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Adapting agriculture to climate change: which pathways behind policy initiatives?

Raphael Belmin^{1,2,3} · Maeva Paulin^{1,2,4} · Eric Malézieux^{1,2}

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Abstract

Climate change is increasingly affecting agriculture worldwide, causing yield losses and undermining food security. Behind the international consensus on the urgent need for ambitious policies to adapt agriculture to climate change (AACC) hides a competition between three agricultural models—agroecology, climate-smart agriculture, and conventional agriculture—each carrying distinctive perspective on how agriculture should adapt to climate change. To date, no study has shown which of these three agricultural models is promoted the most by climate change adaptation policies. To shed light on this question, we undertook semi-structured surveys with resource persons, a literature review and a multi-criteria analysis, identifying and characterizing 226 AACC policy initiatives in seven countries or regions in the north (Andalusia, Occitanie, California, Guadeloupe) and the south (Colombia, South Africa, Senegal). Our aim was to identify (1) concrete strategic options mobilized by policy initiatives to adapt agriculture to climate change and (2) agricultural models that are implicitly or explicitly promoted by these policy initiatives. We identified 14 climate change adaptation options that mobilize a set of three complementary levers of action: (i) transforming production systems or enabling access to productive resources, (ii) providing access to knowledge that is useful for AACC, and (iii) coordinating and financing adaptation actions at territorial or sector scale. Agroecology and climate-smart agriculture are the two agricultural models favored in the mix of policy initiatives in all the studied sites. Despite conceptual differences, in real-life situations, these models do not conflict with each other since they are often promoted concomitantly. AACC policy initiatives, although diversified, seem too fragmented and not sufficiently restrictive to bring about rapid and profound change. This paper presents a new classification of AACC adaptation options, and is the first to reveal which agricultural models are promoted by policy initiatives in a wide range of regions.

Keywords Adaptation options · Agroecology · Climate-smart agriculture · Conventional agriculture · Policy initiatives

1 Introduction

In many parts of the world, agriculture is already experiencing the full impact of climate change, with yield losses that impact the economy and undermine food security in the short, medium, and long terms (Bezner Kerr et al. 2022).

Climate change comes in the form of higher temperatures, changes in precipitation patterns, and increasingly frequent extreme weather events (IPCC 2014). Recent analyses show that climate change is accelerating, increasing the risk of disasters in terms of both magnitude and frequency (IPCC 2022). The agriculture sector is particularly vulnerable to climate change because production is primarily influenced by climate and weather factors. The impacts of climate change are both direct (crop and livestock productivity) and indirect (changes in food availability and prices, reduced farm incomes). Climate change threatens all aspects of food security, i.e., food supply, access, use, and price stability (FAO 2016; Gregory et al. 2005; Khanal et al. 2021). It affects the world's most vulnerable countries, regions, and population groups most severely (IPCC 2022).

In response to this worrying situation, policy initiatives for the Adaptation of Agriculture to Climate Change

✉ Raphael Belmin
raphael.belmin@cirad.fr

¹ Agricultural Research Centre for International Development (CIRAD), UPR HortSys, F-34398, Montpellier, France

² HortSys, University Montpellier, CIRAD, Montpellier, France

³ Institut Sénégalais de Recherche Agricole, Route de Hydrocarbures Bel-air BP 3120, Dakar, Senegal

⁴ Graduate School of International Agri-Development (ISTOM), Angers, France

(AACC) have proliferated around the world (Ford et al. 2015; Berrang-Ford et al. 2021). Since the 2000s, adaptation of agriculture to climate change and mitigation of its impacts have become a priority on national and international agendas (Lesnikowski et al. 2016; Von Lampe 2022). The Kyoto Protocol and the 2015 Paris Agreement set targets for reducing greenhouse gas (GHG) emissions and promoting more sustainable forms of agriculture that take climate change into account. Official strategies have thus aimed to alter the course of the farm sector in the face of climate change.

Climate change adaptation strategies are generally designed and implemented by governments and other actors through public investments, projects, programs, instruments, actions, and interventions. In this article, we refer to these heterogeneous elements as “policy initiatives”. Previous research on policy initiatives for climate change adaptation falls into two categories:

- (1) On the one hand, an abundant political science literature analyzes the conditions of construction and implementation of climate change adaptation policies (Henstra 2016; Pacheco-Vega 2020; Hood 2006, 2007; Vedung et al. 1998; Bemelmans-Videc et al. 2011). This research focuses on the design and implementation of policy instruments by governments and on the processes by which many instruments are integrated into policy mixes of varying effectiveness (Milhorange et al. 2020). This body of literature has produced different typologies of policy instruments. For instance, Ulibarri et al. (2022) used data from a systematic literature review and identified six main types of policy instruments to support climate adaptation: direct regulation (law or policy), plans and strategies, economic instruments (taxes, subsidies, insurance, or other financial mechanisms), information-based instruments (to raise awareness or promote behavior change), capacity building (to enable adaptation), and community networks or inter-organizational collaboration to develop or implement adaptation responses. However, this set of research work has limitations with respect to AACC, as neither adaptation options nor agricultural models promoted by the policy initiatives were questioned. Rather, political scientists have generally dealt with the design and governance of policy instruments, i.e., the way in which instruments are chosen and how these instrument bundles evolve over time (Capano and Howlett 2020; Jordan et al. 2003; Pacheco-Vega 2020).
- (2) On the other hand, some research has focused on classifying the options taken by governments to adapt agriculture to climate change (Cooper et al. 2013; IPCC 2022; Smit and Skinner 2002; Sorgho et al. 2020; Wall and Smit 2005; Zougmore et al. 2016). However, most of these classifications of adaptation options were

constructed from data collected in a single country (Alam et al. 2012; Smit and Skinner 2002; Wall and Smit 2005) or region (Milhorange et al. 2020; Zougmore et al. 2016; Schilling et al. 2012; Sorgho et al. 2020). Except for IPCC (2022), multi-country studies are relatively old, the most recent one dating from 2013 (Cooper et al. 2013). Finally, available studies say nothing about the future paths traced by policies to adapt to climate change.

In this paper, we use a different lens to look at climate change adaptation policy initiatives, to identify the adaptation options proposed, and whether one agricultural model in particular is promoted. This issue is in fact highly controversial: the international consensus on the need to achieve profound changes in our agriculture in fact masks competition between three agricultural models—climate-smart agriculture, agroecology, and conventional agriculture—that all claim to respond to the challenges of adaptation to climate change (Bezner Kerr et al. 2022; FAO 2016; Hrabanski and Le Coq 2022; Torquebiau 2017):

- (1) *Climate-smart agriculture* (CSA) seeks to adapt agriculture to climate change while reducing GHG emissions via a comprehensive approach that takes agricultural practices, public policies, and financing mechanisms into account (Hrabanski 2020). CSA is promoted by the Food and Agriculture Organization (FAO) and other international actors, particularly in sub-Saharan Africa (FAO 2019, 2021). CSA is defined as an “agriculture that increases crop productivity and resilience (adaptation) in a sustainable manner, promotes greenhouse gas reduction/removal (mitigation), improves national food security and contributes to the achievement of the country’s development goals” (FAO 2021). CSA is based on three pillars: adaptation, mitigation, and food security (Torquebiau 2017). It aims to combat GHG emissions (e.g., storing carbon in the soil) while making agriculture more resilient to climate hazards (e.g., the use of drought-resistant varieties) (IPCC 2022). CSA proposes to transform cropping systems by introducing agroforestry and conservation agriculture, among other approaches (Nciizah and Wakindiki 2015). Nevertheless, it does not integrate all the aspects of these concepts and, above all, it considers the use of chemical inputs and genetically modified organisms possible or desirable under certain conditions (Torquebiau 2017).
- (2) *Agroecology* (AE) is defined as “an integrated approach that applies ecological and social concepts and principles concurrently to the design and management of food and agricultural systems” (FAO 2018). This approach, based on holistic principles, aims to combine

knowledge from agronomy, ecology, and sociology to design more resilient agricultural systems by mimicking natural processes (Ollivier et al. 2018; Gliessman 2018; Altieri et al. 2015; Méndez et al. 2013). Agroecology seeks to create synergies between the components of the agroecosystem (plants, animals, humans, and the environment) so as to reduce external inputs and preserve the system's key immune, metabolic, and regulatory processes (IPES Food 2016). Beyond the research community, agroecology is the subject of increasing attention from decision-makers and donors, and is recognized by the IPCC (2022) and the FAO (2018) as a promising option for adaptation (Fig. 1). For example, diversification of crop and livestock species can mitigate the impact of extreme weather events or the arrival of new pests, weeds, and diseases. Agroecology also helps reduce agriculture's dependence on fossil fuels, limits carbon dioxide emissions, and stores carbon in the soil (De Schutter 2011). Numerous authors conclude that agroecology is effective for AACC (Holt-Giménez 2002; Saj and Torquebiau

2018). These features make it one of the agricultural models at the heart of discussions concerning AACC. (3) *Conventional agriculture (CA)* has been the main agricultural model promoted since the 1960s. CA consists of modifying and artificializing the environment, making intensive use of labor, capital, or inputs to increase agricultural productivity (Mazoyer and Roudart 2017). It is based on specialization and on the use of chemicals to intensify production. It is characterized by relatively standardized technical management protocols and massive use of chemical inputs, irrigation, and mechanization to maximize production. This system was the basis of the yield increases obtained through the green revolution (Overton 1996). It requires significant financial investment and involves rapid dissemination of technological innovation. The responses proposed by conventional agriculture to adapt to climate change include boosting investment in the agricultural sectors to increase production, building frameworks that favor private investment, establishing public-private partnerships to facilitate the transfer of technology and biotechnology, and implementing policies designed to help

Fig. 1 To adapt to climate change, farmers all over the world innovate by adapting concepts and techniques from both agroecology and climate-smart agriculture. The photos show a variety of cases in West Africa: **a** Yacine (Ndiob, Senegal) has successfully tested a crop association between groundnut and cowpea; **b** Oulimata (Podor, Senegal) is part of a group of women who practice agroecology in a collective garden, a place of emancipation, mutual help, and strengthening of social ties; **c** Irene (Akpessekro, Côte d'Ivoire) decided to transform his farm to move towards agroecology; **d** Boubacar (Fatick, Senegal) uses recycled tires to concentrate manure and water around the roots of his pepper plants; **e** Fatou (Mboro, Senegal) intercroops egg plants with lime trees; **f** Bassirou (Diogo, Sénégal) builds the fertility of his soils through crop rotations, fallowing, and regular additions of manure. Photo Credit: Raphael Belmin/Cirad.



farmers (for example, land titling, creating safety nets, distributing high-yielding seeds). However, in the current context of climate change, conventional agriculture is being re-examined because of its heavy dependence on fossil fuels, its role in GHG emissions and pollution caused by pesticides, and its low resilience to extreme weather events and pest attacks (FAO 2016). Despite these reservations, conventional agriculture is still the most widespread agricultural model in the world and is supported by most agricultural policies in the north and south alike.

Although many authors point to the interest of politically supporting one or the other of the three approaches, to date, no study has shown which of these three agricultural models is promoted the most by climate change adaptation policies.

For this purpose, we performed a cross-sectional analysis of 226 policy initiatives in seven different countries or regions, in the south (South Africa, Senegal, Colombia) and in the north (Andalusia in Spain, California in the USA, and the French regions Occitanie and Guadeloupe), with the aim of identifying the adaptation options and the main agricultural models conveyed by these initiatives, if any. The case studies were selected to obtain contrasted climate contexts, “levels of development,” and agricultural sectors. We hypothesized this would provide contrasted study sites in terms of climate vulnerability (Füssel and Klein 2006), adaptive capacities (Eakin et al. 2014), and policy mix. By “policy mix,” we mean a set of government policies which, by design or by fate, interact to shape R&D and innovation systems (Flanagan et al. 2011; Rogge and Reichardt 2016).

The choice of study sites was also guided by the partnership set up for the “Typoclim” project, of which this study was part. Table 1 lists the specific features of each study site.

We seek to answer two questions:

- What are the climate change adaptation options promoted by public policy initiatives?
- Which agricultural models are promoted by these policy initiatives as ways to adapt agriculture to climate change?

First, we describe how we collected and analyzed the data. In the following results section (Section 3), we explain how we categorized the adaptation options promoted by the policy initiatives, and present our typology of the policy initiatives based on the agricultural models they promote. In Section 4, we discuss our results in light of the existing literature.

2 Material and methods

2.1 Identification and categorization of policy initiatives from seven regions

In 2019, we identified and characterized the AACC policy initiatives in each of the seven selected areas using the same method: (i) analysis of a bibliographic corpus comprising scientific articles, dissertations and theses, regulations, projects, and programs; (ii) semi-structured interviews with resource people, including policy makers, development actors, and farmers. The interviews

Table 1 Climate issues and agricultural sectors in our 7 study areas.

	Climate issues	Agricultural sectors included in the study	Number of initiatives studied
France—Occitanie	Occitanie is a Mediterranean region exposed to rising temperatures, drought, and intense rainfall leading to flooding	Winegrowing Market gardening	24
USA—California	California’s climate is Mediterranean (on the coast) and continental (in the Rockies). Climate change is accompanied by repeated wildfires and depletion of water resources	Winegrowing Market gardening	53
Colombia	Colombia is experiencing an increase in average temperature, a decrease in precipitation, and climate fluctuations caused by the La Niña and El Niño phenomena	Mango Market gardening	30
France—Guadeloupe	Guadeloupe is a tropical island exposed to the intensification of cyclonic phenomena and flooding. The population is vulnerable to sea level rise because it is concentrated in coastal areas	Market gardening	19
South Africa	In South Africa, climate change impacts include droughts, floods, and tropical cyclones	Winegrowing Horticulture	30
Senegal	Senegal is a Sahelian country with a semi-arid climate affected by decreasing rainfall, increasing temperatures, and salinization of the land	Market gardening Mango Rainfed cereals	37
Spain-Andalusia	In Andalusia, the increase in temperature and decrease in precipitation cause droughts, forest fires, and aridification	Winegrowing Mango	33

targeted resource people known for their expert knowledge of AACC policies and people directly involved in their design, implementation, or evaluation (e.g., staff from ministries, agencies, and R&D organizations). The objective of the interviews was to identify a set of policy initiatives, to characterize each initiative using the same analysis grid, and to understand the role of the different actors in implementing the initiatives. The analysis grid was a set of questions designed to get the interviewees to describe an AACC policy initiative (see Supplementary material). We triangulated information from the different sources (interviews, literature review, regulations, etc.) in successive iterations until information saturation was reached (Olivier de Sardan 1995). The results of this inventory were assembled in seven project reports: France—Occitanie (Panossian 2019); USA—California (Decroocq 2019); Colombia (Noblanc 2019); France—Guadeloupe (Biabiany 2019); South Africa (Hadrot-Galaup 2019); Senegal (Vincennes 2019); Spain—Andalusia (Begey 2020). A total of 226 policy initiatives were identified.

We sampled policy initiatives taking into account the following dimensions:

- Time: the analysis covered both ongoing and past policy initiatives;
- Scale: we studied all policy initiatives irrespective of their scale. Some are applied locally though they may be structured on a larger scale, for example, the Agri-Environmental and Climate Measures (AECM) of the Common Agricultural Policy, which apply in Andalusia and Occitanie. Conversely, some policy initiatives are specific to one area, for example, the sustainable banana plan in Guadeloupe.
- Focus on climate change: we included in our analysis policy initiatives that are explicitly or implicitly address AACC.
- Focus on agriculture: our study does not include climate change adaptation policies for livestock.

The policy initiatives were then grouped into categories based on the adaptation strategies they support. This inductive categorization process was carried out by the three authors of the article, by grouping initiatives with the same intervention logic and then refining the categorization iteratively. The data corpus we used for categorization is a document containing a 10- to 15-line description of each initiative (Supplementary material). The result of this process was 226 policy initiatives classified in 14 adaptation options. Studied sites were then compared based on the proportion of the different categories of policy initiatives.

2.2 Identification of the agricultural model(s) associated with each policy initiative

The agricultural model promoted by a given policy initiative is rarely explicitly mentioned in its wording. We therefore developed a systematic method to identify the agricultural model(s) associated with each initiative. Based on a rapid review of the literature on the three agricultural models (conventional agriculture, climate-smart agriculture, agroecology), as well as on our expert knowledge, (i) we identified 16 criteria that enabled us to distinguish the three agricultural models from each other. For example, considering the use of chemical fertilizers as a criterion, a policy initiative aimed at promoting conventional agriculture will encourage their use, while a policy initiative that promotes agroecology will favor their elimination; (ii) we checked that the criteria covered all the standard components of farming systems (Darnhofer et al. 2012), with the exception of the components that affect family and labor; and (iii) we established three modalities for each criterion, one for each agricultural model. Finally, we considered that the dominant agricultural model promoted by a given policy initiative could be deduced from the set of modalities attributed to our 16 criteria.

The 16 criteria (Table 2) concern the use of chemical fertilizers; water; plant protection; genetic resources; energy; biomass; land management; the degree of dependence on chemical inputs and seeds; the relationship with technology; mechanization, materials, and equipment; the type of knowledge mobilized and the training provided; the relationship with trees; soil management; links to agro-industries (seed, food, agrochemicals); waste management; and biodiversity.

The 226 policy initiatives were examined one by one for links with the 16 criteria. A modality was allocated to an initiative by analyzing the corpus of data in the seven project reports and other documents linked to the policy initiative, e.g., framework documents for plans, projects, programs, or regulations. In addition to the first three modalities (corresponding to the three agricultural models), two other modalities were added to account for situations where the policy initiative had no effect on the criterion (“neutral” modality, coded “N”) and cases in which the initiative was not applicable to the criterion (“not applicable” modality, coded “/”). For example, an agricultural insurance aimed at covering losses linked to climatic events will not, a priori, have an effect on biodiversity and, as a result, will not interact directly with the biodiversity criterion.

Each policy initiative was thus characterized by a range of 16 criteria, with 5 possible modalities for each criterion: agroecology (A), conventional agriculture (C), climate-smart agriculture (S), neutral (N), and not applicable (/). The systematic analysis of the 226 initiatives gave

Table 2 Modalities of each criterion for each of the “conventional agriculture,” “climate-smart agriculture,” and “agroecology” agricultural models.

Criteria	Agricultural models		
	Conventional agriculture	Climate-smart agriculture	Agroecology
<i>Fertilizer</i>	Promotes the use of exogenous chemical fertilizer	Efficient use of exogenous fertilizers	Reduces the use of chemical fertilizers and produces organic fertilizers on-farm
<i>Water</i>	Promotes the use of water	Efficient use of water	Reduces exogenous water inputs, conserves and protects water
<i>Plant protection</i>	Promotes the use of plant protection products	Efficient use of plant protection products	Reduces the use plant protection products by using biological interactions and synergies
<i>Genetic resources</i>	Choice of cultivars to maximize yield potential in monoculture	Choice of varieties more resistant to biotic and abiotic stresses	Increases varietal and species diversity and use of varietal mixes
<i>Energy</i>	Promotes fossil/non-renewable energy consumption	Efficient use of energy	Limits the use of non-renewable energy
<i>Biomass</i>	Exported	Technology for on-farm energy generation and recycling	Reorganization of production for biomass recycling at farm or territory scale
<i>Land management</i>	Promotes developments that increase productivity (drainage, increase in the size of plots, etc.)	Promotes measures for mitigating climate change (water saving, planting trees, etc.)	Promotes a landscape mosaic for biodiversity
<i>Dependence on chemical inputs and seeds Technology</i>	High dependence Dependence	Average and decreasing dependence Promotes the use of Information and Communication Technologies (ICT), computer-assisted agriculture	Independence, autonomy Independence
<i>Mechanization, materials and equipment</i>	Massive use to increase productivity	Optimized use	Small-scale machinery and/or manual labor to conserve and protect the environment
<i>Knowledge/training</i>	Knowledge based on agrochemistry and focused on increasing production	Knowledge based on optimized use of digital information on agriculture, high technology and practices promoting mitigation and adaptation	Biodiversity-based traditional and scientific knowledge for sustainability
<i>Relationship to trees</i>	None/negative	Introduction of trees in cropping systems for climate change mitigation	Introduction of trees in cropping systems for productivity and agroecosystem regulation
<i>Soil management</i>	Optimization of productivity by taking into account edaphic constraints with no consideration for the soil	Promotes the conservation and sustainable management of soils	Soil rehabilitation, preservation and improvement by managing organic matter and soil biological activity
<i>Relationship to agro-industry</i>	Dependence	Neutral	Independence
<i>Waste management</i>	Waste management outsourced	Promotes recycling through technology	Promotes waste recycling through actions at farm and regional level
<i>Biodiversity</i>	Negative effect on associated biodiversity, low cultivated biodiversity (use of a few elite cultivars)	Neutral	Positive effect on associated biodiversity, greater cultivated biodiversity

rise to a matrix (226, 16) correlating the instruments with the 16 specific criteria that characterize the agricultural models identified (Supplementary material). For each initiative, the sum of the modalities obtained was then calculated for the 16 criteria. Using this method, we were able to identify the “distance” between a given initiative and each of the three forms of agriculture (conventional agriculture, agroecology, climate-smart agriculture), based on objective analysis of the 16 criteria.

2.3 Data analysis

The data from the matrix (226, 16) were first aggregated according to the adaptation options and study sites. The data were then analyzed by principal component analysis (PCA), using normalized variables. We used R software (version 4.2.1) with the packages “dplyr,” “stats,” “base,” “FactoMineR,” “factoextra,” “ggplot2,” “readxl,” and “xlsx.” The PCA enabled us to construct a hierarchical classification of principal components (CHCP) based on the agricultural models. We used the results of the PCA and CHCP to highlight the agricultural models promoted by AACC policy initiatives.

3 Results

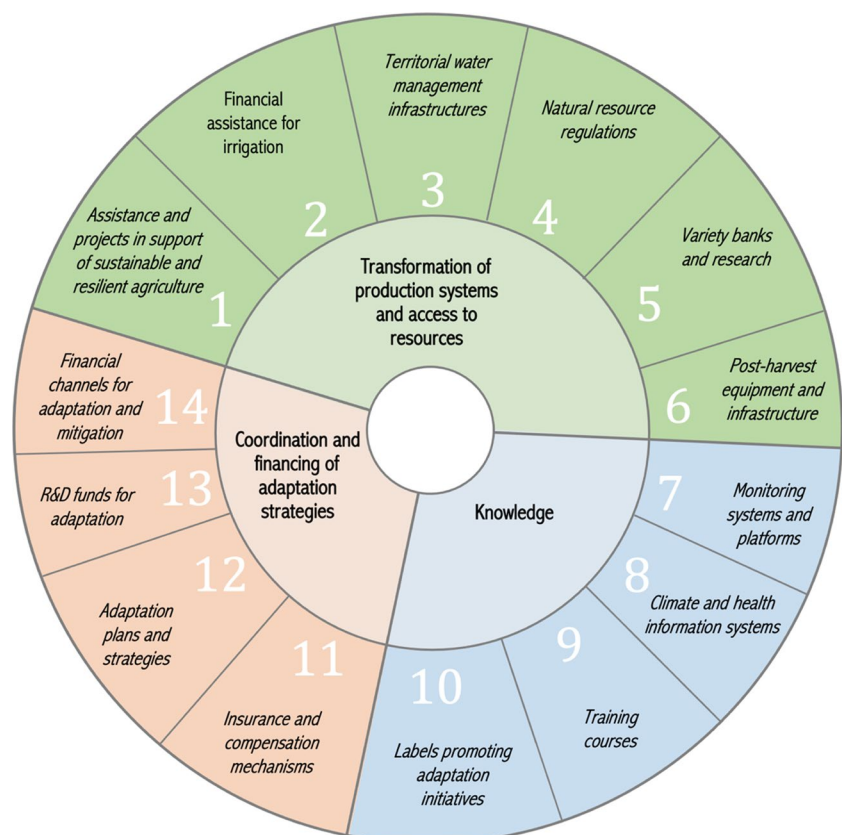
3.1 Diversity of adaptation options promoted by the policy initiatives

The 226 policy initiatives identified in the seven study areas were classified in 14 adaptation options (Fig. 2). Each adaptation option groups policy initiatives that have the same purpose and the same modality of intervention in favor of AACC. We then grouped the different adaptation options into three main classes, depending on whether the adaptation relies on material, cognitive, or financial resources (Fig. 2). A distinction was thus made between policy initiatives that target (i) the transformation of production systems and access to productive resources, (ii) access to knowledge that is useful for AACC, and (iii) the coordination and financing of adaptation actions at territorial or sector scale.

3.1.1 Initiatives for the transformation of production systems and access to productive resources

A number of policy initiatives are intended to transform agricultural production systems to make them more agronomically and economically resilient to the different facets of climate change (increasing temperatures, extreme events,

Fig. 2 The 14 adaptation options underpinning AACC policy initiatives.



changing rainfall patterns, invasive pests). One aim is to guarantee access to—and the sustainable use of—productive resources threatened by climate change, such as water and agrobiodiversity.

Adaptation option 1: promoting sustainable and resilient agriculture Category 1 groups financial assistance and projects aimed at encouraging a transition towards sustainable and resilient agriculture in the face of climate change. Regional, national, or international public institutions provide individual or collective grants for varietal conversion to using cultivars adapted to climate change, farm greening (reforestation, reduced use of crop chemicals, non-productive land management, etc.), or conversion to and maintenance of organic farming. For example, in California, the Environmental Quality Incentive Program provides federal cost-share grants to implement conservation agriculture, a production model to match good agricultural yields with environmental protection. Other projects combine economic incentives, equipment, and training to support a transition towards agroecology, agroforestry, or the adoption of varieties adapted to climate change. For example, between 2007 and 2012, the Groundnut Basin Degraded Land Management and Restoration Project in Senegal funded operations to improve agricultural soil management and develop income-generating activities.

Adaptation option 2: providing financial assistance for irrigation Category 2 groups financial assistance and projects to provide farmers with irrigation equipment while simultaneously promoting water saving. These include grants, loans, and subsidies that enable farmers to obtain or maintain irrigation equipment and small water management structures, including wells, pumps, collection devices, reservoirs, irrigation systems, and dykes. The different types of assistance target individual farms or groups of farmers and mainly concern small-scale equipment. For example, the State Water Efficiency and Enhancement Program in California provides financial assistance to farmers in the form of grants to install irrigation systems that save water (e.g., drip irrigation). There are also development projects that finance equipment and structures while training farmers in water management.

Adaptation option 3: improving access to water management infrastructure Category 3 groups policy initiatives designed to extend irrigable areas in places where rainfed crops are being affected by climate change. These are programs, projects, schemes, or measures for the construction or restoration of major water structures (dams, hydraulic transfer networks, desalination plants, etc.). These projects are implemented under the supervision of public institutions and aim to increase the availability of water in a given area. In Occitanie (a region in mainland France), for example, the

Aqua Domitia project involves constructing a large network of pipes to divert water from the River Rhône to areas at risk of drought.

Adaptation option 4: encouraging good management of natural resources Climate change and human activities affect the quality and available quantity of water and natural resources (IPCC 2014). Category 4 groups regulatory policies for good water management and conservation, such as framework decrees, directives, decrees, plans, programs, legal codes, memoranda, and taxes. These are implemented by governments to regulate the use of water resources or to regulate agricultural practices that can pollute water. Examples include (i) permanent water use quotas; (ii) temporary restrictions on water use in the event of drought, which are sometimes modulated according to the severity of the drought; and (iii) restrictions or bans on pumping in sensitive areas (e.g., water catchment protection schemes, aquifers in danger of saltwater intrusion). Regulations are often the means by which governments implement their international commitments (e.g., Sustainable Development Goals, Agenda 21, Paris Agreements). In Senegal, for example, the water code limits withdrawals (i) in catchments where the groundwater is approaching its limits; (ii) in catchments where the resource is channeled through a public water distribution service; and (iii) in catchments where there is a potential danger of saltwater intrusion.

Adaptation option 5: supporting conservation and use of genetic resources With climate change, the crop varieties the farmers normally use may prove to become unsuitable. Changes in precipitation and temperature regimes may disrupt cropping calendars and cause biotic and abiotic stresses that reduce yields and increase the vulnerability of a given production system (Ndour et al. 2017; Tidjani and Akponikpe 2012). This has been observed with many varieties of wheat, cotton, maize, and rice. Category 5 groups projects and programs designed to conserve, analyze, breed, and disseminate plant material adapted to climate change. Gene banks are funded to preserve seeds of different origins so they can be used in plant breeding or variety selection programs. Projects and programs generally aim to develop varieties that are resistant to drought and to bio-aggressors. For example, the mango germplasm bank in Colombia is used to conserve endangered varieties and to select cultivars suitable for use under climate change.

Adaptation option 6: supporting access to post-harvest equipment and infrastructure Extreme climate events (floods, heatwaves, etc.) combined with inadequate storage conditions can lead to loss of foodstuffs after harvest. Category 6 groups projects to help farmers acquire post-harvest processing and storage equipment and infrastructure.

This helps improve farm income and resilience by enabling (i) access to crop storage facilities that are protected from extreme climate events; (ii) pre-storage processing (e.g., drying, threshing or cleaning) for better storage; (iii) enabling products to be sold when prices are most advantageous; and (iv) combining several farmers' harvests to increase bargaining power with buyers (Taruvunga et al. 2014). For instance in South Africa, the projects "Khulisa" from the Western Cape Government and "AgriParks" from the National Department of Rural Development and Land Reform were designed to encourage agro-processing businesses and investments in adaptation to climate change.

3.1.2 Knowledge-based initiatives

Knowledge-based initiatives are designed to produce and disseminate knowledge that is considered useful for farmers' adaptation strategies and for coordination between actors (policy makers, development agents, experts, etc.) involved in the implementation of AACC policies.

Adaptation option 7: monitoring systems and platforms Category 7 groups multi-stakeholder platforms and monitoring systems that centralize, capitalize, and disseminate information useful for AACC. Multi-stakeholder platforms bring together a range of stakeholders (farmers, agricultural advisers, experts, decision-makers, etc.) to exchange and disseminate agroclimatic information. These platforms also enable stakeholders to network, which helps create synergy between their different actions. Finally, the platforms serve as a bridge between stakeholders in the field and decision-makers located elsewhere, enabling AACC issues to become part of the political agenda. Agroclimatic round tables in Colombia, for example, bring together actors of the farm sector to produce and distribute a monthly information bulletin with recommendations for each crop. Monitoring systems are set up by scientists and experts who centralize, analyze, capitalize, and disseminate information about the climate and AACC. Monitoring systems provide expert services such as regional climate analyses. For example, in Occitanie (a region in France), two regional monitoring systems (called ORACLE and Clima-XXI) provide regional climate diagnoses and forecasts at different time horizons.

Adaptation option 8: disseminating climate information Category 8 groups Climate Information Systems (CISs) and Information and Communication Technologies (ICT) aimed at informing stakeholder decision-making in the face of climate variability and instability. CISs disseminate climate and agronomic information (weather forecasts, pest warnings, natural resource monitoring data, etc.) to farmers and public-sector players through internet platforms or mobile phone applications. This information is

used (i) by farmers to foresee extreme events and optimize crop management according to weather trends and (ii) by decision-makers to prepare emergency interventions and to adjust agricultural policies, plans, programs, guidelines, and recommendations for AACC. Unlike category 7 platforms, which rely on expertise and synergy between actors to guide strategic decisions, category 8 initiatives primarily rely on digital tools to disseminate information for adaptation actions, often on a weekly or daily basis. For example in Senegal, climate/weather data is collected by the National Meteorological Agency and communicated to farmers via text messages, voice messages, or community radios. Category 8 ICTs bring together a set of technologies (IT, audiovisual, internet, phone apps, drones, etc.) to help farmers make decisions by providing information on economic aspects, agriculture, weather/climate, crop health issues, and policies. Among the policy initiatives listed in our study, several ICT-based projects are designed to improve the economic and environmental performance of farms in a situation of climatic instability. In Andalusia (Spain), a mobile app developed by the Ministry of Agriculture, Fisheries and Food provides access to real-time data on rainfall and evapotranspiration, enabling farmers to assess their net water needs.

Adaptation option 9: educate and train Category 9 includes initial or continuing education courses for producers, agricultural advisers, and agricultural executives. These training courses are organized by different categories of stakeholders (governments, international institutions, NGOs, etc.) and disseminate information on climate change impact and adaptation strategies. The courses include the following: (i) Master's courses that incorporate the issue of AACC. For example in Senegal, the "Adaptation of Agricultural Practices to Climate Change" Master's course trains experts in climate risk analysis and implementation of adaptation/mitigation policies. (ii) Seminars and lectures to train and inform farmers on AACC issues; (iii) farmer groups who share their experiences at workshops or visits to farms, like the Dimitra listeners' clubs in Senegal created by the FAO; (iv) trial plots used as a training and networking support for producers involved in an AACC approach, such as the farmer field schools in Colombia.

Adaptation option 10: valorizing climate change mitigation and adaptation initiatives through quality labels For farmers, adaptation to climate change requires technical changes and sometimes costly investment in equipment (Dugué et al. 2012). Category 10 groups labels to promote products or farms engaged in sustainable agriculture or climate change mitigation or adaptation. These labels enable consumers to support farms that operate on a sustainable basis. Users of these labels can get higher prices than their competitors,

which they need to offset transition costs. For example in Spain, the “Wineries for Climate Protection” label for the Andalusian wine industry highlights wineries that are reducing their production of waste, consumption of water, and greenhouse gas emissions.

3.1.3 Initiatives for coordinating and financing adaptation strategies

Lastly, some policy initiatives are designed to finance adaptation strategies or to coordinate adaptation initiatives in a given territory or sector.

Adaptation option 11: insuring and compensating climatic risks Category 11 groups financial mechanisms (insurance, emergency funds, agricultural subsidies, etc.) to compensate for the impact of climate change and extreme events on farms. The purpose of agricultural insurance is to protect the market value of crops against natural disasters by covering climate risks (e.g., multi-risk insurance, hail/storm insurance). This insurance is sometimes conditional on compliance with good agricultural practices. For Occitanian wineries, exemption from the production ceiling under the “individual additional volume” system is a way to guarantee both the harvest and the quality of the raw material produced. Subsidies make it possible to compensate for the additional production costs caused by climatic events, by allocating funds or planting material (e.g., seeds) and/or by helping farmers take out agricultural insurance. Finally, emergency funds are monetary funds released after a climatic event that has caused pre- or post-harvest losses or prevented sowing. These funds provide financial assistance to farmers whose crops sometimes cannot be insured. For example, in Guadeloupe, a French island region in the Caribbean, farmers affected by natural disasters receive monetary assistance under the Specific Options Program for Remoteness and Insularity.

Adaptation option 12: adaptation plans and strategies Category 12 groups plans and strategies aimed at coordinating adaptation actions at various scales. Governments set up national or regional plans for adaptation to climate change. These plans involve a variety of measures (research, information dissemination, platforms, development, etc.) for such sectors as crop farming, livestock raising, fisheries, and energy production. They are often based on a diagnosis of vulnerability to climate change. For example, national climate change adaptation plans exist in Colombia, France, Senegal, and Spain. Also, some well-structured agricultural sectors create their own AACC plans, like the Sustainable Banana Plan in Guadeloupe (French overseas region). This plan consists of promoting a set of agricultural practices to make banana production systems more resilient to climate

change, including weekly leaf stripping, use of cover crops, and the use of organic fertilizer.

Adaptation option 13: supporting research and development efforts AACC requires significant Research and Development (R&D) efforts, whether to better understand the manifestations of climate change or to design and test solutions. Category 13 groups policy initiatives that finance and catalyze R&D projects for adaptation to climate change. These initiatives come in the form of funds that encourage the emergence of innovative projects through calls for tenders in diverse fields such as mapping, varietal development, pest control, and cropping innovations. The funds are sometimes managed by incubators or technology platforms that encourage networking among R&D players (laboratories, private companies, producer organizations, etc.) to speed up innovation for AACC. For example, in Guadeloupe (French overseas region), the Agricultural Innovation and Transfer Networks fund research and innovation projects on market gardening and sugarcane growing practices, such as the use of service crops.

Adaptation option 14: funding adaptation and mitigation initiatives Producers who wish to invest in increasing the resilience of their farms often find it hard to obtain loans. Financial institutions do not want to risk lending money to farmers because of the climatic risks they are subject to. Category 14 groups financial channels geared to AACC projects. For example, funds are granted to financial institutions like banks, insurance companies, and microfinance institutions to encourage them to fund investments by stakeholders in the farming world. One example is the AGreenFi agriculture funding label of the French Development Agency in Senegal. Other examples of financial channels are carbon markets and carbon taxes. Carbon markets set a cap on carbon dioxide emissions and allow players to trade emission rights in the same way as financial securities. A carbon tax sets a price for carbon, implying payment based on the level of emissions. The funds collected by these two mechanisms can then be used to finance adaptation and mitigation projects.

3.2 Identification of the agricultural models promoted by the policy initiatives

Principal component analysis (PCA) (Fig. 3a), ascending hierarchical classification (Fig. 3b), and Table 2 were used to identify the agricultural models promoted by the 226 policy initiatives in our dataset. The first two factorial axes of the PCA explain 61% of the data. Factorial axis 1 compares the variables “climate-smart agriculture” (CSA), “agroecology” (AE), and “conventional agriculture” (CA) with the “neutral” variable, while factorial axis 2 compares agroecology

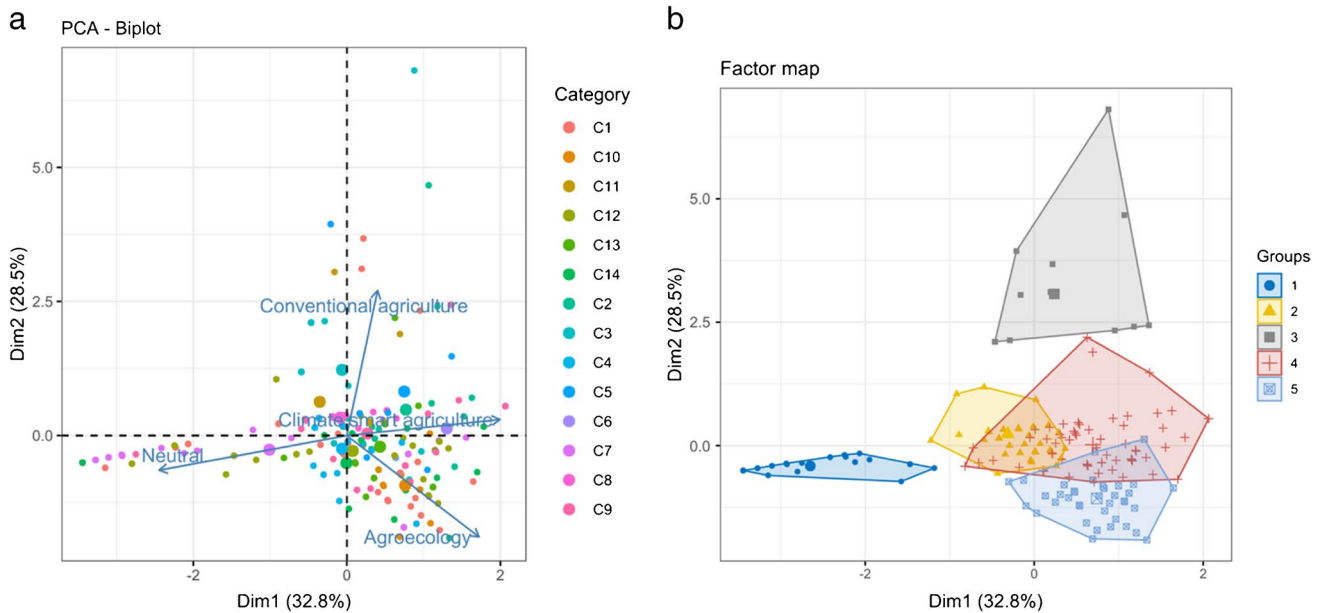


Fig. 3 **a** Biplot map of AACC policy initiatives with categories of adaptation options as illustrative variables. The 226 AACC policy initiatives were analyzed by PCA using, as variables, the sum of the modalities obtained for the criteria “conventional agriculture,” “agroecology,” “climate-smart agriculture,” and “neutral” (see the table in

with conventional agriculture. The conventional agricultural model contrasts with that of agroecology, while climate-smart agriculture is positively linked to both agroecology and conventional agriculture.

Table 3 shows that climate-smart agriculture (CSA) and agroecology (AE) are the adaptation models by far the most frequently promoted by the policy initiatives in our dataset. Some policy initiatives promote both these models (cluster 4 in the hierarchical ascending classification shown in Fig. 3b), although the relative weights of agroecology and climate-smart agriculture vary depending on the category. The policy initiatives that promote climate-smart agriculture (cluster 2) are mainly climate and health information systems, insurance and compensation mechanisms, seed banks and varietal research, and assistance for irrigation (categories 2, 5, 8, 11 of the functional typology). Initiatives that promote agroecology (cluster 5) are the most numerous. These are mainly financial assistance and projects in support of sustainable and resilient agriculture, regulations on natural resources, post-harvest equipment and infrastructure, and labels and financial channels for adaptation and mitigation (categories 1, 4, 6, 10, 14). Conventional agriculture (cluster 3) is rarely promoted by AACC policy initiatives. However, there are some cases of financial aid and projects aimed at improving the availability of water or inputs for agricultural operations (categories 2, 3, 5). Finally, some policy initiatives do not promote a particular agricultural model. These neutral initiatives (cluster 1) mainly play a

Supplementary material). The colors represent the different adaptation options. **b** Hierarchical classification on principal components of AACC policy initiatives. The 226 policy initiatives were classified in 5 clusters. Different symbols and colors are used to distinguish the clusters. The large dots indicate the barycenters of each cluster.

role in disseminating information or coordinating adaptation actions: monitoring systems and platforms (category 7), and plans and strategies (category 12). There are also neutral financial instruments (categories 13 and 14).

3.3 Comparison of the study sites

Figure 4 shows that policies often feature different mixes of adaptation options in a given site. In the cases of Guadeloupe, Occitanie, Andalusia, and Columbia, the most frequently encountered adaptation initiatives are financial assistance and projects promoting resilient agriculture (C1). In the case of Senegal, the most represented categories are financial assistance for irrigation (C2) followed by training courses (C9). In South Africa, the most common adaptation options are plans and strategies to coordinate adaptation actions (C12) and financial circuits for adaptation and mitigation (C14). California is the only site where almost all adaptation options are represented (14/15 categories), reflecting the extremely diverse set of actions that have been undertaken there. In the other sites, at least three categories of adaptation options are missing. The most frequently missing adaptation option concerns post-harvest equipment (C6), which is only represented once. Observatories and platforms is the most common adaptation option for California, and it is also well represented in Occitanie, Andalusia, South Africa, and Senegal.

Table 3 The agricultural models each category of policy initiative points towards.

Adaptation options		Conventional agriculture	Agroecology	Climate-smart agriculture	Neutral
Transformation of production systems and access to resources					
C1	<i>Financial assistance and projects in support of sustainable and resilient agriculture</i>	4%	48%	27%	22%
C2	<i>Financial assistance for irrigation</i>	11%	32%	49%	8%
C3	<i>Water management infrastructure</i>	53%	18%	24%	5%
C4	<i>Natural resource regulations</i>	0%	48%	42%	10%
C5	<i>Seed banks and research</i>	15%	18%	61%	6%
C6	<i>Post-harvest equipment and infrastructure</i>	6%	50%	38%	6%
Knowledge					
C7	<i>Monitoring systems and platforms</i>	0%	17%	37%	46%
C8	<i>Climate and health information systems</i>	0%	2%	95%	3%
C9	<i>Training courses</i>	2%	30%	51%	16%
C10	<i>Labels promoting adaptation initiatives</i>	0%	54%	31%	15%
Coordination and financing of adaptation strategies					
C11	<i>Insurance and compensation mechanisms</i>	6%	6%	83%	5%
C12	<i>Plans and strategies to coordinate adaptation actions</i>	1%	32%	40%	28%
C13	<i>R&D funds for adaptation</i>	2%	35%	41%	23%
C14	<i>Financial channels for adaptation and mitigation</i>	0%	42%	35%	24%
Total		6%	30%	45%	19%

Regarding the agricultural models promoted by policy initiatives, climate-smart agriculture and/or agroecology are the main agricultural models promoted in all the study areas (Fig. 5). It is worth noting that no country or region in our study promoted conventional agriculture as a priority.

4 Discussion

4.1 An overview of policies initiatives to adapt agriculture to climate change

Our study proposed a large-scale map of policy responses to the dangers of climate change for agriculture. Our systematic analysis of 226 policy initiatives in seven regions in the north (Andalusia, Occitanie, California, Guadeloupe) or countries in the south (Colombia, South Africa, Senegal) enabled us to identify 14 climate change adaptation options which mobilize a set of three complementary levers of action: (i) transformation of production systems and access to productive resources, (ii) access to knowledge that is useful for AACC, and (iii) the coordination and financing of adaptation actions at territorial or sector scale.

Past studies have proposed similar inventories and typologies underlining the diversity of climate change adaptation policies and strategic options. For instance, Smit and Skinner (2002) identified four main categories of agricultural adaptation options in Canada: (i) technological

developments, (ii) government programs and insurance, (iii) farm production practices, and (iv) farm financial management. Reviewing AACC policy initiatives in West Africa, Zougmore et al. (2016) found that governments and international donors promote a wide range of climate-smart agricultural options, including cultivar development, water conservation techniques, agroforestry, soil carbon sequestration, seasonal weather and climate forecasting, fertilizer efficiency, and rice water management. Sorgho et al. (2020) conducted a systematic review of policy documents addressing climate change in all 16 West African countries. They found that climate change adaptation policies include development of local risk/disaster plans, microfinance and insurance schemes (public or private), green energy, and development of community groups/farmer organizations. Cooper et al. (2013) reviewed 16 large-scale cases of climate change adaptation/mitigation actions in the agriculture and forestry sectors worldwide. The case studies these authors reviewed included policy and strategy development, insurance, weather information services, and social protection. Finally, IPCC (2022) identified and assessed 9 adaptation categories for the “Food, Fiber and Other” sector: shift in production, policy and planning, livelihood diversification, genetic improvement, collective resource, management, climate services, agronomic management (farm level), agricultural diversification.

The 14 adaptation options we identified in our study of policy initiatives largely converge with past studies. Our

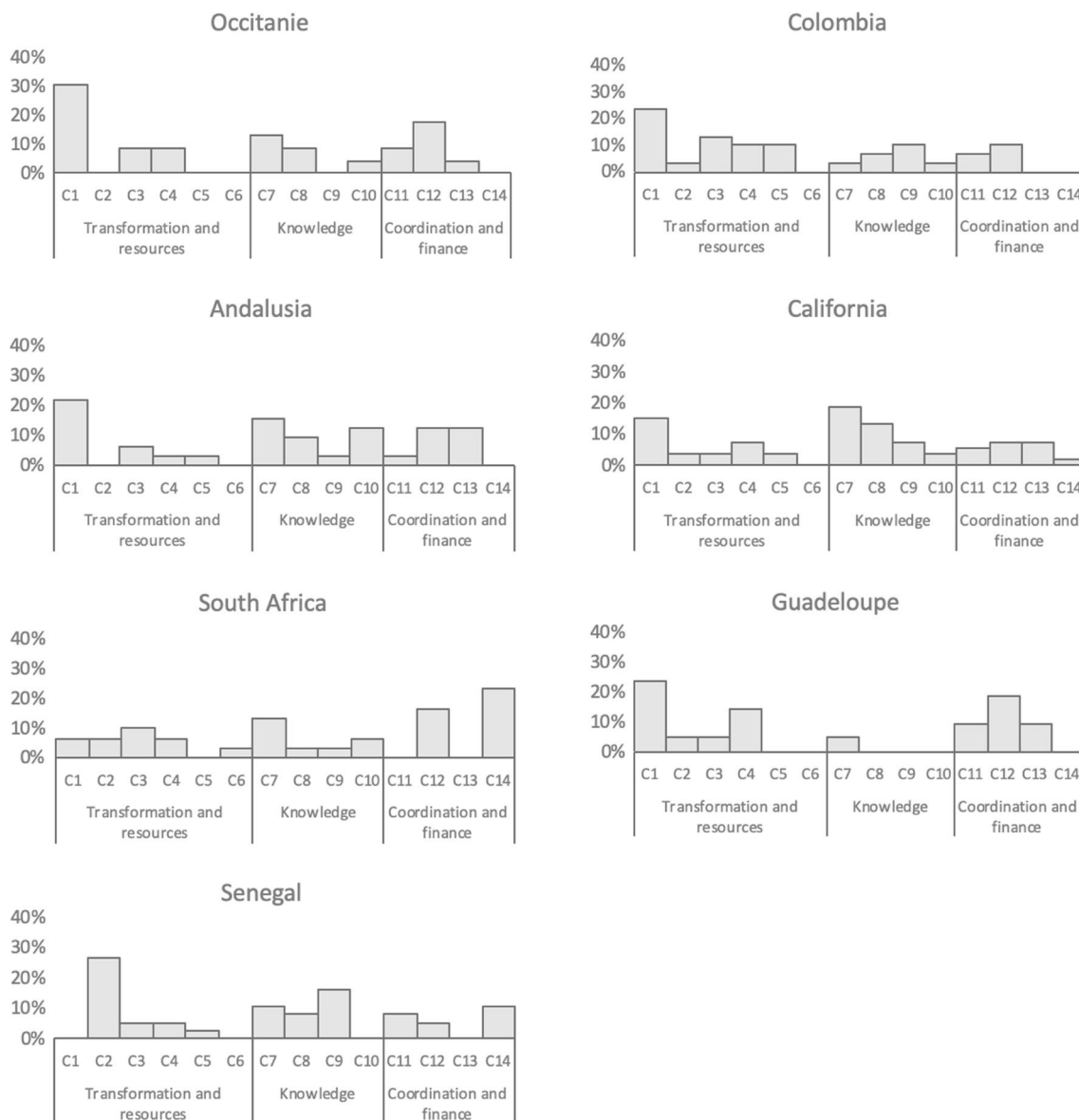


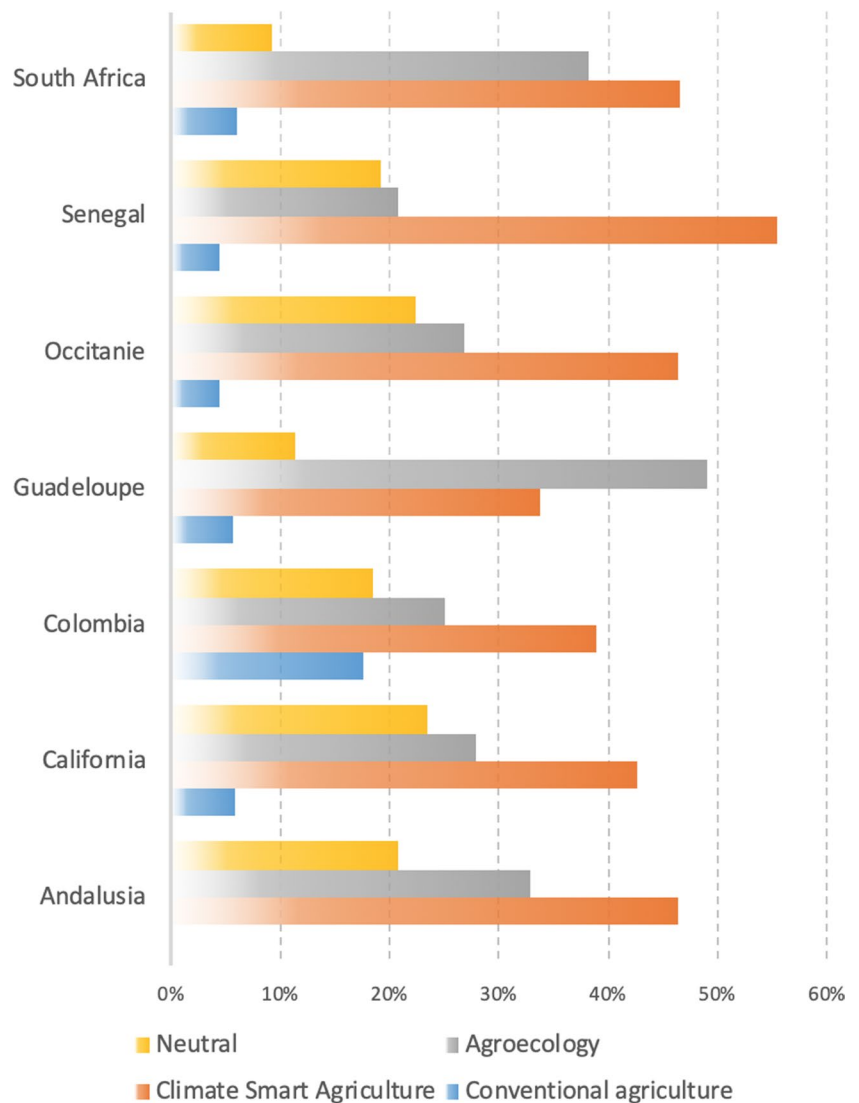
Fig. 4 Percentage of representation of each type of adaptation option in the different study sites.

results update existing knowledge on AACC policies and broaden the spectrum of identifiable coping strategies. What is more, our study addresses some of the limitations of past studies: (i) most studies used data collected in a single country (Alam et al. 2012; Smit and Skinner 2002) or region (Milhorange et al. 2020; Zougmore et al. 2016; Schilling et al. 2012; Sorgho et al. 2020); (ii) with the exception of IPCC (2022) and Ulibarri et al. (2022), multi-country studies are relatively old, the most recent one dating from 2013 (Cooper et al. 2013); and (iii) they do not show which agricultural models guide the policies.

Despite the diversity of responses to the problem, one may wonder whether they will be able to bring about sufficiently profound and rapid changes to address the emergency

we are currently facing. Current adaptation options may have substantial benefits under moderate climate change, but there are limits to their effectiveness under more severe climate changes (Howden et al. 2007). Moreover, the accumulation of policy tools over time can result in increasingly complex and poorly designed policy mixes, and ultimately lead to policy failure and ineffective public action (Ulibarri et al. 2022). Achievement of AACC depends on the smart combination of appropriate policy initiatives in a coherent and effective policy mix (Lesnikowski et al. 2019; Biesbroek et al. 2015; del Rio and Howlett 2013). Moreover, our results show that coercive policy tools are virtually absent, while policies that work through incentive instruments are preponderant. Other policy initiatives are neutral (cluster 1 of

Fig. 5 Distribution of policy initiatives according to the agricultural models promoted for AACC in each study site.



the PCA), meaning they do not favor any particular agricultural model. Under these conditions, it is understandable that AACC relies above all on the good will of the farmers and other food system actors. Yet, many studies have shown that the changes in agriculture that are urgently required are hampered by socio-technical lock-in phenomena that sometimes render transformative policies ineffective (Meynard et al. 2018; Belmin et al. 2018). This conclusion is in line with that of Berrang-Ford et al. (2021), who found that most adaptation initiatives were largely fragmented, local, and incremental, with limited evidence of transformational adaptation and negligible evidence of risk reduction outcomes.

4.2 Adaptation policies that tend towards the greening of farming systems

Our analyses show that agroecology (AE) and climate-smart agriculture (CSA) are the preferred models in the mix of

policy initiatives in each of the cases we examined. The two models do not conflict with one another; on the contrary, they are often promoted concomitantly. Saj and Torquebiau (2018) found similar results, and argue that beyond the conceptual differences and the sometimes partisan interpretations of these approaches, agriculture needs to take advantage of the potential synergies between AE and CSA. So climate change seems to be reinforcing the place of agroecology and climate-smart agriculture in public agricultural policies at the expense of the usual support for conventional agriculture (CA). Our study is thus the first to show which agricultural models are promoted by policy initiatives at an international level.

4.3 Adaptation strategies differ with the region

Our results show that the mix of policy initiatives and the agricultural models promoted differ significantly from one

study site to another. This variability probably reflects the diversity of institutional arrangements and forms of climate vulnerability in the study regions (Table 1). For example, in Senegal, the preponderance of C2 and knowledge-related policy initiatives probably reflects the fact that in the Sahel, the main response to climate change has been to create new irrigation systems and to disseminate information on rain-fed agriculture to farmers. In another example, California is the only site where 13/14 categories of adaptation options are represented. This diversity marks a very strong political commitment, in a context where California, a global leader in agriculture, is being hit hard by extreme weather events (fires, drought) (Pathak et al. 2018; Shonkoff et al. 2011).

The orientation of the mix of policy initiatives towards agroecology is most marked in Guadeloupe, while climate-smart agriculture is the path favored by Senegal, Colombia, California, and South Africa, where policies in favor of agroecology are less present, or even missing altogether. The marked orientation of agroecology type initiatives in Guadeloupe can be linked to the French government's promotion of agroecology, but also to the particular situation in the French West Indies where the chlordecone pollution crisis resulted in strong social pressure. In Senegal, a lower-middle-income country, the promotion of climate-smart agriculture as a way of adapting agriculture to climate change can be explained by the significant influence of the Food and Agriculture Organization, the French Development Agency, and other international organizations in defining public policy and the importance of the food security issue (Nyasimi et al. 2014).

4.4 Limitations of the study

Because of the complexity of the data used (226 initiatives, seven study cases), in order to simplify, we studied only three agricultural models whereas other models could also have been addressed, like nature-based solutions (Hrabanski and Le Coq 2022) or organic agriculture (Reganold and Wachter 2016). However, conventional agriculture, climate-smart agriculture, and agroecology are the three models at the heart of current debates on AACC and more broadly in the future of agriculture in both north and south.

An analysis of impact would have been important, but exceeded our analytical capacity. The questions that need answering are as follows: what have been and are the effects of the policies employed? What impact have they had on the environment (soil, biodiversity, water, etc.)? Are they likely to modify ecosystem services? If so, which? How have they improved the resilience of food and farming systems to climate change? Have they had economic impacts? Have they affected investment in agriculture? Ultimately, very few studies focus on the impact of policy initiatives. While impact is very difficult to assess

in advance, an a priori analysis based on intentions would have been useful.

A further limitation is that our study does not include climate change adaptation policies for livestock. Livestock farming is an integral component of agriculture and is particularly vulnerable to climate change. Moreover, the recoupling of agriculture and livestock is recognized as a promising adaptation option to make agricultural systems more resilient and diversified (Rojas-Downing et al. 2017).

5 Conclusion

Faced with the threat that climate change poses to global agriculture, governments and their technical and financial partners are implementing numerous AACC policy initiatives. We conducted an inventory and a systematic analysis of the AACC policy initiatives in seven case studies, some in countries of the south (South Africa, Senegal, Colombia) and others in regions in the north (Andalusia, Spain; California, USA; Occitanie, France; and Guadeloupe, French West Indies). We sought to identify (1) concrete strategies and levers mobilized by policy initiatives to adapt agriculture to climate change and (2) the agricultural models these policy initiatives promote.

Our results showed that policy initiatives promote a set of 14 different but complementary adaptation options which we classified in the three following categories: (1) policy initiatives to make production systems more sustainable and resilient to climate change and guarantee access to productive resources including water; (2) policy initiatives designed to produce and disseminate knowledge that is useful for stakeholders' adaptation strategies or coordination between stakeholders; (3) policy initiatives designed to fund adaptation strategies or to coordinate adaptation initiatives at territorial or sector scale.

These findings reveal the consensus on the urgent need for ambitious policies to adapt agriculture to climate change worldwide. Our analysis shows that all the study sites favored agroecology and climate-smart agriculture in their mix of policy initiatives. Hence, climate change appears to be helping in some way to removing the specter of conventional agriculture and to strengthening the place of agroecology and climate-smart agriculture in public agricultural policies.

Our study introduced a new classification of AACC adaptation options, and is the first to show which agricultural models are promoted by policy initiatives on an international level. Future studies should focus on the analysis of ex post impact of these policy initiatives regarding the environmental, economic, and social spheres.

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Authors' contributions Conceptualization: R.B., E.M.; methodology: R.B., E.M.; data analysis: M.P., R.B.; investigation: R.B., E.M., M.P.; writing—original draft: R.B.; writing—review and editing: R.B., E.M.; visuals: R.B., M.P.

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Data Availability All data generated or analyzed during this study are included in this published article or in the supplementary material. The seven cases/regions reports are available on request.

Code availability The R code used to construct the principal component analysis and the ascending hierarchical classification is provided in the supplementary material.

Declarations

Ethics approval The study was conducted according to the guidelines laid down in the 1964 Helsinki Declaration and its later amendments.

Consent to participate All study participants gave their informed consent to participating in the study.

Consent for publication The authors affirm that the human research participants provided informed consent for this publication. All the persons recognizable on the photographs in this article were informed of their publication and gave their consent for their publication.

Conflict of interest The authors declare no competing interests.

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