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Scaling weather and climate services for agriculture in Senegal: Evaluating systemic but overlooked effects

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ABSTRACT

In the West African Sahel, climate variability and climate change pose huge challenges to food security and health, particularly for poor and marginalised population groups. Co-production of actionable climate information between scientists and users has been advocated to increase its use in adaptation to climate change. Consequently, Weather and Climate Services (WCS) co-production models have been expanding, but there have been few evaluations of their effects, and those that exist mostly focus on the end user. The empirical contribution of this paper is an evidence based evaluation of the scaling of WSC co-production models and its enabling factors. The methodological contribution is a systemic and iterative evaluation method involving multiple analytical tools. The scaling of WCS in Senegal involved at least 161 actors and resulted in five axes of transformation: 1) continuous improvement of WCS, 2) emergence and consolidation of WCS facilitators, 3) inclusion of WCS in action planning, 4) active mobilisation to sustain WCS scaling, and 5) empowerment of actors. New users and uses emerged beyond agriculture, involving the fisheries, water and energy sectors, producing changes in institutional communication strategies, operational planning, and in coordination between actors. Enabling factors for scaling included capacity strengthening, knowledge-sharing and action platforms, interaction opportunities, and financial and political support. However, reduced precision of forecasts over time is perceived. New challenges are emerging including improving delivery and finer grain information, getting the private sector involved, and building capacity and trust at a large scale, to keep pace with the increase in uses and users.

Practical implications.

- Weather and Climate Services (WCS) are crucial for policy making due to the expected increase in rainfall variability and extreme climate conditions, and the vulnerability of rural communities in the West African Sahel. WCS are the production, translation, transformation into appropriate formats, transmission, access to, and use of scientific information on weather and climate for decision-making. Co-production of actionable information responding to goals shared by scientists and users is advocated to increase the use of weather and climate information, which implies a deliberate approach to building relationships and communication channels. However, the evaluation of the effects of WCS co-production models is relatively new. This is partly because the scientific community has focused on the quality of information and services. Partly, this is due to the non-excludable and non-rivalrous nature of weather and climate information, and its likely transformation throughout the process of transmission and use, which makes evaluation a challenge. Prospective modelling of the value of WCS and retrospective assessments of their use exist but are still rare. Most such evaluations focus on one type of end user, usually farmers or farming households. However, the broader effects of the scaling of WCS on the multiple producers, translators, transmitters, and users of climate information remain understudied, as have the institutional and policy factors that support their scaling.

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- We present a systemic and complexity-aware evaluation that disentangles the multiple changes in practices, actions and interactions experienced by the diversity of actors involved in the production, transmission and use of WCS in Senegal, and the factors which enabled these changes. Furthermore, we provide a methodological contribution in the form of an iterative evaluation with three components: reconstruction of the history of innovation, evaluation of outcomes using the Outcome Harvesting tool, and analysis of systemic transformations using impact pathway analysis.
- The foundations of the WCS co-production model in Senegal were laid down in the 1980s when the Agriculture-Hydrology-Meteorology regional centre (AGRHYMET) created the first national multidisciplinary working group, in response to a devastating drought in member countries of the Permanent Interstate Committee for Drought Control in the Sahel in the West African Sahel. In the two following decades, projects combining climate information and recommendations for farmers and fishers were implemented. The Senegalese National Meteorological Agency (ANACIM) started developing forecasts for farmers after participating in seminars for seasonal agro-climatic forecasting in West African countries organized by the AGRHYMET, the African Centre of Meteorological Applications for Development (ACMAD), and the Niger Basin Authority (NBA). In the late 2000s, the National Meteorological Agency became the national office for weather data and began to strengthen its capacity to improve the quality of the seasonal forecasts by organising seminars to disseminate climate information and trainings. Along with national and international research partners, the Agency set up the first decentralised local multidisciplinary working groups to facilitate the development of WCS, their interpretation, and their dissemination and uptake by local users. Using multiple dissemination channels, climate information combined with agricultural advice that accounted for endogenous knowledge and farmers' practices was systematically transmitted. Promoter farmers known to be influential in their communities were selected to pass on the information to other farmers. Capacity-building workshops familiarised stakeholders with forecasting concepts. In the years leading to 2018, WCS and multidisciplinary working groups were subsequently scaled up to most departments in Senegal. Climate information was incorporated in sectoral and national adaptation plans. Investment in scaling WCS was supported by a favourable global funding environment. At this stage, WCS were also used by other sectors, including fisheries, energy and water resources protection.
- The network of actors who directly or indirectly interacted in the WCS scaling process comprises no less than 161 actors. About one third of the 33 stakeholders represented by the 44 respondents interviewed in our study were simultaneously producers, transmitters, and users of WCS. For instance, decentralised institutions deliver knowledge and relay feedback to the National Meteorological Agency; transmit information through different channels; and use the forecasts to plan their actions. Other actors, including ministries, use weather and climate information for decision-making and in the tools they disseminate to facilitate access to the information. Radios are recognised transmitters, and sometimes co-producers of the information through feedback to the National Meteorological Agency, which with the ministries are key intermediaries between all these different actors.
- The scaling of this innovation to new users, uses, and sectors engendered a transformative process based on five axes of change: 1) continuous improvement of WCS, 2) emergence and consolidation of WCS facilitators, 3) inclusion of WCS in action planning, 4) active mobilisation to sustain the scaling of WCS, and 5) empowerment of actors. The continuous improvement of WCS reinforced scaling, which, in turn, facilitated further improvement through co-production-use-feedback-adaptation loops. As a result, rural populations, as well as members of multidisciplinary working groups, have increased access to WCS, and are now calling for finer and more timely forecasts. Facilitators of WCS made climate information accessible to a broad range of actors. For instance, community radios became *de facto* facilitators to the point of reorganising their programmes to broadcast more weather and climate information. Decentralised state agencies use weather and climate information for operational planning and to target their interventions, whilst improving the coordination of their actions thanks to the dynamics of the multidisciplinary working groups. The environmental context also played a role in creating a demand for climate information, whilst new actors were key in sustaining the scaling process, particularly at national scale. Finally, some actors improved their ability to coordinate with other actors, hence increasing their visibility and recognised role in actions concerning climate variability and climate change.
- The factors underlying the scaling process can be summarised as planned actions, including capacity strengthening, knowledge-sharing and action platforms, and interaction and learning opportunities; national and international financial opportunities, and an enabling political environment. Capacity strengthening and learning happened throughout the scaling process of WCS and at all levels. The action platforms created a space to share information and coordinate actions, which previously occurred in an informal and segmented way. Interaction opportunities, from local seminars to national and international events, where new actors shared their experiences and gained visibility and recognition, sustained the scaling process. These changes were stimulated by national and international support that provided the financial and political resources needed to scale WCS.
- Our evaluation shows that the scaling of WCS from pilot project to national scale in Senegal produced systemic outcomes that crossed institutional, sectoral and governance boundaries. However, current and future challenges include a demand for improved quality and finer-grain WCS delivered in a timely fashion, as new users and uses emerge, which will require significant investment. Issues of trust in who delivers the information and how it is produced, linked with a lack of capacity to interpret and act upon the information has become more important as WCS expand. Large-scale decentralised capacity strengthening actions linked to the function of the multidisciplinary working groups are needed. Public-private partnerships could play an important role, but at present, the involvement of the private sector is limited. At the policy level, the development model promoted through WCS, the use of environmental resources it incentivizes, and the potential trade-offs between productivity and long-term resilience it might entail should be critically analysed.

1. Introduction

1.1. Weather and climate services as an innovation process

In the West African Sahel, climate variability and climate change pose huge challenges to food security (Waongo et al., 2015), particularly to child nutrition and health (Johnson and Brown, 2014). Droughts and floods are part of natural climate variability in West Africa. However, the region is also experiencing widespread warming and more frequent climate extremes, and while future projections of monsoonal rainfall diverge, yield loss is a concern, along with expected increased rainfall variability (Sultan and Gaetani, 2016). The potential consequences for agriculture include harvest failures, fishery collapses and livestock deaths that disproportionately affect poor and marginalized groups with lower adaptive capacity. Seasonal outlooks, seasonal forecasts and long-term scenarios are therefore necessary to prepare for both adverse and favourable conditions (Hansen, 2002), and to support long-term planning through scientific information (Singh et al., 2018). Indeed, Weather and Climate Services (WCS), i.e. the production, translation, transmission, access to and use of scientific information on weather and climate for decision-making (Vaughan et al., 2019), have been

appearing increasingly frequently on research and funding-agency agendas (Lourenço et al., 2016). As services, they must respond to the needs of users, engaging them for diagnosis, co-design and evaluation in an appropriate and sustained manner (Tall et al., 2014). In recent years, considerable attention has been paid to ensuring that climate information is tailored to meet users' needs through regular consultation between actors along the information-dissemination value chain. Consequently, co-production of actionable climate information responding to goals shared between scientists and users is advocated as an approach that increases its use (Meadow et al., 2015; Ndiaye et al., 2012).

Such co-production implies a deliberate approach to building relationships and communication channels (Meadow et al., 2015). Moreover, co-production entails technical features, the creation and incorporation of new knowledge by different stakeholders, and changes in the way their activities are organised. These features are typical of "innovation", which combines new techniques and practices, new knowledge and ways of thinking, and new institutions and organisations (Smits, 2002). Indeed, innovation results from networking and interactive learning among diverse actors in their institutional environments (Klerkx et al., 2010). An innovation process entails social, technical, economic, and institutional change. Power dynamics and negotiations, informal actors and natural environments can influence the dynamics of the innovation, shaped by cross-sector interactions and feedback (Pigford et al., 2018). From an initial niche of scientists and users co-developing new knowledge, technologies and new ways of organising activities (Meynard et al., 2017), the innovation process leads to their widespread availability, access and use, stimulated by institutional support (Faure et al., 2019). As the innovation reaches scale, it can engender transformations in its own features and in the system of actors involved in its development (Geels and Schot, 2007; Woltering et al., 2019). Indeed, when they are scaled out (horizontally) and up (vertically), innovations cross sector boundaries (Wigboldus et al., 2016). This view of scaling transcends the notion of a linear transfer or diffusion, taking into account the adaptations that come with scaling the innovation to new realities. In light of these elements, the scaling of the WCS co-production model can be characterised as an innovation process: from the co-development to the use of information and related advice, to its transmission in multiple formats, by and for multiple interacting producers, translators, transmitters and users, under contextual rules and institutions.

1.2. Evaluating the scaling of WCS

WCS co-production models are relatively new: few studies have evaluated how farmers use them and how their use affects farmers' livelihoods (Tall et al., 2018; Vaughan et al., 2019). This is partly because, up to now, the scientific community has focused on the quality of information and services rather than the effects of their use. This is also partly due to the non-excludable and non-rivalrous nature of weather and climate information, and its likely transformation throughout the process of transmission and use, which makes evaluation a challenge. *Ex ante* or prospective evaluations that model the value of WCS for farmers in Senegal have shown for instance that responding to a drier season forecast by favouring certain types of crops minimizes climate risk (Sultan et al., 2010). Participatory simulations with farmers in Senegal suggest that responding to forecasts supports yield gains (Roudier et al., 2014). On the other side, *ex post* or retrospective evaluations have found that farmers who received seasonal forecast information in drought-affected areas were more likely to use drought tolerant crops (Maggio and Sitko, 2019). Most of these evaluations focus on a single end user, usually a farmer or a farming household. However, broader effects of WCS co-production models for agriculture, taking into account the multiple producers, translators, transmitters, and users of climate information have rarely been studied and the same goes for the institutional and policy factors that support WCS scaling (Vaughan et al., 2017).

Given the features of WCS co-production models, evaluating them only by measuring predetermined effects in a linear cause-effect logic in not appropriate (Patton, 2010). However, evaluations focusing on the attributes of technologies and adopters (Wigboldus et al., 2016) and adoption by numbers (Woltering et al., 2019) are common in agricultural research (Maredia et al., 2014). One answer to this challenge comes from complexity science, which is increasingly promoted as an appropriate approach for the analysis of innovations supported by research in dynamic and adaptive systems (Douthwaite et al., 2017; Faure et al., 2018; Joly et al., 2015). A complexity-informed approach examines the diversity of actors, interests, roles, the changes they bring about and/or experience in their environment, as well as the contextual factors that enable these changes. In the case of WCS co-production models, such evaluations can support positive dynamics of use, transformation, and feedback that improve the design, delivery, adaptation, and evaluation of WCS.

In the peer-reviewed literature on WCS, to the best of our knowledge, only four evaluations assess their effects on the broader system of actors involved in their production, translation, transmission, and use. Our study aims to fill this gap through a multi-level and systemic evaluation of WCS scaling in Senegal. In so doing, we provide an empirical contribution to evidence based evaluation of WCS co-production models after Chaudhuri et al. (2017) in India; Kirshen and Flitcroft (2000) in Burkina Faso; Lemos et al. (2002) in Brazil; and a characterisation of information access and use in Senegal (Catholic Relief Service, 2018). Our case study is based on the WCS scaling process initiated in 2011 by the National Agency of Civil Aviation and Meteorology of Senegal (French acronym ANACIM) and its research partners (Ndiaye et al., 2013). Following previous actions aimed at transmitting climate information to farmers, local multidisciplinary working groups were set up to facilitate the development of WCS, their interpretation in the form of advice, and their dissemination and uptake by users. In the following years, WCS and multidisciplinary working groups were scaled up to cover most departments in Senegal (Ouedraogo et al., 2018), in a rapid expansion from pilot to national scale. An evaluation carried out in 2015 estimated that through rural community radio stations and text messages, about two million people have had access to climate information, with a projected population reach of 7.4 million rural people across Senegal (CCAFS, 2015; Lo and Dieng, 2015). The scaling process of WCS directly or indirectly involved many national and local actors. However, the factors that led to scaling and its effects have not yet been assessed. Taking stock of this process through a systemic evaluation at national and local levels is timely and is necessary to understand the transformative process potentially engendered by the rapid scaling out and up of WCS in Senegal.

The study is one of only two in Africa to conduct a systemic evaluation of WCS, which are indispensable for policy making given sub-Saharan Africa's reliance on rain-fed agriculture and the vulnerability of rural communities. The contribution of our study is twofold. First, our evaluation involves a systemic assessment of the scaling of WCS in Senegal that allows us to draw lessons concerning the scaling process, its enabling factors, and the multiple effects this scaling has had. Second, we provide a methodological contribution through an iterative and complexity-aware evaluation method, the disentangles how research actions contributed to the changes brought about by scaling, while accounting for the roles of other actors and of contextual factors. Additionally, our evaluation is complementary to a quantitative impact assessment at the farmer level detailed in Chiputwa et al. (2020).

2. Methods

2.1. Study area

Senegal is a West African country characterised by significant climatic differences between the coastal area and inland regions and a

Sudano-Sahelian climate with two main seasons: a rainy season usually lasting from June to October, characterised by hot and humid monsoon from the St Helena High; and a dry season characterised by northern Harmattan winds from the Azores and the Libyan high. The South is wet and can receive more than 1000 mm of rain per year, while the dry North receives less than half that amount. Although the whole country has a significant amount of surface water, 95% of the agriculture practiced is still rainfed. Agriculture, accounts for about 15% of national GDP (African Development Bank, 2020). The agricultural sector employs about 70% of the working population (CIAT and BFS/USAID, 2016). The great majority (90%) of agricultural holdings are family farms combining cash crops (groundnuts or cotton), subsistence food crops (millet, sorghum, maize, sesame) and some animals in usually extensive livestock systems mixed with crops. Poor soils and weather conditions, limited access to advisory services and good quality agricultural inputs, and insufficient infrastructure, contribute to Senegal's inability to satisfy the country's food needs which is consequently obliged to depend on food imports (Ouedraogo et al., 2018). Future climate projections for the region are worrying as they predict warming accompanied by less rain in the western parts of the Sahel, including Senegal, particularly in the early monsoon season (Sultan et al., 2014).

2.2. Weather and climate services in Senegal

In West Africa, regional centres including the African Center for Meteorological Application and Development, the Agriculture-Hydrology-Meteorology regional centre (AGRHYMET), the African Centre of Meteorological Applications for Development (ACMAD), and the Niger Basin Authority (NBA), support the production and dissemination of seasonal forecasts in collaboration with national meteorology services (Traore et al., 2014). Since 1998, the Regional Climate Outlook Forum for West Africa, Chad and Cameroon (French acronym PRESAO) has provided training and a three-month seasonal rainfall forecast for the region, which in Senegal, is refined by the National Agency of Civil Aviation and Meteorology (hereafter National Meteorological Agency). The refined forecast is sent to a national multidisciplinary working group[1], which was established by AGRHYMET in the 1980s, who translates it into practical agricultural advice (Domergue and Chanzy, 1987). An agro-climatic analysis is conducted, and the crop calendar used for the selection of seed varieties and the supply of fertilisers and farm equipment (ANACIM, 2020). The National Meteorological Agency produces two daily weather bulletins in the rainy season and transmits forecasts through community and national radio stations. An early warning system provides forecasts to help the population cope with rainfall deficit, late vegetation growth, or floods.

Between 2011 and 2018, a research partnership between the National Meteorological Agency, the National Institute of Agricultural Research of Senegal, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), and the International Crops Research Institute for the Semi-Arid Tropics, implemented three successive projects, hereafter referred to as WCS projects, whose objective was to develop and scale WCS for agriculture in Senegal. The aim was to co-develop appropriate downscaled climate information services by building trust between climate service providers and farmers, enhance the capacity of partners disseminating climate information to farmers, and improve agricultural advisories (Ndiaye et al., 2013). Weather and climate information combined with agricultural advice was transmitted through multiple dissemination channels, incorporating endogenous knowledge and farmers' practices to cope with climate variability. In the years leading up to 2018, the number of multidisciplinary working groups reached 27, covering most departments in Senegal (Ouedraogo et al., 2018).

Fig. 1 shows where multidisciplinary working groups were created in the years leading up to 2018 (Ouedraogo et al., 2018). At the national level, we evaluate the changes brought about by the rapid scaling up of WCS through the actions of multiple actors, with diverse objectives, reach and visions. Our local analysis focuses on two departments, Kaffrine and Kaolack, with similar agro-ecological, productive, economic and social characteristics, but which got involved in the innovation process at different times. The Kaffrine department was the location of the pilot project and the local multidisciplinary working group has been active there since 2011. The Kaolack department entered the process recently: the first meeting of the MWG was only held in 2019.

2.3. Methodological framework

The complexity-aware and systemic evaluation approach we applied has three iterative and integrated components (Fig. 2). The three components are (a) reconstruction of the history of the innovation (Faure et al., 2020); (b) evaluation of the outcomes of the scaling of WCS based on Outcome Harvesting (Wilson-Grau, 2018); (c) analysis of the systemic transformations of the scaling process and their underlying factors, including the contribution of research partnerships, depicted through an impact pathway (Douthwaite et al., 2003). The methodological approach is based on triangulating data sources and data collection methods to build a coherent picture of the scaling of WCS and the systemic transformations it brought about

2.3.1. Reconstruction of the history of the innovation

First, we reviewed existing documentation to reconstruct the history of WCS, actors, events and contextual factors (Faure et al., 2020), and to identify the first changes in the innovation system that could be linked to the scaling process. Second, we organised a workshop in Dakar in October 2018, during which national and local actors reconstructed the WCS timeline and detailed its key events, actors, interventions, and contextual factors. The participants included 16 representatives of institutions including the National Meteorological Agency, the Directorate of Agriculture, the Center for Ecological Monitoring, ENDA *Energie* (national NGO), the Agricultural and Rural Prospective Initiative, the Regional Union of Farmers Associations of Diourbel, one promoter farmer, and a deputy from Kaffrine. They were invited because of their involvement in WCS projects at the national level or in Kaffrine (at that time, the Kaolack MWG was not yet operational). The workshop allowed us to identify other actors involved in the process we interviewed in the following stage. Third, we conducted individual interviews with 44 key informants (Table 1). In the interviews, we first asked the respondents to trace back the history of WCS, and to explain how their institution was involved in their development and scaling. We then asked them to formulate and validate outcomes, as detailed in the following paragraph. Finally, we asked them to describe the system of actors involved in the scaling of WCS, to tell us with whom their institution had interacted in the production, transmission and/or use of weather and climate information and related recommendations, and to describe the interactions in terms of collaboration, conflict, capacity building and funding. We chose these topics based on the type of actions we had identified in our review of documents and during the national workshop.

Analysis of the interviews with the key informants enabled us to refine the innovation history drafted during the national workshop, and to build a network map of the actors involved in the upscaling of the WCS and their interactions. We depicted the network using Gephi

[1] The national multidisciplinary working group includes the Department of Agriculture (French acronym SDDR), the National Institute of Agricultural Research of Senegal (French acronym ISRA), the Ecological Monitoring Center (French acronym CSE), the National Agricultural and Rural Council Agency (French acronym ANCAR), the National Agricultural Insurance Company of Senegal (French acronym CNAAS), the Pest Disease Control Department (French acronym DPV), the Union of Community Radios (French acronym URAC), Water Resources Management Services (French acronym DGPRE) and ANACIM.

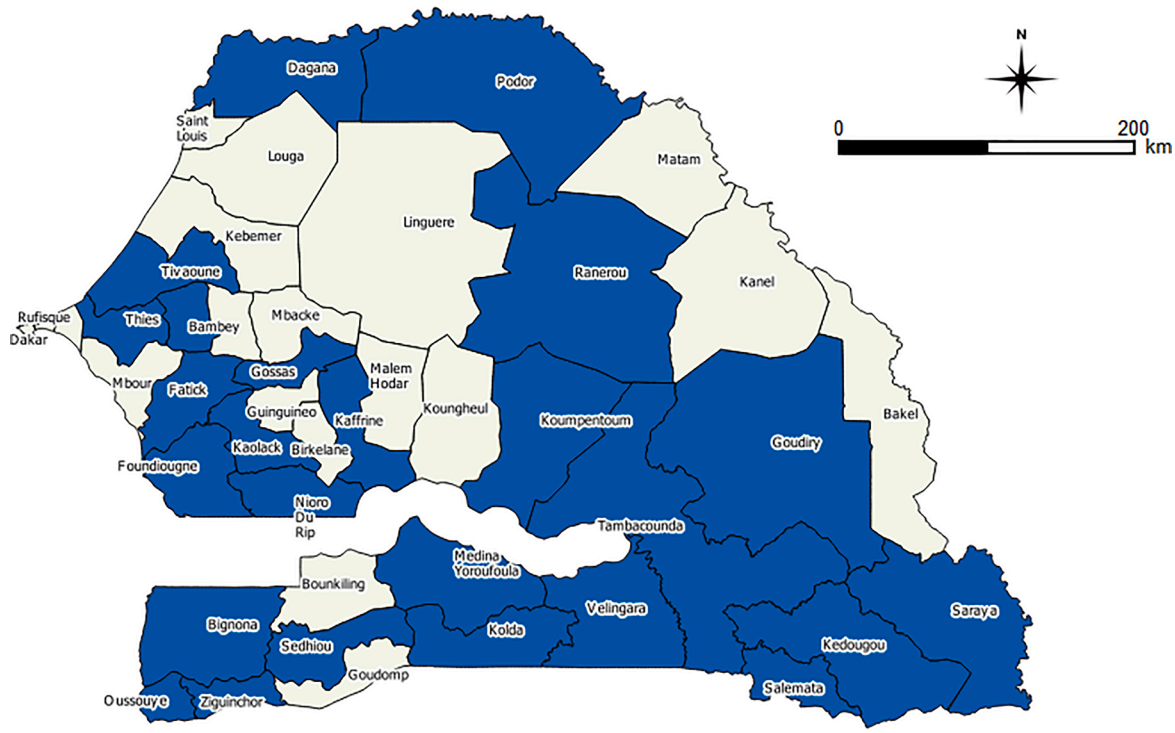

Fig. 1. National and local study areas. Adapted from (Ouedraogo et al., 2018). The thin borders correspond to administrative departments. The thick borders indicate the two local study areas. Departments in blue are those where local multidisciplinary working groups were created up to 2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

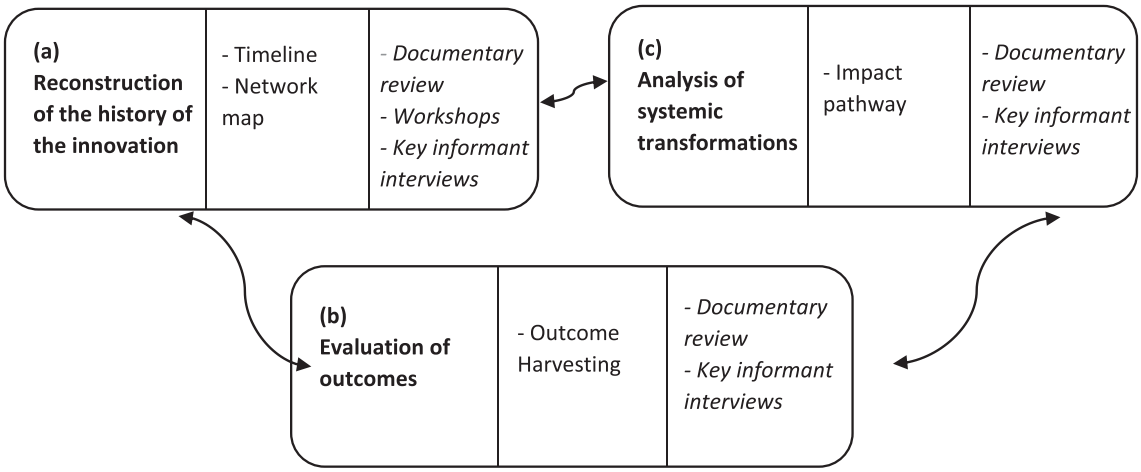

Fig. 2. Methodological framework. The figure shows the **components**, the tools used, and the *data collection methods*.

graphs and network visualisation software (Bastian et al., 2009). We visualised the network in terms of three types of interactions: collaboration, capacity building, and funding (only two conflictual interactions were reported).

2.3.2. *Evaluation of the outcomes*

To analyse the outcomes of WCS scaling and how the research partnerships contributed to enabling them, we adapted the Outcome Harvesting tool and approach (Wilson-Grau, 2018). Outcome Harvesting is a qualitative evaluation tool which identifies, describes, checks, analyses, and interprets observed outcomes (changes in behaviour, e.g. actions, practices, interactions), and retrospectively defines the contribution of an intervention to these outcomes. In our study, we define outcomes as:

- Changes in practices: systematic changes in the way actors carry out their activities and take decisions related to the production, transmission or use of WCS (e.g. an organisation implements new functions or systematically deploys new tools);
- Changes in actions: *ad hoc* activities that were undertaken as a result of their participation in the production, transmission or use of WCS, but which did not involve a systematic change (e.g. an advocacy document that states the position of actors, a political statement, an *ad hoc* funding action);
- Changes in interactions: new or different relations between actors related to their participation in the production, transmission or use of WCS (e.g. new collaborations, new conflicts, new knowledge sharing).

Table 1
Key informants interviewed.

Type of institution	Number	Number of people interviewed	Scale
National Meteorological Agency	2	3	National and local
Champion farmer (deputy)	1	1	National
Funders	1	2	National
Government program	3	6	National and local
Local government agency	10	10	Local
Media	5	7	Local
Ministry	3	6	National
National government agency	2	2	National
National research institute	1	2	National
National NGO	2	2	National and local
Producer organisation	3	3	National and local
Total	**33**	**44**	

The Outcome Harvesting approach aims to capture all positive, negative, expected and unforeseen changes concerning all actors who are directly or indirectly influenced by an intervention, rather than focusing on the expected beneficiaries of the intervention and against predetermined outcomes (Wilson-Grau, 2018). The approach involves six steps: 1) designing the evaluation, 2) reviewing documentation, 3) getting the actors who participated in the intervention to formulate outcomes, 4) substantiating the outcomes with knowledgeable and independent informants, 5) analysing and interpreting the outcomes, and 6) supporting use of the results. 'Substantiation' is the Outcome Harvesting term to describe the interviewee's complete or partial validation of the outcomes formulated by the actors who implemented the intervention and/or their reformulation. The knowledgeable and independent informants go 'on the record' with their answers, which aims to address reporting bias.

In our study, the 'intervention' is the scaling of WCS, with a focus on the contribution of the three WCS projects. As the evaluation team, we designed the Outcome Harvesting (Step 1) in collaboration with the staff member of the National Meteorological Agency who had been responsible for the three WCS projects and supported the documentary review (Step 2). We then formulated the outcomes based on the documents reviewed, the national workshop and the knowledge of the National Meteorological Agency agent (Step 3). At this stage, we had formulated 12 outcomes to which the research partnerships carrying out the three WCS projects contributed.

We then interviewed independent informants with diverse knowledge (Step 4), who were first identified by the National Meteorological Agency agent, and subsequently by the interviewees themselves in a snowball approach. We started the interview by asking the informants for their account of the innovation story based on their own knowledge and experience. We then asked them whether their institution had implemented any changes as a result of their participation in the production, transmission or use of WCS, and if they had, what the changes were. Only after collecting their opinion, did we ask them to substantiate (Step 5) the outcomes formulated in Step 3. Because we were not only interested in evaluating the contribution of the research partnerships, but in reconstructing the whole picture of the scaling process, we asked them to describe any other changes (positive or negative) their institution had introduced because of their participation in the process. For each outcome, we asked them to qualify the contribution of the three WCS projects, if any, that of other interventions, and the influence of contextual (e.g. economic, political, international) factors on these changes. We also asked them to state the significance of the outcome, or whether it was significant in terms of the effects it entailed for the institution or other actors, including for end users (local populations).

After the interviews, we asked the interviewees to validate their written outcome statements and, when possible, provide tangible evidence to support them. For the analysis (Step 5), each outcome statement taken from the interviews was characterised by four elements: formulation (the change the actor had experienced), significance (the change in practices, actions or interactions generated, according to the interviewee), contribution (of the WCS and of other projects), and influence of contextual factors.

When data collection and analysis were complete, one national and two local workshops (Dakar, Kaffrine, Kaolack) were held in November and December 2019 to present the results and obtain feedback from the actors who had participated in the evaluation (Step 6).

2.3.3. *Analysis of systemic transformations*

After completing the above parts of the evaluation, we characterised the scaling process through an impact pathway (Douthwaite et al., 2003; Faure et al., 2020). An impact pathway is an explicit sequence of hierarchized items that reveals the causal process linking products or outputs, such as multi-stakeholder platforms, forecasts, recommendations, trainings, bulletins, and so on, to the changes in practices, behaviour, and interactions (outcomes) the production, transmission or use of these products has influenced, and to the long-term impacts of these outcomes. To draw the impact pathway, we analysed the information gathered from the project documents and the interviews to identify key outputs. The outputs were not only those generated by the research partnership through the WCS projects, but also those produced by other actors. We then used the outcomes substantiated in Step 3 of Outcome Harvesting and identified the impacts linked to them, which were derived from the interviewees' answers concerning the significance of the outcome. In analysing the impact pathway, we identified the axes of change related to the WCS scaling process. We define them as "transformative axes" in order to highlight trends in how the actions and relationships between actors evolved over the course of the scaling process, culminating in outcomes, and how research partnerships, other actors and factors supported and enabled these transformations. For each outcome, we identified its effect on the system of production, transmission and use of WCS. The transformative axis correspond to a set of outcomes that lead to specific effects on the production, transmission and use of WCS In this way, five axes were identified: 1) continuous improvement of the WCS, 2) emergence and consolidation of facilitators of WCS, 3) inclusion of WCS in action planning, 4) active mobilisation to sustain continuous WCS scaling, and 5) empowerment of actors.

3. Results

3.1. *The innovation history: from pilot to national scale*

Three stages can be distinguished in the scaling process of WCS in Senegal: 1) the foundations, 2) the consolidation of the National Meteorological Agency, and 3) investment in scaling.

3.1.1. *The foundations (1984–2009)*

The WCS as an innovation have their roots in the 1980s, when AGRHYMET set up the first national multidisciplinary working group to monitor the agricultural season (Traore et al., 2014) in response to a devastating drought that affected member countries of the Permanent Interstate Committee for Drought Control in the Sahel (French acronym CILSS) in the West African Sahel. The multidisciplinary working groups were platforms for engagement where meteorologists and stakeholders from different sectors such as agriculture and water could collaborate and produce early warning information (Hansen et al., 2019). The first projects which combined climate information and recommendations for farmers and for the fisheries sector started in the 1980s, with the support of the appropriate ministries and foreign aid. The international context led to the creation of a National Committee for Adaptation to Climate

Change (French acronym COMNACC), which was institutionalised in 2003 as a sharing platform for government institutions. In the late 2000s, the Infoclim project and the regional Climate Change Adaptation in Africa (CCAA) programme facilitated access to climate information and agricultural advice for multiple stakeholders. The official recognition of the National Meteorological Agency (formerly ANAMS) as the national office for weather data, clarified exchange protocols and marked the beginning of a new stage.

3.1.2. Consolidation of the National Meteorological Agency (2008–2014)

In its new role, the National Meteorological Agency of Senegal started strengthening the capacity of its agents in the Regional Climate Outlook Forum to improve the quality of seasonal forecasts by organising seminars to disseminate climate information to institutional stakeholders, and by training community radios through an agreement with their Union to broadcast weather reports. After participating in seminars for seasonal agro-climatic forecasting in West African countries organised by the African Center for Meteorological Application and Development, the Agriculture-Hydrology-Meteorology regional centre (AGRHYMET), the African Centre of Meteorological Applications for Development (ACMAD), and the Niger Basin Authority (NBA), supported by the World Meteorological Organisation, in 2009, the National Meteorological Agency started producing forecasts for farmers. A key actor in the innovation and scaling process emerged, who later became Director of Meteorology, who provided new scientific knowledge to be piloted in the first WCS co-production project, which began in 2011 within a research partnership led by the National Meteorological Agency.

During the first WCS project (2011–2013), so-called promoter farmers were selected to help disseminate weather and climate information and technical recommendations to other farmers. They were selected among farmers who were keen to experiment the use of forecasts and related recommendations, farmer leaders, or farmers with a strong influence, such as religious leaders. Capacity-building workshops raised local stakeholders' awareness of the importance of climate information in decision-making and familiarised them with weather forecasting and with the jargon used by forecasters. Rain gauges were distributed to farmers to enable them to collect and interpret rainfall data. Local multidisciplinary working groups were set up in three pilot areas: Kaffrine, Bambey and Niakhar (Fig. 1). Chaired by the local authority (the Prefect), they are decentralised government agencies and services, farmer organisations, local media, and non-governmental organisations (NGOs). In the rainy season, the local multidisciplinary working groups receive climate information from the National Meteorological Agency and meet at 10-day intervals. They run the early warning system, review the situation concerning the current cropping year, pests and diseases, pastoralism and market supplies, interpret these data in relation to climate information, and disseminate climate and agricultural advice to farmers through reports and different dissemination channels. Training extension officers, promoter farmers, and radio presenters, aimed at filling the "missing link'' between the multidisciplinary working group and remote farming communities, and reaching more users (ANACIM, 2013).

The second WCS project was implemented in 2013–2015 in Louga, Thiès and Diourbel regions, where new multidisciplinary working groups were set up. Dissemination formats were improved, the partnership with the Union of rural community radios (French acronym URAC) expanded, along with training for personnel providing technical services, farmers and journalists.

Finally, as part of the "Climate Information Services for Increased Resilience and Productivity in Senegal" (French acronym CINSERE) project funded by USAID between 2016 and 2019 (Ouédraogo and Diouf, 2017), the number of multidisciplinary working groups reached 27, most of which are still active today (Ouedraogo et al., 2018). Voice-based early warning calls in local languages were broadcast for the first time. With the involvement of a private firm, a new broadcasting platform was created, Météo Mbay, with climate information reaching a potential audience of 100,000 beneficiaries through SMS and voice calls on mobile phones. During the implementation of these projects, at the beginning of each rainy season, the National Meteorological Agency organised seminars with all local partners, to inform farmers of major trends in the rainy season, based on the seasonal forecast. The seminars were also an opportunity to collect farmers' forecasts based on their empirical and traditional knowledge and to get relevant feedback.

The National Platform for Dialogue on the adaptation of agriculture and food security to climate change (C-CASA) which involves scientists, donors, and national policy makers, was then created to promote the synergies between key national actors involved in policy orientation and strategies to address climate change (Diouf et al., 2015). Contextually, with the national Adaptation to Climate Change (PAA/INTAC) programme, a favourable political environment began to emerge. Regional Climate Change Reflection Committees were established, who called for climate change to be taken into account in policies designed by local authorities. The success of the first WCS projects encouraged the Department of Agriculture of Senegal to incorporate climate information in the National Adaptation Plan for the agricultural sector.

3.1.3. Investment in scaling (2015–2019)

At this stage, a variety of funders supported the dissemination of WCS throughout Senegal which was also facilitated by the favourable global funding environment for climate change research and development actions. The decentralisation of Climate Funds, funded by UK cooperation and implemented by IED *Afrique*, integrated climate change adaptation in plans for actions to be undertaken by local authorities and producers, and outscaled WCS to all administrative departments in the Kaffrine region. The United Nations and USAID funded additional projects to train more journalists and other actors and to establish new multidisciplinary working groups. Since 2010, the Conference of the Parties (COP) has also promoted policies to support climate adaptation actions. The upscaling stage saw the expansion of WCS beyond the primary sector to the energy and water resources protection directorates, among others.

Finally, different media outlets specialised in resilience and adaptation themes, including the Network of Journalists Associated with Agricultural and Environmental Issues in Senegal, and the Agora30 platform, agreed to pool their efforts to capitalise on the knowledge produced by the increasing number of projects on the subject.

3.2. The complex innovation system that emerged

The network of actors who directly or indirectly interacted in the WCS scaling process comprised no less than 161 actors. These actors have been involved in WCS scaling at different levels and with different roles, which have evolved over time. About a third of the 33 institutions represented by the 44 respondents we interviewed were simultaneously producers, transmitters, and users of WCS. This multiplicity of roles is typical of local institutions involved in multidisciplinary working groups. They deliver knowledge and feedback to the National Meteorological Agency to develop and improve the forecasts and their format; they transmit information through several different channels; they use the forecasts to produce bulletins and to plan their actions. Other actors, including ministries, use climate information as inputs in their decision-making or in the tools and publications they disseminate. Others, such as journalists, are recognized transmitters.

Based on our classification, 15 types of actors emerged (Fig. 3), of which national and international funding bodies account for a significant proportion (24%). This information is the result of our specific question on funding-based ties, and clearly reveals the interest of funding bodies in the development and upscaling of WCS. Local government services (18%) include decentralised agriculture and animal production services in Kaffrine and Kaolack, the Departmental Rural Development Services, and local authorities. These actors were actively

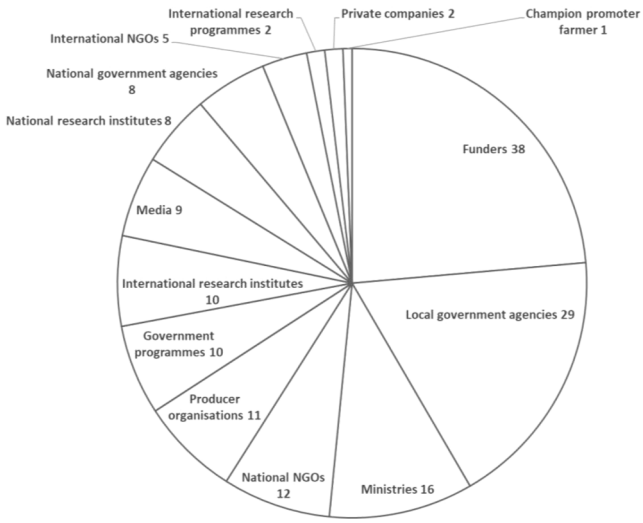

Fig. 3. Actors that participated to the scaling of WCS.

engaged in the dynamics of the multidisciplinary working groups, and their predominance in the network reflects this engagement. Different ministries and their bureaus (10%) in different sectors including environment, livestock, energy, finance and the Water Resources Management and Planning Planning, participated in the scaling process. Senegalese NGOs (7%), including IED *Afrique* and the local Red Cross, participated in the process as enablers of the development and transmission of WCS. The different producer organisations, often involved in the innovation process via training, co-production, and generation of information for the improvement of WCS, are at the same time, producers (through feedback), transmitters, and users of the information (7%). Government programmes were identified by respondents as *de facto* actors in the system. International and national research institutes and universities have also been involved in the innovation process, particularly in the improvement of WCS development and delivery (6%). Finally, media outlets, from community radios to newspapers and journalists who specialise in climate change issues, actively participated in the innovation process (6%).

Concerning collaboration in the production, transmission and use of climate information, ministries, the National Meteorological Agency, local government agencies, producer organisations, and national research institutes were engaged in the highest number of collaborations. Fig. 4a shows that the ministries and the National Meteorological Agency play key roles as intermediaries able to connect the largest number of actors in the network, thanks to their national role and their links with local institutions.

In terms of capacity building, National Meteorological Agency is the main institution which provides training in WCS. Research programmes, international and national research institutes also provide capacity building, especially for producer organisations and the media. Ministries and directorates receive a fair amount of capacity building in the network, but also train others. Local and national government agencies are more often receivers of capacity building (Fig. 4b). This can be linked with training actions for members of the multidisciplinary working groups but also national seminars on the interpretation and use of climate information. Funders also appear to be involved in capacity building actions, especially those targeting the media. Finally, funding for WCS related actions is provided by funding bodies including international and national cooperation agencies, delegations of the European Union and of United Nations agencies, but also international NGOs and research programmes. The actors who have received the most funding are the National Meteorological Agency, national research institutes, government programmes, national and local government agencies, ministries, and the media (Fig. 4c).

3.3. Outcomes and systemic transformations

3.3.1. Outcomes

Altogether, the key informants identified 75 outcomes. Of these, 55% were changes in practice, 37% were changes in interactions, and 8% were changes in *ad hoc* actions. Zooming in on the contribution of research partnerships to these outcomes, we found that the actions of the three WCS projects contributed to 26 out of the 75 outcomes identified. Most outcomes were changes in practices (18) both at local (Fig. 5a) and national scale (Fig. 5b), followed by changes in interactions (7) and one change in *ad hoc* actions. In 17 cases (65%), WCS projects contributed to these changes by triggering actions that enabled actors to implement the change. In other cases, activities such as trainer training (e.g. farmer promoters, journalists) sustained the upscaling process by enabling it to reach new actors. At the local scale (Fig. 5c), the main change in practices involves the way actors plan their activities using weather and climate information and associated recommendations. At the national level (Figure c), some actors were empowered as focal points on climate

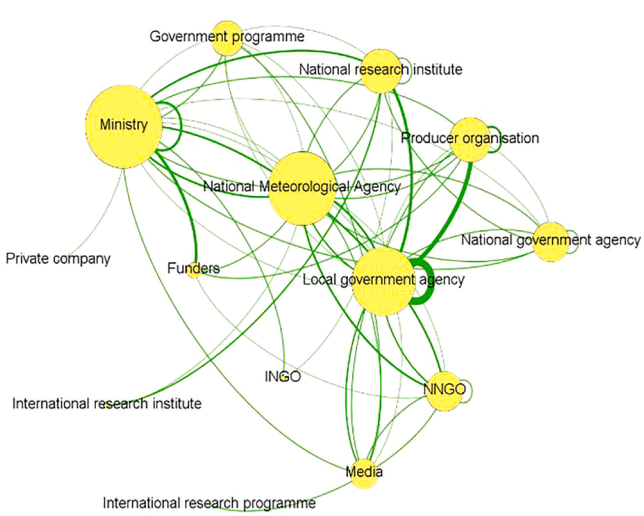

Fig. 4a. Map of interactions based on collaboration: The bigger the circle representing each actor, the larger the number of other actors with whom they collaborated during WCS scaling.

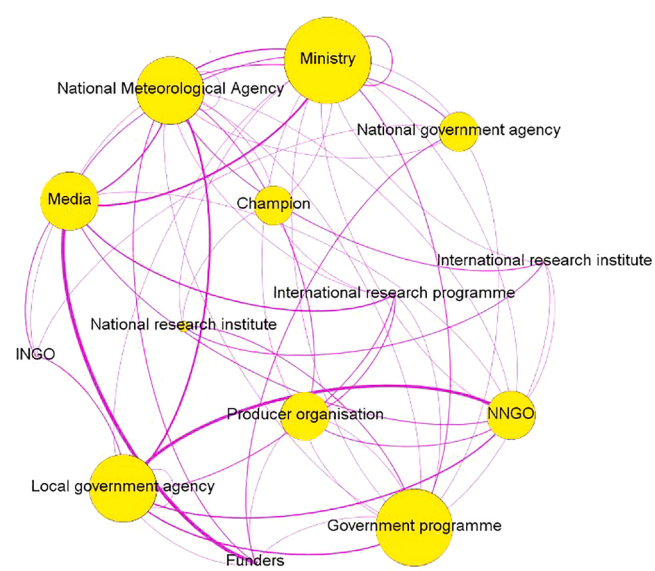

Fig. 4b. Map of interactions based on capacity building. The bigger the circle representing each actor, the larger the number of actors who provided them with capacity building during WCS scaling.

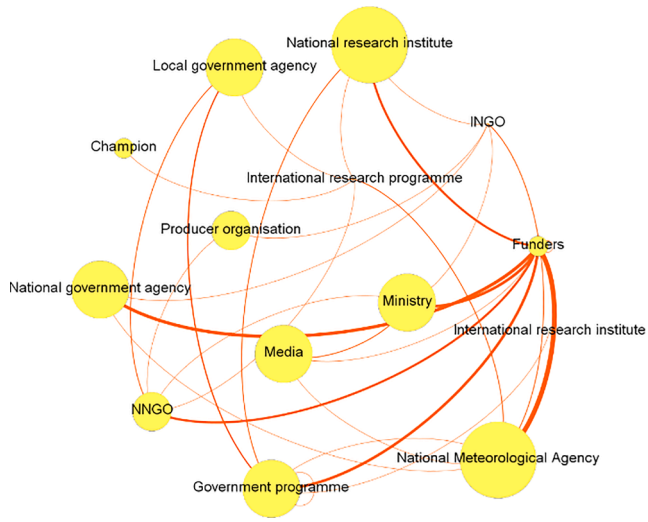

Fig. 4c. Map of interactions based on funding. The bigger the circle representing each actor, the larger the number of actors who provided them funding during WCS scaling.

and environment related issues, others have created new activities to support decision-making by other actors, incorporating weather and climate information.

Interestingly, many of the changes occurred early in the process, when the pilot project in Kaffrine created the local multidisciplinary working group, trained promoter farmers, and held knowledge-sharing workshops. Importantly, changes in practices, or systematic and permanent changes in the way actors plan their activities, communicate, or offer services, continue today. This means that the scaling process led to a "permanent" change in the practices of some actors compared to before they became involved in the development, transmission, or use of WCS. Supplementary material S1 lists the type of changes (outcomes) to which the research partnerships contributed, the scale, the year of emergence, the evidence and its robustness, the actor(s) who changed, the type of contribution, and whether this contribution triggered or sustained the scaling process. Supplementary material S2 presents the database with details of each outcome.

3.3.2. *Systemic transformations*

Figs. 6 and 7 depict the main elements of the impact pathway of the scaling process, or the process connecting the key outputs that contributed to changes in practice, behaviour and interactions, and the impacts these changes brought about in the system. Given the complexity of the impact pathway, only feedback loops that show a continuous feedback process are illustrated (double headed arrows). Other feedback processes take place during the development of outputs as actors produce them, use, and transform them, but because the impact pathway is not a chronological representation of a causal process, single-loop feedback processes are not included.

3.3.2.1. Axis 1: Continuous improvement of WCS. First, the continuous improvement of WCS sustained the scaling process, which in turn, supported their improvement through feedback between users, transmitters, and producers of information. The National Meteorological Agency improved forecast quality by participating in international research initiatives and adopting new models, but also by incorporating feedback from users concerning the language and formats used (Fig. 6). At times, this quality improvement process was accelerated by targeted projects. Specifically, the research partnership contributed through trigger strategies aimed at accelerating the process of development, transmission or use of WCS. These strategies included knowledge sharing and capacity building, but also funding of dissemination actions. For instance, local radio broadcasters were trained to collect data from rain gauges themselves, they then forwarded the data to the National Meteorological Agency to improve the quality of the forecasts. At the same time, the funding of multidisciplinary working group meetings held every ten days in the rainy season, provided a space to share knowledge and experience, providing with feedback on identified needs for improvement of WCS and enabling a continuous co-production-use-feedback-adaptation loop. According to the key informants, as a result, rural populations, as well as members of the multidisciplinary working groups, have increased access to improved WCS, and are now demanding finer and more timely forecasts, taking ownership of this information to adapt their short-term and medium-term action planning (Fig. 7).

3.3.2.2. Axis 2: Emergence and consolidation of WCS facilitators. A second transformative axis is the emergence and consolidation of actors who facilitate the dissemination and use of WCS, making climate information accessible to a broad range of actors. At the national level, this resulted in new communication strategies but also new activities including WCS to support decision-making by other actors (Fig. 6). For instance, since 2017, the Directorate of Fisheries and the Dakar-Thiaroye Oceanographic Research Centre have published a quarterly scientific and analytical environmental monitoring newsletter on fisheries and climate change, which includes scientific information on climate. This newsletter democratises access to environmental monitoring information relevant to the fishing sector to a wider readership. WCS projects enabled funding and raised awareness of the importance of environmental issues for fisheries, fuelling the need to produce the newsletter. The Civil Protection Department, responsible for managing risks for the population associated with extreme weather conditions, has also improved its use of the information in their newsletter. The WCS projects trained the institutions' agents in methods and techniques for communicating and transmitting climate information.

Locally, the participatory approach of co-production and learning with farmers increased the dissemination of climate information (Fig. 7). Community radios became *de facto* facilitators to the point of reorganising their programmes to broadcast more weather and climate information, and created targeted trailers so that listeners would know when to tune in. Journalists are therefore better able to transmit the information and make it easier for farmers to understand weather and climate information. The research partnerships contributed through targeted training, but also by building on previous conventions between the National Meteorological Agency and Union of community radios. The environmental context played a role in generating a demand for climate information. For instance, the changes observed in the patterns and frequency of rainfall, which make it necessary to adapt forage production and to store forage, encouraged the Departmental Service of Livestock and Animal Production to include climate information in their communication strategy.

3.3.2.3. Axis 3: Inclusion of WCS in action planning. The third axis illustrates how actors incorporate information on climate and weather in their decision-making and action planning. Climate information supports public policy, such as the new Sectoral Development Policy Letter (2016–2025) of the Directorate of Water Resources Management and Planning (Fig. 6). Similarly, the National Agency for Renewable Energy uses weather and climate information to monitor climate variables that can influence the potential for renewable energy production across the country. At the national level, the outputs and actions of the three WCS projects did not contribute directly to these changes. The direct contribution came from the actions of the National Meteorological Agency in terms of seminars, training sessions and workshops, and its involvement in international and national platforms on climate change. Contextual factors, for example, the African Water Vision 2025 influenced changes at the level of the Directorate. At the level of national adaptation plans,

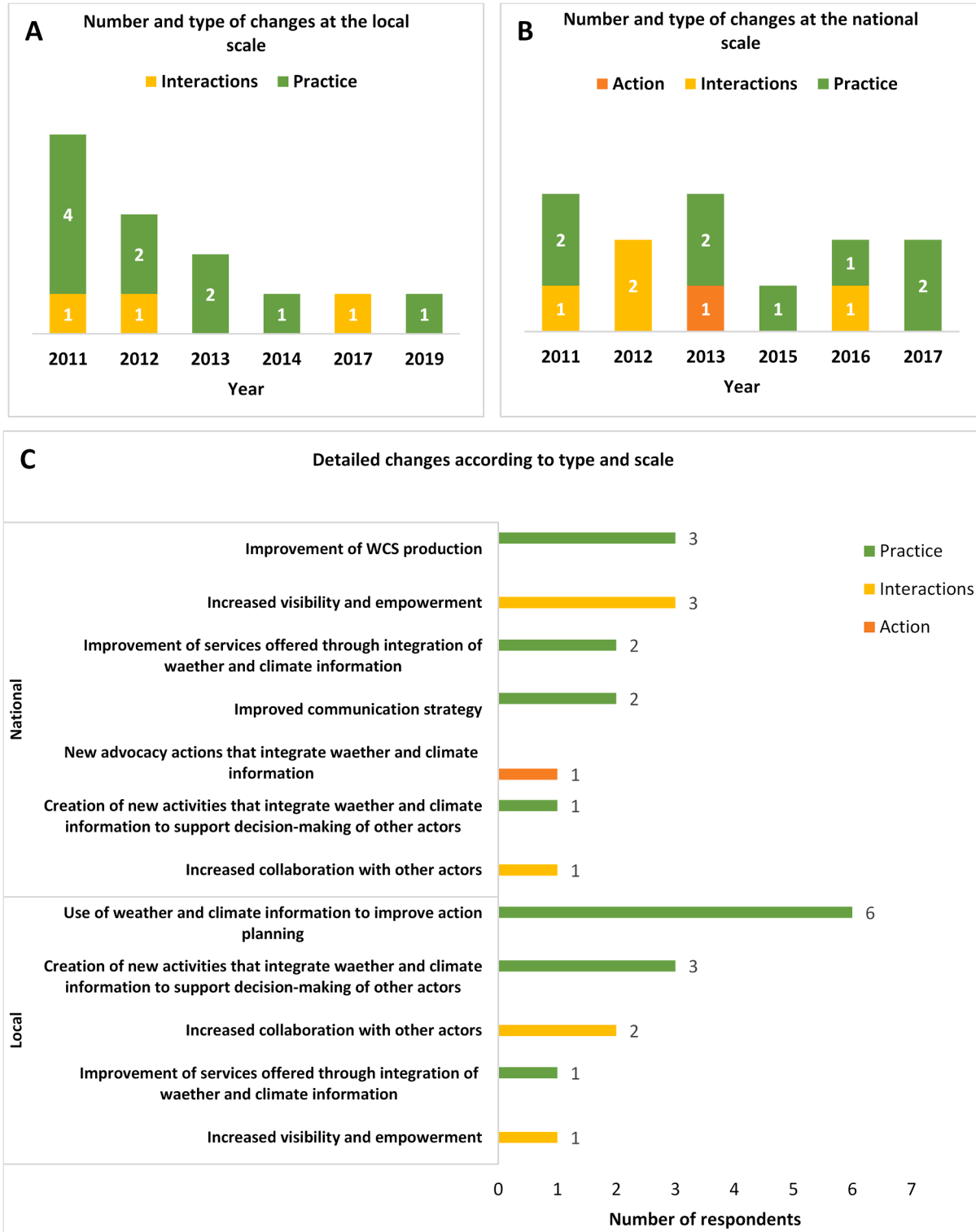

Fig. 5. Outcomes of the scaling process to which the research partnership contributed.

the international context, in particular, set by the Conferences of the Parties (COP) in Cancun and Paris and their resulting agreements, influenced ministerial decisions to develop such plans for different sectors. Moreover, international research consortia in the framework of the Future Climate For Africa programme, such as the African Monsoon Multidisciplinary Analysis (AMMA) 2050 project, increased political interest and ownership of climate related issues. The financial context was also supportive. Adaptation Funds from the Senegalese government, international organisations and cooperation supported cumulative effects of subsequent or concomitant projects to increase the resilience of different sectors, and the implementation of national adaptation plans.

At the local level, decentralised state agencies identified the use of weather and climate information as a key input for strategic decision-making, operational planning and targeting interventions, thereby increasing coordination of their actions in the dynamic of the multidisciplinary working groups. This affected the efficiency of prevention

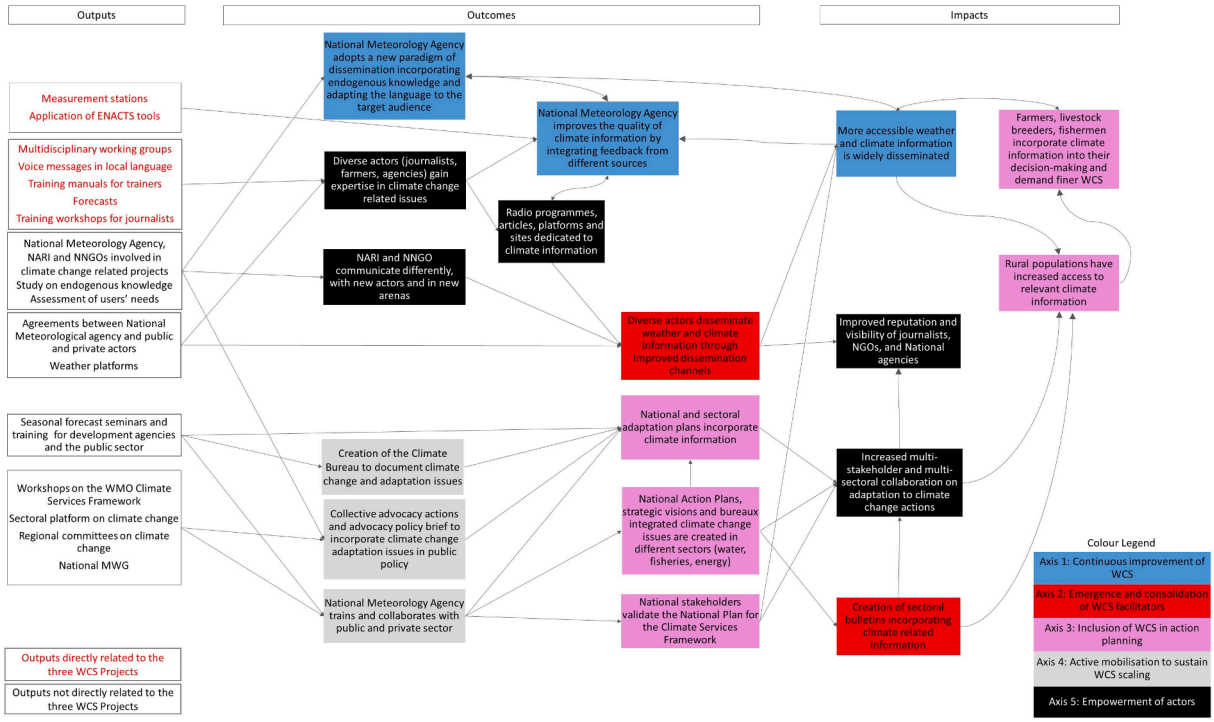

Fig. 6. Synthesized impact pathway and transformative axes at the national level.

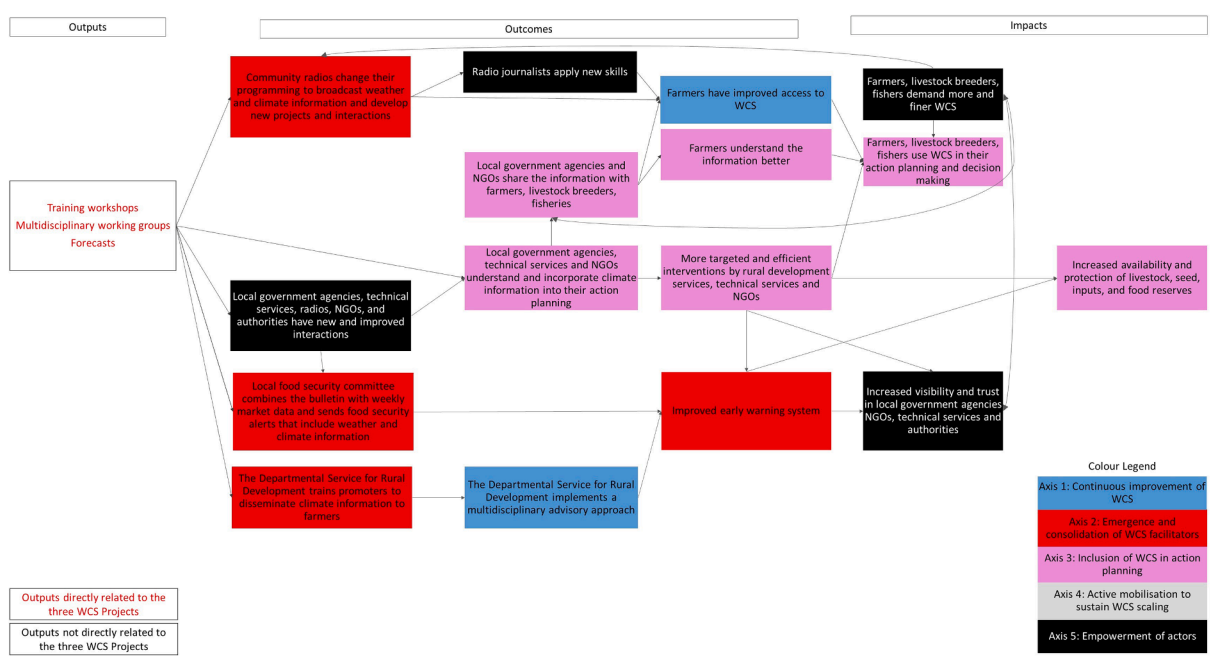

Fig. 7. Synthesized impact pathway and transformative axes at the local level.

actions, the availability and distribution of farming inputs, the availability of food and input reserves to face scarcity, and the protection of populations and their assets (Fig. 7). For example, since 2013, the Kaffrine Direction of Plant Protection has used climate information to rationalise its interventions in pest-affected areas, rather than intervening systematically or without targeting specific areas as they did previously. This enables savings on both products and in operating costs, and increases treatment efficiency. The WCS projects contributed to this change by creating opportunities for interaction and by supporting collective action through the multidisciplinary working groups, capacity building and knowledge sharing, and tools to support decision-making (e.g. the ten-day bulletin).

3.3.2.4. Axis 4: Active mobilisation to sustain continuous WCS scaling. A fourth transformative axis involves the active mobilisation of new actors to sustain the scaling process, particularly at national level. It includes advocacy actions such as a policy brief pledge with administrative authorities to include adaptation in public policies, or the National Meteorological Agency's pledge to involve a wide range of stakeholders to validate the national Climate Services Framework (Fig. 6). The policy

brief, developed within the National Adaptation to Climate Change (PAA/INTAC) programme, was partly based on the testimonies of farmers who benefited from the WCS projects. This advocacy action also provided guidance for the activities of the (2014–2017) USAID-COMFISH project through a study of the coherence of research results and user needs. Specific bureaus for systematisation and information sharing and policy dialogue platforms, managed to obtain funding to sustain scaling and improvement of WCS. Political interest in climatic forecasts has increased also through new research findings obtained by national research actors, such as climate prediction scenarios and millet resilience mapping. Such results have attracted the interest of parliamentarians in including weather and climate information in agricultural investment strategies.

3.3.2.5. Axis 5: Empowerment of actors. Finally, the fifth transformative axis involves the empowerment of actors in terms of their improved ability to interact and coordinate with other actors, and increased visibility and recognition of their role in WCS or climate change related issues. New interactions to increase resilience of multiple sectors have been created, for instance through projects for the national community radio association and the creation of the Agora 30 platform (Fig. 6). At the national level, actors are empowered as focal points on climate and environment related issues. Capacity building for the interpretation and use of climate information either triggered or sustained these changes. Moreover, international arenas reinforced the visibility of actors including national NGOs and journalists on climate change issues.

For instance, the network of journalists has become a focal point in covering events on environmental issues and is called upon by national and international actors. In 2017, a farmer promoter was elected to parliament to represent her home community. She links her election to her engagement in the pilot WCS project, which, through the skills and knowledge acquired by participating as a farmer promoter, gave her visibility and the confidence to take on a more political role. Another example, a national NGOs was invited to participate in the Regional Climate Outlook Forum, thereby recognising their role in developing good practices of incorporating endogenous knowledge in research actions.

At the local level, the multidisciplinary working groups not only triggered new dialogue and coordinated actions, but also increased farmers' trust in local government agencies, NGOs, technical services and authorities. Community radios have gained visibility through their role in transmitting climate information (Fig. 7). The research partnerships contributed to these changes particularly by creating opportunities for interactions and learning through the multidisciplinary working groups, and capacity strengthening activities.

4. Discussion and conclusion

4.1. The scaling process of WCS and its enabling factors

Our results shed light on the long-term, cross-domain and cross-scale consequences of the scaling of Weather and Climate Services in Senegal. WCS are an innovation combing new techniques and practices (e.g. climate and weather information and related recommendations, transmission channels), new knowledge and ways of thinking (e.g. how forecasts are produced, notions of risk, probability), and new institutions and organisations (e.g. multidisciplinary working groups). The history of this innovation in Senegal began with the interest shown by national actors in forecasts as a tool to support action planning and the pre-existing regional experience acquired in the production and transmission of WCS. Subsequently, the reflection of national agencies, NGOs and research institutes on the role of knowledge co-production, combined with a favourable institutional environment, enabled a (at least partial) paradigm shift in the way scientific knowledge is created and transmitted. The third stage witnessed a major increase in funding for WCS and their inclusion in decision-making, planning and communication by multiple actors at different scales and sectors, who played different roles in their production, transmission and use.

The factors underlying the scaling process can be summarised as planned actions, emerging national and international financial opportunities, and enabling national and international political environments.

Planned actions enabled the scaling process through strategies that triggered or sustained the production, transmission and use of WCS. The effects of this process mainly involved changes in practices, such as improved action planning, management and communication strategies; and interactions, such as coordination of actions. Planned actions were largely led by the National Meteorological Agency with the support of other actors, including a research partnership comprising national and international institutions that supported the expansion of the multidisciplinary working groups to most departments in Senegal.

Capacity strengthening, knowledge-sharing and action platforms, and the creation of interaction opportunities characterised these planned actions. Capacity strengthening and learning happened throughout WCS upscaling and at all levels, including between 'producers' and 'funders' of knowledge, the latter being ideally placed to promote a co-learning approach (Vogel et al., 2019). This includes improved capacity of producers, transmitters, and users. Faure et al. (2018) show how strengthening the capacity of different actors, including researchers, is a key but understudied change generating mechanism. The importance of capacity strengthening in areas and actors who often lacked formal training and had few opportunities to improve their skills, also helps explain the rapid expansion of WCS and of the multidisciplinary working groups, despite the uncertainty concerning the quality of the data and the robustness of the forecasts as they reach an increasingly large number of users. Other studies report that the lack of capacity in production, transmission and use hinder the effectiveness of seasonal climate forecasts (Lemos et al., 2002).

Knowledge-sharing and action platforms were originally built based on previous collaboration between national and local actors but were formalised throughout the scaling process to allow different stakeholders to systematically interact in decision-making. At the local level, many of these actors were already interacting but in smaller sub-networks and in more informal ways. Matt et al. (2017) show how existing networks can trigger a transformative process through multidisciplinary research activities. The multidisciplinary working groups and promoter farmers played a key role in supporting organisation and networking between heterogeneous decision-makers with different mandates and objectives, from decentralised state services to community radios to individuals, who exchanged their knowledge and coordinated their actions. This exchange of resources and information requires organisation and networking (Hall and Clark, 2010), which was supported by national and local public institutions, reaching new areas and new users and uses outside the agricultural sector.

Opportunities for interaction, from seminars to discussions of seasonal forecasts at the local level, to national and international events, in which new actors share their experiences and gain visibility and recognition, sustained the scaling process over time. This recalls enabling factors in climate services science including co-production, lasting relationships and communication between scientists and stakeholders, and focusing on usable science (Meadow et al., 2015). Moreover, the role of networks and the ability of actors to negotiate throughout the process has been identified as a key mechanism in generating outcomes related to weather information systems (Chaudhuri et al., 2017). The newly acquired ability of multiple actors to use WCS for different purposes and the emergence of facilitators, including advisory services and sectoral directorates, enabled new users to understand and act upon the information received. These facilitators often filled multiple roles simultaneously in formal and informal ways (Pigford et al., 2018), participating in the production, transmission and use of WCS.

These changes were also stimulated by institutional support (Faure

et al., 2019), which provided the financial and political resources required to scale WCS. Ministries, directorates, and national agencies participated in the transformative process as facilitators and disseminators, but also as actors who incorporated WCS in their own practices and strategies. The systemic approach to climate change adaptation initiated by the government in 2010, and international support provided by the Conferences of the Parties (COP) and regional projects, produced an enabling environment for the scaling of WCS. The combination of planned actions, financial, and political support enabled the innovation to cross boundaries of sectors and scales (Wigboldus et al., 2016) to reach new market segments (Klerkx et al., 2012), e.g. users in the agriculture, fisheries, water, and energy sectors.

The role of a strong leading and facilitating agent should not be underestimated in this process. The National Meteorological Agency acquired unprecedented visibility in the system. At the same time, the sustainability of the use of WCS depends on the stable financial, relational and technical engagement of the Agency, or on the integration of new actors mandated with this task. Indeed, the consistent provision of better quality and finer-grained weather and climate information is being called for by multiple users. Barriers to the use of such information have been identified at different levels, and include uncertainties in climate projections, lack of high precision or high-accuracy information, and lack of competency to deal with data (Sultan et al., 2020). On the other hand, the engagement by the Senegalese private sector could support sustained use of WCS, but is currently weak.

4.2. Strengths and weaknesses of the evaluation method

Our evaluation was based on a methodological framework composed of three inter-related and iterative components. We adapted the Outcome Harvesting tool (Wilson-Grau, 2018) for the evaluation of outcomes, and incorporated it in an impact pathway analysis (Douthwaite et al., 2003) and tracing the history of this innovation (Faure et al., 2020) to provide a robust, systemic and complexity-aware evaluation. We argue that our 'hybrid-approach' provides a fuller understanding of the complexities and intricacies of scaling WCS co-production models and their effects than standard approaches based on few predetermined outcomes. The articulation of different tools increases the credibility of both the causal analysis and of the contribution (Gates and Dyson, 2017) and the trustworthiness of the findings (Anastas, 2004). Furthermore, the restitution of the results of the evaluation in national and local workshops gave participants the opportunity to become aware of and reflect on the diversity and width of the process to which they had contributed (Faure et al., 2020).

The method allowed us to identify unexpected and unintended changes we would not have captured if we had only focused on the activities undertaken as part of the projects that supported scaling. It also highlighted the interlinked contribution of multiple actors and factors to these changes. By systematically enquiring what changed and for whom, and which actions contributed to these changes, the approach enabled us to grasp both the diversity of actors and transformations they experienced across sectors and scales, and the multiple roles they played in WCS scaling. However, while we were able to capture few controversies linked to power relations, these might be important to address specifically (Pigford et al., 2018), particularly in the production of climate services (Vogel et al., 2019). Nonetheless, we consider that the experience of WCS in Senegal suffers less from the potentially top-down scientist-to-user approach that this might embed, because of the development of a system of facilitators and transmitters of information that range from promoter farmers, decentralised agencies, community radios, to national institutions.

On the other hand, our approach has limitations. A system view is inherently partial: it is based on the perspectives of those who draw its boundaries, introducing a potential bias, as these boundaries are limited by the researchers' knowledge of these changes (Blundo-Canto et al., 2017). This can be overcome by substantiating these outcomes with independent, knowledgeable informants who go 'on the record' with their answers, and by triangulating multiple perspectives (Wilson-Grau, 2018), data collection methods and data sources (Bamberger, 2012). Additionally, asking informants to identify the most relevant outcomes or to prioritize them according to predefined criteria and benchmarks, would have reduced researchers' bias in the analysis of outcomes and of the systemic transformations and should be applied in the future. What is more, harmonising the definition of « outcomes » and « contribution » with informants can be challenging, and it is important to attend to the creation of a shared language with the interviewee.

4.3. Conclusion

Our complexity-aware, systemic and iterative evaluation revealed how the scaling of Weather and Climate Services in Senegal from a pilot project to national scale, produced systemic outcomes that crossed institutional, sectoral and governance boundaries. This resulted in a transformative process based on the improvement of WCS, the emergence and consolidation of WCS facilitators, the inclusion of WCS in action planning, the mobilisation of stakeholders to sustain scaling, and the empowerment of actors. The factors that supported the scaling of WCS in Senegal include capacity strengthening, knowledge-sharing and action platforms, interaction and learning opportunities, and enabling national and international political environments.

The demand for improvement by users is increasing as they use forecasts, particularly seasonal ones, to better plan their actions. The challenge now is to provide finer grain forecasts in a timely fashion, which will require significant investments. Public-private partnerships can play an important role, but the involvement of the private sector is still limited. Moreover, international funding, which significantly supported the development of WCS in Africa, raises questions concerning the embeddedness of the innovation in local contexts and cultures. As the scaling process implies expansion to even more users and uses, issues of trust will inevitably arise in who delivers the information and how it is produced, linked with the inability to interpret and act upon the information. Large-scale decentralised capacity strengthening actions should be devised to address this.

In terms of research, there is a gap in understanding how users arbitrate between biophysical indicators, traditional knowledge and scientific climate information when making their decisions, and the role of leaders and promoter farmers in this arbitrage. At the policy level, the changes in practice that the use of WCS generates should be assessed taking into account the agricultural development model they promote, the use of environmental resources it incentivizes, the impacts on agricultural diversity and ecosystem services, and the potential trade-offs between productivity and long-term resilience.

On the methodological level, our qualitative approach makes it possible to identify both expected and unexpected changes related to the scaling of an innovation and how these changes came about for multiple actors. Future studies could incorporate quantitative assessments based on *ex-ante* modelling tools to identify potential (sub)sectors of the economy or the population that should be interviewed, for whom estimates identify significant gains or losses. Conversely, the qualitative evaluation could precede an *ex-post* quantitative assessment that collects data on specific outcomes and impacts identified for different types of users.

These are few of the possible ways forward to improve the knowledge produced by evaluations of WCS on how they contribute to or eventually hinder systemic changes in the way actors plan, coordinate, interact and ultimately act upon the information to adapt to climate variability and change.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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