: α_{can} : albedo of the crop canopy; α_{soil} : albedo of the soil; α_{snow} : albedo of the snow; f : fraction of soil covered by snow (f_{snow}) and canopy (f_{can})	[109]
Total weed density (TWD) = sum of the individual density of all weeds (no. m^{-2}) Relative weed density (RD, %) of species in the whole weed community = density of a given weed species/total weed density in each scenario Species richness (S): number of species that exist in a quadrat Species diversity: $H' = -\sum Pi \times \ln Pi$ and ($Pi = Ni/N$) (Shannon–Wiener index) Degree of community dominance: $D' = \sum Pi^2$ (Simpson index) Community evenness: evenness index (Pielou index): $J = H' / \ln(S)$	Y: Weed density and diversity X: Density; species richness; community dominance; community evenness	[110]
Energy use efficiency ($MJ^{-1} MJ^{-1}$) = Total Energy Output ($MJ ha^{-1}$)/Total Energy Input ($MJ ha^{-1}$) Energy productivity ($kg MJ^{-1}$) = Yield output ($kg ha^{-1}$)/Total energy input ($MJ ha^{-1}$)	Y: Energy use efficiency X: Yield; Energy input; Energy output	[21,51]
(I) CCAFS—MOT: Climate Change Agriculture and Food Security (CCAFS)-Mitigation Options Tool (MOT) Global warming potential (GWP) ($kg CO_2\text{-eq.} ha^{-1}$) = ($CO_2 (kg ha^{-1}) + N_2O (kg ha^{-1}) \times 298 + CH_4 (kg ha^{-1}) \times 34$) GWP = Total CO_2 Emissions $\times 44/12 + CH_4 ac \times 21 \times 16/12 + N_2O ac \times 310 \times 44/28$	Y: GWP X: CO_2 ; CH_4 ; and NO_2 All GHGs are transformed into CO_2 -equivalents ($CO_2\text{eq.}$) using 34 and 298 GWP for CH_4 and N_2O , respectively	[21,51,105,111]
FAO Ex-Ante Carbon-Balance Tool (EX-ACT)	Y: GHG emissions and C sequestration X: Methane (CH_4) and Nitrogen oxide (N_2O) emissions expressed in tons per hectare of carbon dioxide equivalent (t $CO_2\text{-eq/ha}$)	[77,83]
GrowAsia Counter Tool GHG emission is measured in terms of total annual emissions of carbon dioxide equivalents ($CO_2\text{eq}$)	Y: Estimating the GHG emissions for different rice management scenarios X: Tillage and other soil management practices, nutrient management practices, liming, crop residue burning and decomposition, pesticide and herbicide use, agroforestry practices, fossil fuel use, and rice irrigation.	[101]
Net life cycle GHG emission: $NGHG (t CO_2eq ha^{-1}) = TGHG - SOCA$	Y: GHG emissions X: TGHG: Total GHG emission (t $CO_2eq ha^{-1}$); SOCA: Soil Organic Carbon accumulation per unit land (t $CO_2eq ha^{-1}$)	[107]
Sustainable SOC Index: $SSOCI = (\overline{SOC} - \sigma_{SOC})/SOC_{max}$ Sustainable Yield Index: $SYI = (\overline{yield} - \sigma_{yield})/yield_{max}$	Y: SOC; Yield X : $\overline{SOC}$ and $\overline{yield}$: mmean of the detrended SOC and yield; σ_{SOC} and σ_{yield} : standard deviations of SOC and yield; SOC_{max} and $yield_{max}$: maximum SOC and yield detrended values	[112]
Soil Organic Carbon (SOC) stock = soil C content $\times$ BD $\times$ soil depth $SOC Stock [Mgha^{-1}] = \sum_0^n SOC [gkg^{-1}] \times BD [Mgm^{-3}] \times T[m]$ Soil carbon stock: $C = (SOC \times BD \times L)/10$ Soil Carbon sequestration ($Mg ha^{-1}$) = SOC stocks (AFS) – SOC stocks (control) $\Delta C = (CCSA - CREF)/t$	Y: SOC X: Soil carbon (C) content (%); BD: bulk density (g/cm^3); T: Soil depth (cm); L: thickness of the soil layer (cm); ΔC : rate of soil C stock change ($Mg ha^{-1} yr^{-1}$); CCSA: soil C stock in an area under given CSA practice ($Mg ha^{-1}$); CREF: soil C stocks in the reference area ($Mg ha^{-1}$); t: time since the adoption of the CSA practice (years)	[23,24,68,113,114]
Soil Carbon sequestration ($Mg ha^{-1}$) = SOC stocks (AFS) – SOC stocks (control)	Y: C sequestration X: Soil organic carbon (SOC) stocks under agroforestry (AFS); Soil organic carbon (SOC) stocks (control)	[24]
Response Ratio (RR): $\ln RR = \ln (\overline{X}_t / \overline{X}_c) = \ln \overline{X}_t - \ln \overline{X}_c$	Y: SOC X: X_t and X_c : SOC values for the treatment and control groups, respectively	[19,115]
CSA effectiveness index (CSAEI) = $w_1 \times$ Productivity (%) + $w_2 \times$ Income (%) + $w_3 \times$ Resilience (%) + $w_4 \times$ Mitigation (%) Upscaling potential of CSA interventions (CSAUPI) = $[(v_1 \times$ Technical feasibility + $v_2 \times$ Cost of technology + $v_3 \times$ Gender inclusivity + $v_4 \times$ Synergy with Government plans)/maximum possible score] $\times$ 100	Y: CSAEI X: Productivity, income, resilience, mitigation w_1, w_2, w_3, w_4 : weight for respective indicator of CSA estimated based on farmers’ response Technical feasibility, cost, gender, synergy v_1, v_2, v_3, v_4 : values indicating the weights estimated based on principal component analysis (PCA).	[61]

Adaptation and Resilience: Resource-Use Efficiency

The adaptation and resilience of agricultural systems towards weather events are primarily assessed through the efficient use of resources such as water, energy, and nutrients. This study has compiled and synthesized different equations, including statistical methods like the logit model and other mathematical equations, such as water-, nutrient-, and energy-use efficiency models, and water productivity equations [51,117,118]. Input variables such as crop yield, water input (irrigation and/or rainfall), soil depth, nitrogen inputs from fertilization, atmospheric deposition, and energy input [21,51,99,106].

GHG Mitigation

The evaluation of the mitigation pillar in the CSA approach focuses on several key aspects, such as GHG intensity, which estimates GHG emissions from agricultural activities, and C sequestration, which enhances C removal from the atmosphere through sequestration into soil and forest biomass. The assessment of GHG mitigation has been conducted using many equations. These equations assess C sequestration in terms of soil organic carbon (SOC) and GHG emissions from the agricultural system through global warming potential (GWP) [24,77,107,114]. Additionally, different assessment tools, such as the FAO Ex-Ante Carbon-Balance Tool (EX-ACT) and the GrowAsia Counter Tool were used in some studies to estimate both GHG emissions and C sequestration [83,101]. This approach ensures a comprehensive evaluation of the mitigation pillar, highlighting the importance of both reducing emissions and enhancing carbon sequestration in agricultural systems. The input variables used for GHG mitigation were crop yield, soil organic carbon or soil carbon content, carbon dioxide, nitrogen, methane, bulk density, soil depth, and so on [106,111,113,115].

Other Variables

The results show data from many studies that have evaluated the impact of CSAP adoption in the agricultural system through numerous outcomes identified as ecosystem services, including changes in soil albedo, abundance of soil fungi, natural weed control, and increases in forested areas. The assessment methods reported provide information on outcomes related to plants (e.g., natural control of weeds and forestry), biodiversity (microbial and fungal expansion), and land (e.g., areas expanded into forests and soil albedo) [68,93,109]. Among these assessment methods, a tool developed by the Tropical Agricultural Research and Higher Education Center (CATIE) is used to estimate the overall biodiversity index [55]. Input variables considered at that level of assessment include crop canopy and snow cover, soil, soil organisms, weed species, land use, etc. [100,108–110].

Output and input variable detection: Information on the input and output variables for the three different pillars of CSA is provided in the RAPTURE tool database. For each pillar, detailed information about the input and output variables used in previous studies is available to assess CSPs. Another group of assessment methods estimated specific output variables not identified in the three pillars of CSA but primarily focused on certain ecosystem services obtained from CSP adoption, which are also documented in this study.

Availability of output and input data: This step also requires confirming the data availability needed to estimate these variables. The data can be primary data collected from fieldwork and/or secondary data gathered from previous scientific studies.

Why This Step is Important: Knowing the input and output variables that will be considered for the assessment of CSPs enables users to easily determine the availability of variables necessary for the process. This step is very helpful in simplifying the selection of the mathematical assessment method corresponding to the users' objectives.

Step 5: Assessment Methods of CSPs

The fifth and last step of the RAPTURE tool's database documents and synthesizes 24 equations that assess CSPs. These comprehensive approaches are important for understanding the effects of CSPs on agricultural sustainability and adaptation to climatic challenges. Drawn from multiple studies, these equations provide a comprehensive framework for evaluating the main pillars defining CSA as the primary outcome of using CSPs in agriculture. The assessment methods are classified as evaluating the level of acceptance of CSPs among farmers and their level of adoption, which can be increased or decreased based on specific factors. In addition, these methods assess the impact of CSPs on agriculture, considering the three pillars (goals). Some methods, like logic models, are used for all pillars, while others have been applied for the assessment of one to two pillars [19,66,97].

Selection of Mathematical Assessment Methods

Main pillars for mathematical assessment selection: The three pillars consist of the main goals achieved through the adoption of CSA. The first pillar, agricultural productivity, has specific outcomes such as improved crop yield, farmers' income, and food security. The expected outcomes for adaptation and resilience, the second pillar of the CSA approach, are resource-use efficiency, considering the use and importance of resources such as water, nutrients, and energy to maintain agricultural productivity. For the third pillar, mitigation, the expected outcomes are GHG emission reduction/suppression and C sequestration or soil organic carbon augmentation. Other estimation methods related to various ecosystem services are also provided, in which expected outcomes vary, including soil albedo, soil fungi abundance, natural weed control, and expanded forestation in areas under CSPs.

Why This Step is Important: This step is crucial to select the right mathematical equations where the available data can be applied to assess the CSPs and demonstrate their capability to meet the main pillars of CSA. The RAPTURE tool provides equations to assess CSP impacts based on the main goals of the CSA approach: to increase productivity (crop yield and income) and ensure food security, to build resilience to climate challenges, especially by improving resource-use efficiency, and to mitigate GHG emissions (reduce or eliminate GHG emissions and enhance atmospheric cleansing through C storage).

Overall, the RAPTURE tool provides a structured, data-driven approach to selecting and assessing CSPs, making it easier for stakeholders to choose practices well-suited to their local conditions and needs. It facilitates a comprehensive understanding of how CSPs can impact agriculture, helping to make informed decisions that support sustainable, environmentally friendly, and climate-resilient farming practices. The assessment tool further provides a flowchart that schematizes the stages to consider and follow for assessing CSPs (Figure 7). The RAPTURE tool is a document that will be available online for all types of stakeholders, regardless of financial conditions.

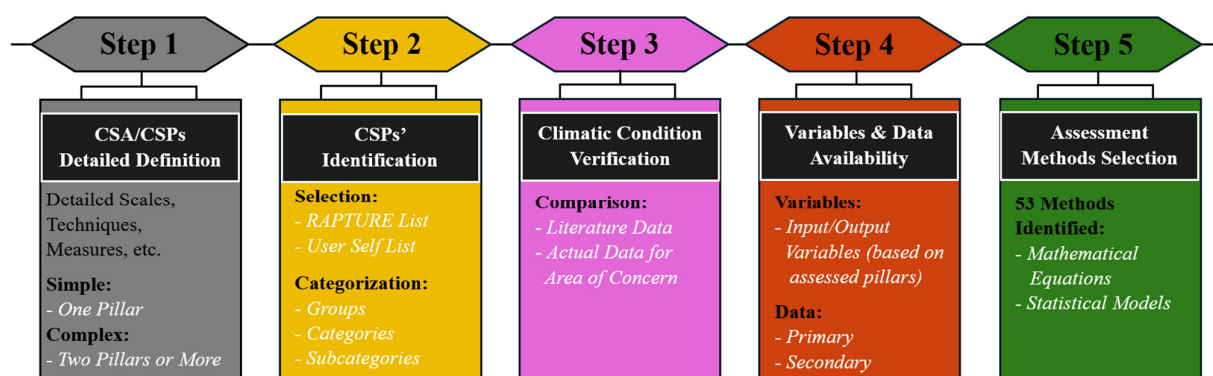


Figure 7. RAPTURE tool flowchart describing the steps for CSPs assessment.

RAPTURE Tool in Different Scenarios

The RAPTURE tool contains information on its operability and applicability across different contexts considering the area, the users' culture, and their economic conditions (Table 2). The definitions accepted by users of the tool may require translation based on their geographic location or may differ in the concepts and outcomes provided by the tool according to cultural context. For the selection of CSPs, users may face economic constraints related to the high costs of materials and/or their installation and operability. The selection of certain CSPs may present geographic and cultural restrictions explained by the accessibility of specific equipment and local features related to weather conditions and/or soil type, as well as attachment to traditional practices that make it culturally difficult to adopt new ones. Verification of climatic conditions can also create economic pressure for users, as some may not have access to devices (e.g., radios, televisions, phones, electricity, and/or batteries) to obtain weather information due to financial constraints. In some geographic contexts, weather forecast services may be unavailable, while in certain cultural contexts, users may not believe in scientific weather data due to traditional beliefs. Users may access data availability and select assessment methods easily without major economic or cultural barriers. However, data on some required variables may be difficult to obtain in geographic areas lacking a database, which may require users to collect data themselves, making the process more time-consuming and cost-intensive.

Table 2. Operability and adaptability of the RAPTURE tool across different geographical, economic, and cultural contexts.

RAPTURE Steps	Economic Context	Geographic Context	Cultural Context
1. CSA Definition	No economic impacts	Possibility of language constraints	Cultural concerns linked to concept acceptance
2. CSP Selection	Economic constraints due to high material costs and requirements	Geographic issues related to accessibility, weather conditions, and soil type	Attachment to traditional practices
3. Climatic Condition Verification	Economic difficulties related to the acquisition of devices	Absence of weather forecast services	Lack of belief in scientific weather data
4. Input/Output Variable Availability Identification	No economic impacts	Data not available due to lack of database	No cultural impacts
5. Assessment Method Selection	No economic impacts	No geographic impacts	No cultural impacts

Most Used Assessment Methods Documented

Among the assessment methods registered for CSPs, the logit model and the cost-benefit analysis (CBA) model were the most commonly used. Therefore, this study provides information on specific features of both assessment methods to help users select appropriate assessment techniques (Table 3). Ultimately, the logit model has been widely used by researchers to assess all the pillars of the CSA approach, which are productivity, adaptation, and mitigation, as well as to analyze factors influencing farmers' behavior in adopting CSPs. The CBA approach has been effectively used to analyze the economic profitability of several CSPs, allowing adopters to make informed decisions when investing in agricultural innovations. Therefore, the selection of an assessment method may consider the outcomes expected by users in relation to the CSA pillar of interest. For instance, the logit model is more applicable for users seeking information on the effects of certain CSPs across multiple pillars, while the CBA is better suited to evaluating CSPs with the greatest potential economic benefits.

Table 3. Presentation of certain features in using the logit model and cost–benefit analysis (CBA) approach for assessment.

Equations	Attributed Names	Data Types	Accuracy	Expertise Requirement	Areas of Assessment
$Y_i = \beta_0 + \sum_{i=1}^n \beta_i X_i + \epsilon_i$	Bivariate correlation and multiple linear regression [86,87] Double-log production model [88] Endogenous switching regression Strategy [49,90] Instrumental variables (IVs) approach [93] Regression model [17,44] Multivariate probit model/Probit regression model [54,76,84,94,97] Dynamic mixed multinomial logit model for panel data (dynamic MMNL) [91] Binary logistic regression model/Binomial logistic regression [82,83] Micro-econometric structural Ricardian model [96] Multiple ordinary least squares (OLS) regression/Ordinary least squares (OLS) regression models [85,89] Generalized Linear Mixed Models (GLMM) [98] Conditional logit (CL) and two-stage panel-based censored Tobit model [80]	Primary and secondary datasets used	Commonly used model Problem with heteroscedasticity or nonconstant variance Accounts for the selection bias Ability to split the random error term's impact from the inefficiency effect Flexibility to estimate either a standard, uniform, or log-normal choice distribution Determine possible complementarities (positive correlation) and substitutability (negative correlation) between the CSPs Captures unobserved heterogeneity Most efficient when data contain repeated choices by the same respondents	Software expertise for: Data conversion Test the fitness of the models Validate the models Adjust continuous independent variables due to non-normality Avoid potential multicollinearity Test data for normality and homogeneity of variance Separate the means when the Fisher test was significant	Productivity Food security Income Crop Yield Adaptation Mitigation Drivers of CSPs adoption Adoption decision and intensity of CSPs
	NPV = $\sum_{t=1}^n \frac{BN_t}{(1+i)^t} - I_0$ $NPV = \sum_{t=1}^n \frac{B_t - C_t}{(1+r)^t}$ $NPV_J^{CSS-bau} = \sum_{t=1}^T \frac{1}{(1+r)^t} \left[\sum_{j=1}^J \left\{ P_{jt} * \left(\Delta Y_{jt}^{CSS-bau} - \Delta C_{jt}^{CSS-bau} \right) \right\} \right]$ $\Delta Net Benefit_t^{CSA} = \left[\sum_i Price Product_{i,t}, i, *, Yield_i^{CSA}, -, Yield_i^{CP} \right]_t - \left[Cost_i^{CSA}, -, Cost_i^{CP} \right]_t$ $\frac{B}{C} = \sum_{t=0}^T \frac{B_t}{(1+r)^t} / \frac{C_t}{(1+r)^t}$ $Benefit\ Cost\ Ratio\ (BCR) = \frac{Total\ Revenue\ (TR)}{Total\ Cost\ (TC)}$ $Payback\ Period\ (PP) = \frac{Initial\ Investment}{Net\ Cashflow\ Period}$				
	Cost–benefit analysis (CBA) model [55,56,91,101,102] Economic cost–benefit analysis (CBA) [29] Economic tool/Deterministic CBA model approach [102] Probabilistic cost–benefit analysis [55]	Primary dataset used	Comparing the net economic benefits of different options to make a better choice A project or CSPs with an NPV > 0 is deemed viable Evaluate the risk associated with investing in agricultural innovation such as CSPs Help determine the worthiness of given investment activity Simple and provides reliable results for decision-makers	Based on four decision criteria also called economic indicators: net present value (NPV), internal rate of return (IRR), benefit-cost ratio (BCR), and payback period (PP)	Productivity Economic profitability Profitability of the adoption of CSPs

Advantages of the RAPTURE Tool

The RAPTURE tool covers all aspects of the CSA approach by providing assessment methods for all three pillars. Compared to existing assessment tools that only cover specific aspects of the CSA approach, users of the RAPTURE tool will have more options and greater flexibility in assessing CSPs. In addition, this tool can be used under varying conditions and can handle uncertainties related to future climate scenarios. In fact, the application of the tool (Section 3.3) includes a predictive scenario in which data on incremental changes in weather conditions for Florida in 2050 are considered. Moreover, the RAPTURE tool can be applied in any environment, including resource-scarce environments. For data-scarce environments, simpler methods are available that require minimal data for CSP assessment (e.g., Quantitative changes = current land-use class quantity minus the past land-use class quantity for land-use change, or Water Productivity (Irrigation) = Yield/Irrigation water used to evaluate water-use efficiency, among others (Table 1)).

3.2. Background of the RAPTURE Tool

3.2.1. Spatial Distribution of the Journal Articles Documented in This Study

The results present the frequency and distribution of previous studies on CSA and CSPs (Figure 8), which is essential to prove the globalization of the database used to develop the RAPTURE tool that can be applied by stakeholders worldwide. The bibliometric analysis results registered and mapped 76 countries from the 222 studies spread over five continents (Figure 8a). It also shows the number of publications registered by year and continent (Figure 8b,c). The African continent had the highest number of countries represented by publications, some of which appeared repeatedly—24 times (Ghana), 23 times (Kenya), and 21 times (Malawi), among others. Some Asian countries also appeared in multiple publications, with India ranking first (23 times) and others appearing between one and five times. The Americas (North, South, and Central) were the third most represented region, with the United States and Guatemala appearing five times each, Brazil four times, Honduras and El Salvador three times, and others two times or less. Although Europe showed the highest number of countries represented, only Belgium appeared in three studies, while other European countries were mentioned in two or fewer. Oceania showed the lowest representation in the publications on CSA, with only Australia mentioned in one publication, making it the continent with the fewest studies. Others in the figure refer to studies that did not specify a geographic area (Figure 8c). Overall, RAPTURE's accuracy is supported by the fact that the data used for its creation were drawn from scientific studies conducted in more than 76 countries across all continents, published between 2014 and 2023.

3.2.2. Descriptive Aspects of the Reviewed Studies

The findings of this study synthesize previous review articles regarding the CSA approach (Figure 9) to determine what has already been accomplished in the scientific domain concerning CSA and CSPs. This part of the study is important for identifying existing gaps and proposing novel ideas that advance scientific understanding of the topic. Among the 222 journal articles collected, 37 review articles were reported in the results, distributed among six types of reviews (Figure 9). Literature review was the most common, with nine papers written at the country level, seven at the global level, and six at the continental/regional level. The systematic review type ranked second, subdivided into systematic review itself (eight articles), systematic narrative review, and systematic policy review, with one article each. Among the overall systematic review articles collected, four were at the country level, and three each at the global and regional/continental levels. The bibliometric analysis review type accounted for two collected review articles,

with one at the global level and one at the regional/continental level. Lastly, the short communication, desktop review, and opinion article types were represented by one article each, the first two at the regional/continental level and the third at the global level.

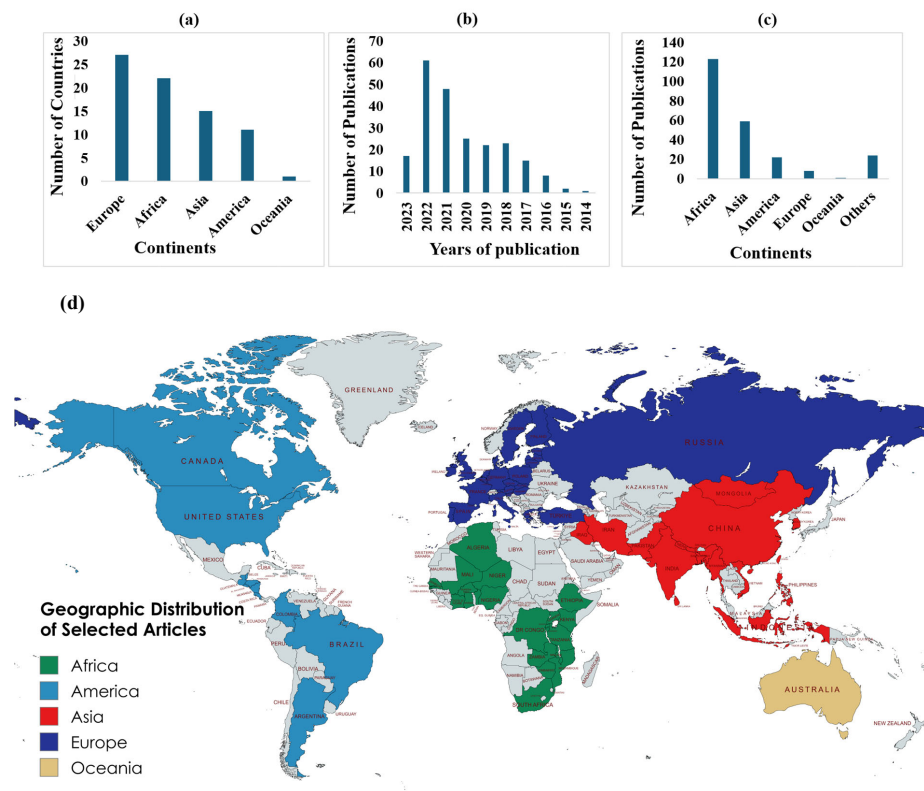


Figure 8. (a) Number of countries by continent registered as areas of study from 222 journal articles; (b) number of publications by continent; (c) number of publications by year; (d) map of the countries (study areas) specified with different colors according to continent.

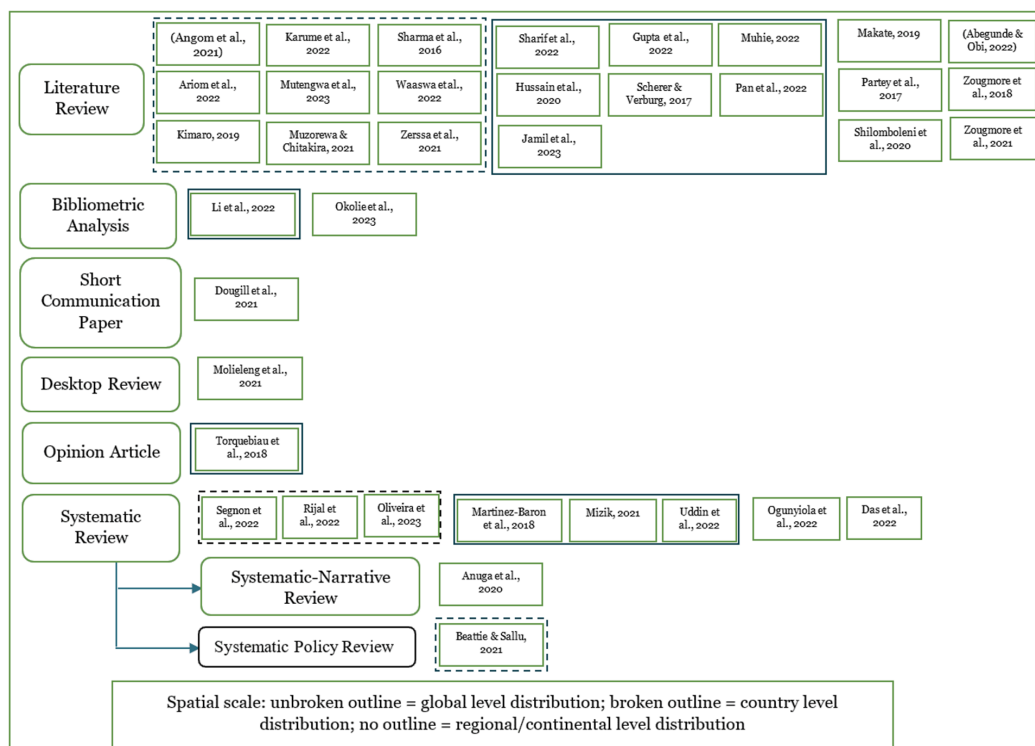


Figure 9. Categories of review articles on CSA [14,23,31,45,46,50,52,59,65,72,104,114,117,119–142].

Moreover, 19 of these review articles addressed the three pillars of CSA, highlighting the effects of CSPs on agricultural productivity, adaptation, and mitigation (Figure 10a). Furthermore, studies on the CSA approach identified opportunities, challenges, and contributions encountered by adopters (Figure 10b). The CSA approach and related practices have been studied based on the factors influencing their uptake among farmers. According to many review articles, farmers have faced several challenges or constraints—social, economic/financial, technological, infrastructural, informational, institutional, and policy-related, among others—when implementing CSA in their farming activities [65,72,126]. These results highlight the uniqueness and reliability of the RAPTURE tool, as it uses relevant data from peer-reviewed articles covering all three pillars of CSA.

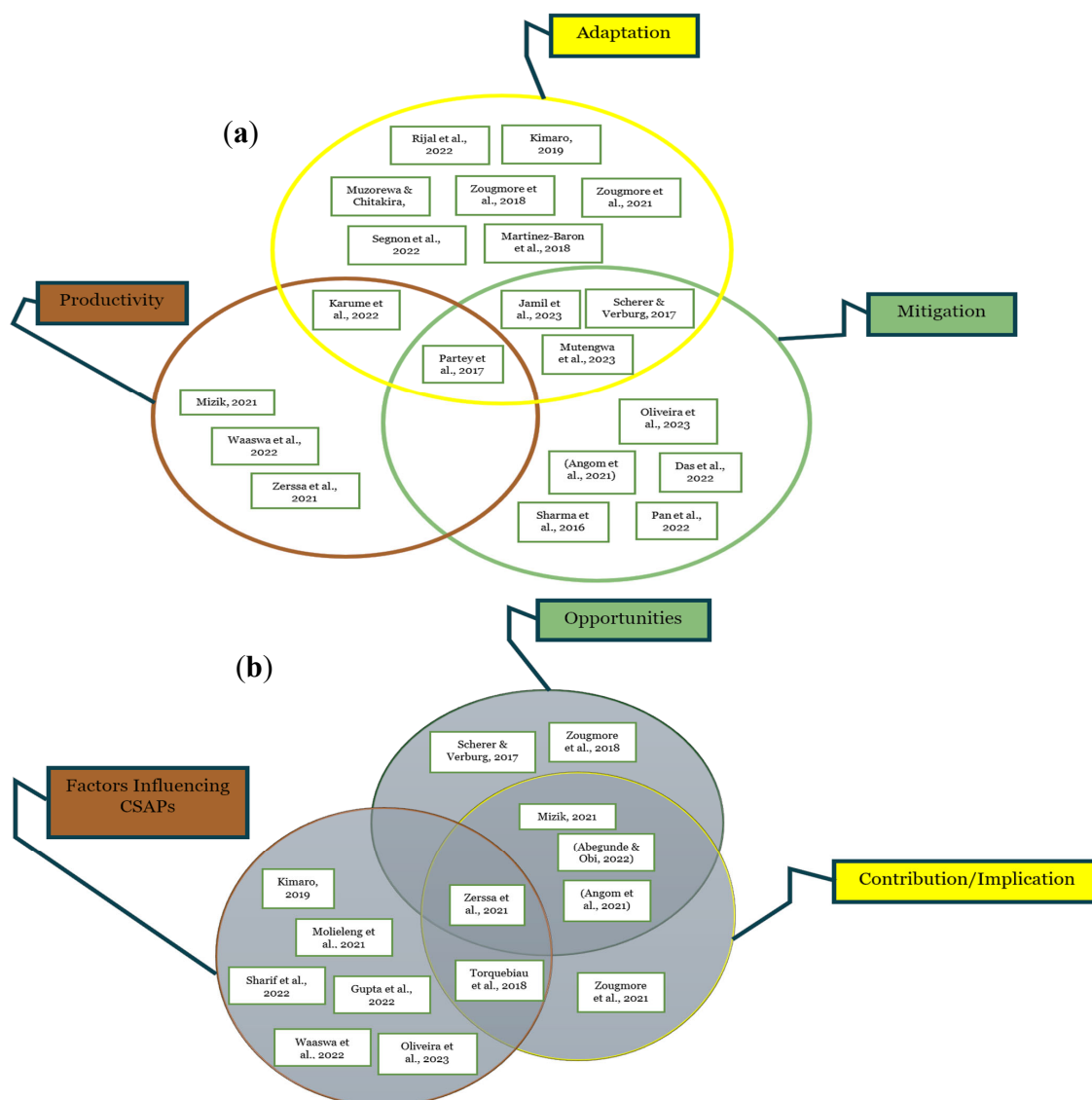


Figure 10. (a) Review articles addressing one or more CSA pillars and (b) review articles highlighting factors influencing CSAP adoption, associated benefits, and outcome implications [23,31,45,46,50,52, 59,65,72,104,114,117,120–124,126,128,131–134,140,142].

3.2.3. Factors Influencing CSP Implementation in the Agricultural System by Farmers

While considered a promising approach for the agricultural sector to build resilience to climate challenges and meet global food needs, many factors affect the use of CSPs by either promoting or hindering their adoption among farmers worldwide (Figure 11). These factors influence farmers' awareness, acceptance, and adoption of CSPs, which play important

roles in the uptake of CSA within agricultural systems. This study synthesizes eight groups of factors reported to significantly impact the adoption of CSPs by farmers (Figure 11a), with detailed information on actions that can promote and/or hinder adoption (Figure 11b). For example, factors such as farmers' education level, age, gender, farming experience, and household size, classified as social factors, have been studied for their influence on CSP adoption [25,69,96]. Other factors, such as distance between household and farm, agricultural income, and access to credit and extension services, can also significantly promote and/or hinder CSP adoption and success in farming activities [25,69,96]. This study also highlights personal factors, such as lack of knowledge and familiarity with specific practices and psychological traits like risk-taking, which influence farmers' decisions when adopting CSPs [14,143,144]. There are also many economic factors, including the source of income (on-farm/off-farm), the cost for implementing CSPs, and the capital available in terms of resources (land, money, water, etc.), highlighted in this study for their role in limiting the use of CSPs [48]. Another key factor influencing CSP uptake is the level of support provided by governmental as well as non-governmental institutions to farmers in terms of policy regulating agricultural activities related to CSP use, financial support for farmers, necessary training by extension officers, and information on weather forecasts [14,143,145]. Moreover, knowledge-sharing among farmers about successful and unsuccessful practices greatly benefits resilience to extreme weather events (e.g., flooding, drought, etc.). The technological factor within CSPs themselves may also limit adoption due to the knowledge and cost requirements for successful implementation. Furthermore, tenancy factors, such as land ownership type, and farm characteristics (size, topography, irrigation potential, among others), have been documented as significantly affecting CSP adoption.

The RAPTURE tool's database provides specific methods (Table 1) that have been used by scientists in many studies to evaluate the impact of these factors (Figure 11) on influencing farmers when adopting CSPs [26,28,84,85]. Assessment methods such as the logit model [28,85], endogenous switching regression (ESR) [84], ordinary least squares (OLS) regression [85], multinomial logit (MNL) model [91], and ordered probit (MVP) model (OPM) [84] are among the tool assessment methods (Table 1) that have been used to quantify the influence of these factors on farmers' decisions to adopt CSPs.

3.2.4. Advantages and Benefits Associated with CSP Adoption

The benefits associated with adopting CSPs extend beyond optimizing resource-use efficiency in the agricultural system to increase productivity and mitigate GHG emissions, but also to affect the overall lifestyle of stakeholders (Figure 12). Adopting CSPs provides many benefits, such as: (1) allowing farmers to produce food and gain income to sustain their livelihoods [56,146,147]; (2) stabilizing soil and nutrients by increasing water filtration into the soil while preventing erosion, thereby enhancing the agricultural system's resilience to extreme climate challenges—advantages achieved through practices such as agroforestry and conservation agriculture [24,55,130]; (3) Reducing the impacts of natural disasters, such as flooding, while providing agricultural services like food production and increased soil humidity [34]; (4) facilitating biological nitrogen fixation through legume trees in an agroforestry system, where specific root-dwelling organisms convert atmospheric N into assimilable compounds that can be used for crop growth, and reduce the use of inorganic fertilizer by farmers [97,148]; (5) significantly reducing chemical contaminants released in the environment to pollute water, soil, air, and living organisms by adopting CSPs such as agroforestry, using species to naturally fertilize the soil and/or limit pest invasion [34,149]; (6) protecting the environment by reducing the emission of toxic gases into the atmosphere while enabling the storage of C in natural biomass [13,104].

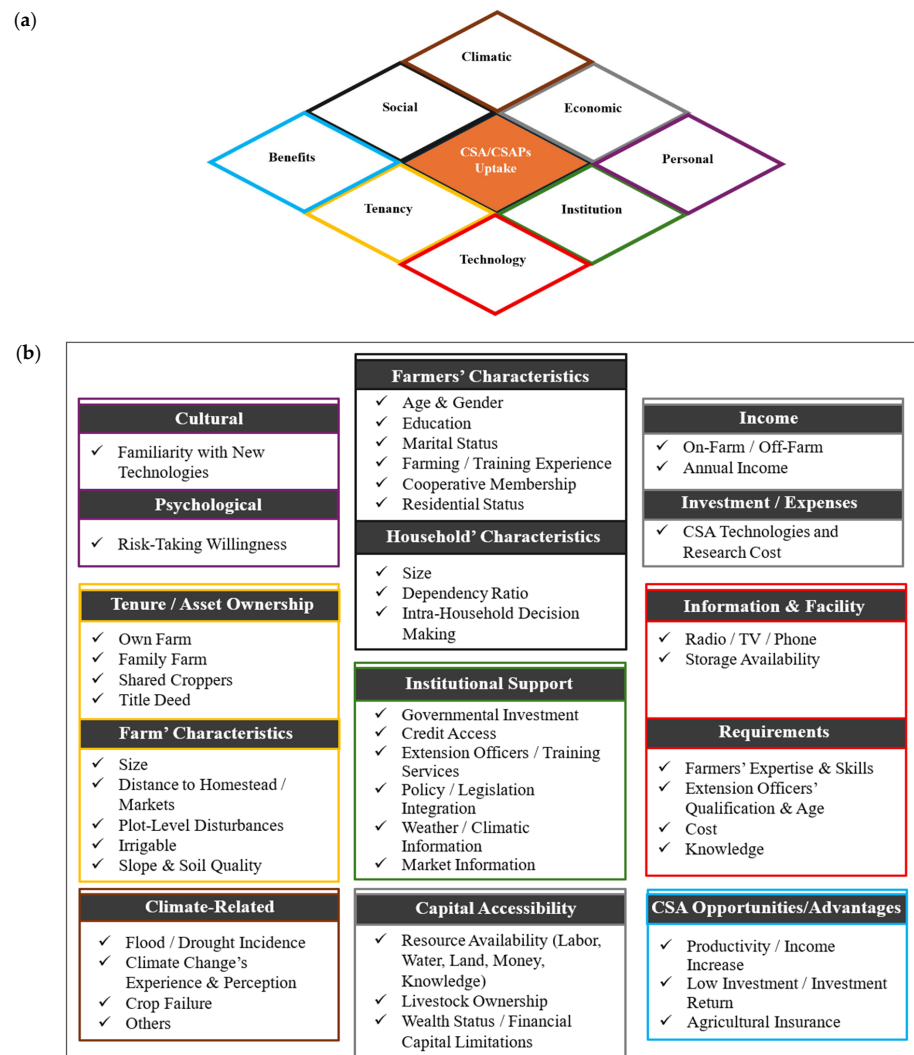


Figure 11. Classification of factors influencing CSP adoption; (a) group of factors and (b) detailed factors, with the groups they belong to identified by outline colors.

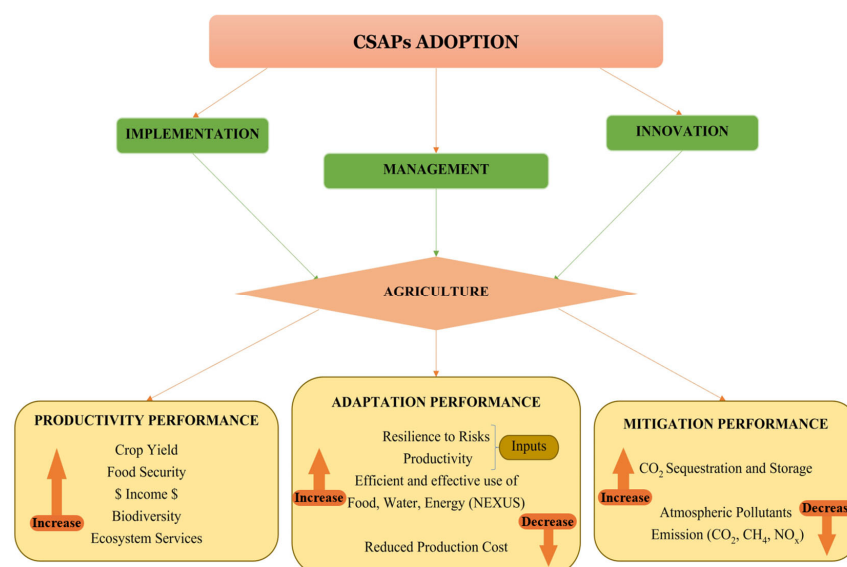


Figure 12. Benefits and advantages of CSPs in the farming sector in terms of the three pillars of CSA.

3.3. RAPTURE Tool Applications

Tables 4 and 5 show the application of the assessment tools considering one and two pillars, respectively. Yield data for the state of Florida has used to realize the scenarios. Therefore, the first scenario shows how the adoption of CSPs in farming can ensure a better increase in yield as one of the main outcomes of the productivity pillar (Table 4). In the second scenario, not only yield increase was shown, but also sustainable used of rainwater was proven through CSPs adoption, which explained the capacity of the practices to ensure the adaptation pillars enabling water availability for agricultural production (Table 5).

Table 4. Application of the assessment tool considering one pillar.

Step	Key Variables and Selection	Control (Present Data)	Treatment with CSPs (Present Data)	Treatment with CSPs (Future Prediction)
1. Selection of a Definition of CSA and CSPs	Outcome: Improved yield Scales: regional (Florida) Techniques: CSPs Trade-offs: Low-cost technology Pillar: Productivity	Not applicable Reason: No CSPs adopted	Definition: increase productivity by the adoption of CSPs to meet food needs considering a low implementation cost in Florida.	Definition: increase productivity by the adoption of CSPs to meet food needs considering a low implementation cost in Florida.
2. Identification of the practices to assess	CSPs Selection Residue retention and short-cycle seed varieties	Not applicable Reason: No CSPs adopted	Residue retention Subcategory: CA Category: Implementation Group: CSAPs Early maturing varieties Subcategory: Improved Seed Varieties Category: Implementation Group: CSAPs	Residue retention Subcategory: CA Category: Implementation Group: CSAPs Early maturing varieties Subcategory: Improved Seed Varieties Category: Implementation Group: CSAPs
3. Climatic Condition Verification	Florida's weather ranges for the year of assessment, 2022 (applied for the control) compared to literature data ranges of weather conditions for the assessed practices (applied for treatments with CSPs).	Florida's registered weather conditions (2022) Temperature (°C): 14.2–28.4 Precipitation (mm): 30.226–245.364	Weather conditions from the literature CA Temperature (°C): 4–45 Precipitation (mm): 50–3000 Stress-tolerant varieties temperature (°C): 0–45 Precipitation (mm): 50–3000	Projected incremental changes in Florida's weather conditions for 2050 [40] Temperature change (°C): 0–6 Precipitation change (mm): (–20)–30
4. Variables and Data Availability	Year of data: 2022 Variables: crop yield Area harvested: 27,100 acres Type of crop: Sweet Corn	Yield = 115 cwt per acre = 12,880 pounds per acre	An increase of 20% considered [21,112] Yield = 15,456 pounds per acre 2576 pounds per acre is the estimated production increase expected with CSP implementation	
5. Selection of one or more assessment methods	Estimation of the difference in productivity in farming without and with CSPs $\Delta X_{CSAP} = (X_{CSAP} - X_{control})/X_{control}$	Florida harvested 12,880 pounds of sweet corn in 2022 without CSP implementation.	A 20% increase in productivity was observed in previous studies following CSP implementation.	With all conditions remaining the same, the change in productivity increase in the 2050s might be 20%.

Table 5. Application of the assessment tool considering two pillars.

Step	Key Variables and Selection	Control (Present Data)	Treatment with CSPs (Present Data)	Treatment with CSPs (Future Prediction)
1. Selection of a Definition of CSA and CSPs	Outcome: Improved yield and rain-use efficiency (RUE) Scales: regional (Florida) Techniques: CSPs Trade-offs: Medium initial cost technology Pillars: Productivity and Adaptation	Not applicable Reason: No CSPs adopted	Definition: To ensure the resilience of the agricultural system through rainwater use efficiency for an increase in agricultural productivity at an affordable cost for farmers in Florida	Definition: To ensure the resilience of the agricultural system through rainwater use efficiency for an increase in agricultural productivity at an affordable cost for farmers in Florida
2. Identification of the practices to assess	CSPs Selection Intercropping with leguminous crops and precision irrigation	Not applicable Reason: No CSPs adopted	Intercropping with leguminous Subcategory: Soil Fertility Management Category: Management Group: CSAPs Precision irrigation Subcategory: Water Management Category: Management Group: CSAPs	Intercropping with leguminous Subcategory: Soil Fertility Management Category: Management Group: CSAPs Precision irrigation Subcategory: Water Management Category: Management Group: CSAPs
3. Climatic Condition Verification	Florida's weather ranges for the year of assessment, which is 2023 (apply for the control), compared to literature data ranges of weather conditions for the assessed practices (apply for treatments with CSPs).	Florida's registered weather conditions (2023) Temperature (°C): 16.28–29.39 Precipitation (mm): 44.704–224.536	Weather conditions from the literature Soil Fertility Management Temperature (°C): 0–45 Precipitation (mm): 200–2500 Water Management Temperature (°C): 4–45 Precipitation (mm): 50–3000	Florida's future incremental changes in weather conditions for 2050 [40] Temperature change (°C): 0–6 Precipitation change (mm): (–20)–30
4. Variables and Data Availability	Year of data: 2023 Variable: crop yield Total area harvested: 160,600 acres = 64,992.514 hectares (ha) Types of crops: 7 vegetable types (snap beans, cabbage, sweet corn, cucumbers, bell peppers, squash, and watermelons)	Yield Total = 1401 cwt per acre = 156,912 pounds per acre = 175,875 Kg per ha	An increase of 20% considered [21,112] Yield = 1681 cwt per acre = 188,272 pounds per acre = 211,024.9 Kg per ha 35,149.9 Kg per ha is the estimated production increase for 7 types of vegetables expected with CSP implementation	

Table 5. Cont.

Step	Key Variables and Selection	Control (Present Data)	Treatment with CSPs (Present Data)	Treatment with CSPs (Future Prediction)
5. Selection of one or more assessment methods	Estimation of the difference in yield in farming without and with CSPs $SYI = \frac{(\bar{yield} - \sigma_{yield})}{yield_{max}}$ SYI = Sustainable Yield Index $\bar{yield}$ = Average yield σ_{yield} = Standard deviation Yield max is expressed as potential yield Potential yield (Kg/ha) = WUE * (Stored Soil Water + Growing Season Rainfall—Evaporation) (2) Growing season rainfall period => from Apr. 1st to Oct. 31st = 4.51 + 4.26 + 8.84 + 6.86 + 6.08 + 6.00 + 2.70 = 39.25 inches = 996.95 mm The growing season rainfall period is considered for Florida 2023 since the average precipitation of this same year falls within the rainfall ranges collected from the literature. The situation for stored soil water and typical combination of evapotranspiration and WUE: Considering a regular season under decile 6 (soil qualified as duplex with better rain in spring) WUE = 15 kg/ha/mm; Evaporation = 90 mm Source: https://www.agric.wa.gov.au/climate-weather/potential-yield-tool (accessed on 28 October 2025) Potential yield (Kg/ha) = 13,694.25 kg/ha	Average Yield: 200.14 cwt per acre = 22,415.68 pounds per acre = 25,124.64 Kg per ha Standard deviation: 115.29 cwt per acre = 12,912.48 pounds per acre = 14,472.96 Kg per ha SYI = (25,124.64 Kg/ha – 14,472.96 Kg/ha)/13,694.25 kg/ha SYI = 0.778	Average Yield: 240 cwt per acre = 26,880 pounds per acre = 30,128.5 Kg per ha Standard deviation: 138.35 cwt per acre = 15,495.2 pounds per acre = 17,367.81 Kg per ha SYI = (30,128.5 Kg/ha – 17,367.81 Kg/ha)/13,694.25 kg/ha SYI = 0.932	
	Estimation of the difference in rainwater-use efficiency (RUE) in farming without and with CSPs $RUE = Yield (kg\ ha^{-1}) / precipitation (mm)$	Yield = 175,875 Kg per ha	Yield = 211,024.9 Kg per ha	
	Precipitation is the total rainfall registered for rainy season Rainy season for 2023 in Florida: March–December 2.24 + 4.51 + 4.26 + 8.84 + 6.86 + 6.00 + 2.70 + 3.73 + 5.32 = 44.46 inches = 1129.284 mm	RUE = 154.74 Kg/ha/mm	Yield = 186.86 Kg/ha/mm	

4. Discussion

4.1. Simplicity and Complexity in Defining CSA

The database of this study presents the three core objectives defined by CSA: increasing productivity, building resilience, and reducing GHG emissions [2]. Whether the purpose is simple or complex, CSA requires reliable measures, techniques, and technologies that can be adapted to specific contexts to achieve its goals. Implementing CSAPs requires consideration of spatiotemporal conditions, regional challenges (e.g., water scarcity, flooding), and trade-offs between adaptation and mitigation [36,37,55,63,130]. Therefore, CSA has always been defined in the scientific field by considering the three pillars as outcomes.

4.2. Importance of an Updated Classification of CSPs

Moreover, the new classification developed in this study considers all practices within the CSA approach to be CSPs. It categorizes them into agricultural system practices known as CSAPs, and smart-behavior practices affecting overall livelihoods. On one hand, the CSAP group includes the categories of practices used throughout the agricultural process to enable sustainable resource management with environmentally friendly methods, as well as farmers' personal efforts and institutional interventions supporting sustainable agriculture under specific climatic conditions to make maximum use of favorable seasons [53,58,60,104]. On the other hand, the group of smart behavior involves adopting sustainable lifestyles through activities such as expanding social networks for information sharing among farmers and diversifying income sources by engaging in non-agricultural activities or migrating to areas with better opportunities [42,61,66]. Adopting and evaluating these practices is crucial for breaking the systemic cycle characterized by the increasing intensity and severity of climatic events and the declining resilience capacity of agricultural systems. Among more than 20 classifications found in previous studies, many focused on resource management, including soil, water, nutrients, carbon, and energy [57,58,60,148]. The classification by [62] considers the three pillars of CSA as productivity, resilience/adaptation, and mitigation. However, this study provides a classification that groups practices into two main categories, CSAPs and smart behavior, with all practices collectively referred to as CSPs. The main objective of this classification is to enable a better understanding of CSPs by adopters, which is crucial for successful implementation. It is also essential for informed

decision-making, as it serves as guidance for adopters to have sufficient knowledge of each CSP's capacity before adoption.

4.3. Key Indicators Necessary for CSP Assessment

The effectiveness of CSPs is evaluated through three key indicators: productivity, referring to increased crop yields and efficiency; resilience, defined as the ability to resist and/or recover from climate impacts while preserving resources; and mitigation, referring to the reduction of GHG emissions from agricultural systems [2,25]. Various mathematical methods have been developed to assess the impacts of CSAPs on agricultural systems, including outcomes such as the effects of CSPs on farmers' productivity (crop yield and income), resilience, particularly resource-use efficiency, and GHG emission mitigation. CSPs also contribute to several ecological benefits referred to as ecosystem services in this study, such as increased biodiversity by providing habitats, food, and water to animals; improving soil quality; enhancing carbon sequestration; and modifying local microclimates [70,93]. The results obtained from adopting any of the CSPs in agricultural systems are multiple, and the outcomes vary according to the CSA pillars. For example, agroforestry, a CSP that introduces trees into farming areas, offers multiple benefits, including food provision (e.g., fruits), improved soil water infiltration and moisture storage, natural supply of essential nutrients (e.g., nitrogen), and GHG mitigation through carbon sequestration [93,147,150].

4.4. RAPTURE Tool for CSP Assessment

This study presents RAPTURE, an assessment tool for CSPs that stakeholders can use to make informed decisions regarding the crucial interconnection between climate change and agricultural systems. Therefore, this assessment tool considers the pillars and specific outcomes associated with CSA adoption. This comprehensive approach, structured in five main stages, allows for a holistic evaluation of CSP effectiveness in addressing climate challenges while supporting a sustainable agricultural system. The application of the tool shows an increase in agricultural production for sweet corn, reaching 2887.3 Kg/ha in 2023 in Florida when CSPs are applied. It also shows a higher sustainable yield index and improved rain-use efficiency, with greater productivity in agricultural systems adopting CSPs. Similarly, previous studies have reported increases in agricultural productivity of more than 20% with the implementation of CSPs in the sector [21,105]. In summary, the RAPTURE tool's database is accessible and usable by multiple stakeholders, regardless of their knowledge and awareness level of the CSA approach or CSPs. This tool can be adapted and applied in multiple environments, whether resources are abundant or scarce. In addition, its database includes assessment methods that can be used for different scenarios, considering both current climate conditions and uncertainties in future predictions.

4.5. Summary of Factors Influencing CSA Implementation

Many factors have been studied for their significance in influencing the adoption of CSPs and technologies, including socio-economic characteristics of farmers such as age, education, farming experience, household size, membership in social groups, access to credit and extension services, farm location and size, farm and off-farm income, etc. [81,116]. There are also institutional factors, including land tenure systems, financial assistance, extension services, and training, among others [143,147]. Moreover, several factors have been identified as significant barriers to adoption, including limited market access for selling produce, insufficient credit for agricultural expenses and CSP implementation, and technological complexity requiring specific knowledge [14,151,152]. Other barriers include labor supply constraints, lack of technical knowledge, weak policy integration, insufficient institutional support and agricultural extension advice, limited capacity in local farming communities, and poor access to improved technologies, among others [14,144,151,152].

Further, resource constraints such as water, land, labor, financial resources, and access to knowledge and training also play a major role in limiting CSP adoption [153]. Understanding these factors is crucial for successful CSP implementation, as it clarifies the responsibilities of different sectors involved in the process. This knowledge can help policy-makers, agricultural extension services, farmers, and other stakeholders develop targeted strategies to overcome adoption barriers and promote widespread CSP implementation.

Assumption, Limitations, and Future Work

The journal articles for this research were collected from the Web of Science database using specific keywords outlined in the methodology section. The PRISMA framework was employed to analyze the obtained articles, select those eligible for the study, and exclude those that lacked information relevant to the paper's objectives. It is important to note that a search using other keywords related to CSA and CSAPs would likely have yielded different articles. Further, the use of a single database is considered a limitation due to the fact that many relevant studies published in other databases, such as Scopus and Google Scholar, may have been missed and excluded. Nevertheless, the selected articles provided sufficient data to conduct this research and develop the RAPTURE tool for assessing CSPs. Future work will focus on evaluating selected CSPs to test the feasibility of the created tool. This approach will help validate the tool's effectiveness and applicability in real-world scenarios. The future development of the RAPTURE tool aims to transform it into an application accessible to multiple stakeholders, regardless of language or time of use. Therefore, by documenting data on the CSA approach and the multiple methods that can be used to assess the impacts of practices achieving CSA goals, this study provides the methodology for developing the tool and creating the related application in future work. Moreover, this application can be multilingual, and its database, along with the evaluation methods (climate data, CSP lists, and mathematical methods), can be updated regularly to maintain scientific relevance and timeliness.

5. Conclusions

The primary purpose of this work was to present the novel tool RAPUTRE, conceptualized in five detailed steps that assess CSP adoption in agricultural systems. This tool compiles a wide variety of CSPs from previous studies, along with the equations used to assess them, forming the foundation of its database. The study highlights the reference terms used to define the CSA approach and the effectiveness of CSPs adoption worldwide in ensuring food security, enhancing farming resilience, and protecting the environment. Therefore, assessing CSPs is essential for understanding their effectiveness in mitigating climate challenges in agricultural activities. Using this tool to evaluate CSP effectiveness will facilitate their dissemination among stakeholders in a world where weather events such as drought, flooding, and soil salinity, among others, are increasing. CSPs are crucial for enabling food production through practices that address the effects of these events on agriculture. This study provides a clear understanding of the differences among CSPs through an updated categorization, distinguishing practices adopted for agricultural needs from those supporting sustainable lifestyles. Moreover, the RAPTURE tool's database also includes multiple estimation methods used to evaluate CSPs, notably the logit model and CBA approach, which are most efficiently employed by scientists in the field to study CSP benefits. Given the climate challenges facing the agricultural sector today, it is urgent to adopt effective methods that can sustainably address these issues. As CSPs aim to tackle these challenges, referring to the RAPTURE tool in assessing and understanding them offers a significant advantage for ensuring effectiveness in rapid, evidence-based decision-making.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17219722/s1>, The information collected from previous studies regarding CSA approach, CSP implementation, and assessment methods can be found and consulted as Supplementary Materials.

Author Contributions: Conceptualization, E.D. and A.A.; methodology, E.D. and A.A.; validation, E.D. and A.A.; formal analysis, E.D. and A.A.; resources, A.A.; data curation, E.D., A.S. and A.A.; writing—original draft preparation, E.D.; writing—review and editing, E.D., A.M. and A.A.; visualization, E.D., A.S. and A.A.; supervision, A.A.; project administration, A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

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