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Agro-climate service delivery and scaling at the last mile

A case study in Dien Bien District, Vietnam

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Summary

Smallholder farmers, particularly in the Global South, are among the groups experiencing the most direct impacts of weather, climate variability and climate change. These direct impacts might disrupt or reverse development achievements such as poverty reduction and improved food security. Therefore, supporting farmers and other decision-makers in incorporating weather and climate information in their farming decisions (i.e. agro-climate services – ACS) is fundamental to reducing farmers' vulnerability and safeguarding their farm productivity and income. Despite its importance, ACS delivery at the last mile is a critical gap and faces complex socio-economic and technical barriers. While investments in ACS have increased to pilot ACS innovations in recent years, such projects endure challenges translating experimental evidence to large-scale rolling-out in a real and complex socio-economic landscape. Thus, about 300 million smallholder farmers globally have no or limited access to ACS. As the demand to accelerate ACS access and finance has increased, it is necessary to provide scientific support to decision-makers and stakeholders to make scaling decisions in such a complex and uncertain environment. Therefore, my dissertation aims to understand these dynamics and provide decision support to ACS adoption and scaling processes. To this end, I applied different methodologies as part of a case study in Dien Bien District, Vietnam.

1. In Chapter 2, I describe a novel method to test hypothesized causal relations in ACS delivery pathways using confidence interval interpretation. In two distinct settings, farmer groups experience different pathways to access and uptake ACS while they share a similar high adoption rate. Generating awareness and creating demand, enhancing peer-to-peer exchange and farmers' attitudes appear to be influential in driving the impact pathway. Adoption of ACS by a critical mass might be sufficient to trigger systemic changes within social groups. Employing a pathway approach can be beneficial in supporting tactical decisions in delivering and outscaling ACS.
2. In Chapter 3, I apply decision analysis to characterize and analyze the socio-economic impacts of upscaling decisions. Across four candidate options for scaling, our simulation results indicate a very high chance (98.35–99.81%) of the ACS interventions providing net benefits. With 90% confidence, investments in ACS would return benefits between 1.45 and 16.02 USD per 1 USD invested. The results demonstrate how decision analysis approaches can be helpful in valuing ACS and provide decision support under uncertainty. I suggest replacing deterministic with probabilistic approaches when analyzing decisions in complex environments.
3. In Chapter 4, I highlight the potential of integrating stakeholder engagement and decision analysis approaches for generating ACS system knowledge and incorporating it in development planning processes. The results show that defining and considering stakeholders' multi-dimensional attributes are essential for mobilizing their individual knowledge and engagement. I consider in my study nine attributes, including gender, availability, experience, expertise, interest, influence, relevance, attitude as well as individual costs and benefits of each stakeholder. By combining these attributes with stakeholders' system knowledge and insights about the decision-making process, I am able to explicitly recommend where, when and how stakeholders can support complex and uncertain decisions.

Overall, my research contributes to the advancement of decision-support methods and assists decision-making within and beyond the ACS context. These results and methods provide insights for researchers, governments, civil societies and donors to understand the dynamics, complexity and uncertainty of ACS and inform decision-making for sustainability transition processes.

Zusammenfassung

Kleinbauern, vor allem im globalen Süden, gehören zu den Bevölkerungsgruppen, die am stärksten unter den direkten Auswirkungen von Wetter, Klimaschwankungen und Klimawandel leiden. Diese direkten Auswirkungen können Entwicklungserfolge wie die Verringerung der Armut und die Verbesserung der Ernährungssicherheit beeinträchtigen oder sogar zunichtemachen. Daher ist die Unterstützung von Landwirten und anderen Entscheidungsträgern bei der Einbeziehung von Wetter- und Klimainformationen in ihre landwirtschaftlichen Entscheidungen (d. h. Agro-Klimadienstleistungen – *Agro-Climate Services* – ACS) von entscheidender Bedeutung, um die Klima-Vulnerabilität der Landwirte zu verringern, sowie ihre landwirtschaftliche Produktivität und ihr Einkommen zu sichern. Trotz ihrer Bedeutung ist die Bereitstellung von ACS insbesondere auf „der letzten Meile" eine kritische Lücke und stößt auf komplexe sozioökonomische und technische Hindernisse. Obwohl in den letzten Jahren vermehrt in ACS-Pilotprojekte investiert wurde, ist es bei solchen Projekten schwierig, experimentelle Erkenntnisse in großem Stil in einem realen und komplexen sozioökonomischen Kontext zu implementieren. Daher haben etwa 300 Millionen Kleinbauern weltweit keinen oder nur begrenzten Zugang zu ACS. Angesichts der steigenden Nachfrage nach schneller Finanzierung und einem schnellerem Zugang zu ACS, besteht ein Bedarf an wissenschaftlicher Unterstützung für Entscheidungsträger und Interessengruppen, um in diesem komplexen und unsicheren Umfeld fundierte Entscheidungen über die Verbreitung von ACS zu treffen. Daher zielt meine Dissertation darauf ab, diese Dynamik zu verstehen und Entscheidungshilfen für die Einführung und Verbreitung von ACS zu liefern. Zu diesem Zweck habe ich im Rahmen einer Beispielstudie im Distrikt Dien Bien, Vietnam, verschiedene Methoden angewandt.

1. In Kapitel 2 beschreibe ich eine neuartige Methode zur Überprüfung hypothetischer kausaler Zusammenhänge, die ACS-Bereitstellungspfaden zugrunde liegen, mittels der Interpretation von Konfidenzintervallen. Obwohl zwei Gruppen von Landwirten auf unterschiedliche Weise Zugang zu ACS erhalten, ist die Adoptionsrate vergleichbar. Die Wirkungspfade scheinen durch die Schaffung von Bewusstsein und Nachfrage für ACS, die Förderung des gegenseitigen Austauschs unter den Landwirten sowie deren Einstellung gegenüber ACS beeinflusst zu werden. Die Übernahme von ACS durch eine kritische Masse könnte ausreichen, um systemische Veränderungen innerhalb gesellschaftlicher Gruppen auszulösen. Die Anwendung eines Wirkungspfad-Ansatzes kann bei der Unterstützung taktischer Entscheidungen zur Bereitstellung und Ausweitung von ACS von Vorteil sein.
2. In Kapitel 3 führe ich eine Entscheidungsanalyse durch, um die sozioökonomischen Auswirkungen von Upscaling-Entscheidungen zu charakterisieren und zu analysieren. Unsere Simulationsergebnisse zeigen, dass die ACS-Maßnahmen bei vier möglichen Skalierungsoptionen mit sehr hoher Wahrscheinlichkeit (98,35-99,81%) einen Nettonutzen erbringen. Mit einer Wahrscheinlichkeit von 90 % würden Investitionen in ACS einen Nutzen zwischen 1,45 und 16,02 USD pro investiertem USD erbringen. Die Ergebnisse zeigen, wie entscheidungsanalytische Ansätze bei der Bewertung von ACS hilfreich sein können und eine Entscheidungshilfe unter Unsicherheit bieten. Ich schlage vor, bei der Analyse von Entscheidungen in komplexen Systemen deterministische durch probabilistische Ansätze zu ersetzen.
3. In Kapitel 4 zeige ich das Potenzial der Integration von Stakeholder-Engagement und Entscheidungsanalyseansätzen zur Generierung von ACS-Systemwissen und dessen Einbindung in Entwicklungsplanungsprozesse auf. Die Ergebnisse zeigen, dass die Definition und Berücksichtigung der mehrdimensionalen Attribute der Stakeholder wesentlich für die Mobilisierung ihres individuellen Wissens und deren Engagements ist. In meiner Studie berücksichtige ich neun Attribute, darunter Geschlecht, Verfügbarkeit, Erfahrung, Fachwissen, Interesse, Einfluss, Relevanz, Einstellung sowie individuelle Kosten und Nutzen der einzelnen Stakeholder. Durch die Kombination dieser Attribute mit dem Systemwissen der Stakeholder und den Erkenntnissen über den Entscheidungsprozess kann ich explizite Empfehlungen bezüglich der Unterstützung von komplexen und unsicheren Entscheidungen durch die Einbeziehung von Stakeholdern aussprechen.

Insgesamt trägt meine Forschung zur Weiterentwicklung von entscheidungsunterstützenden Methoden bei und hilft bei der Entscheidungsfindung innerhalb und außerhalb des ACS-Kontextes. Diese Ergebnisse und Methoden bieten Forschenden, Regierungen, Zivilgesellschaften und Geldgebern Einblicke, um die Dynamik, Komplexität und Ungewissheit von ACS besser zu verstehen und die Entscheidungsfindung für nachhaltige Transitionsprozesse zu unterstützen.

Abbreviations, acronyms and units

ACS	Agro-climate services
a.s.l.	above sea level
BCR	benefit-cost ratio
CARE	Cooperative for Assistance and Relief Everywhere
CCD	Dien Bien Centre of Community Development
CI	Confidence Interval
COVID-19	Coronavirus Disease 2019
CVN	CARE in Vietnam
DA	Decision analysis
DAEC	District Agricultural Extension Centre
DASC	District Agricultural Service Centre
DDARD	District Division of Agriculture and Rural Development
DPC	District's People's Committee
e.g.	exempli gratia
EVPI	Expected Value of Perfect Information
et al.	et alia
etc.	et cetera
GHG	Greenhouse Gas
FGD	Focus Group Discussion
Fig.	Figure
i.e.	id est
kUSD	thousand United States Dollar
MARD	Ministry of Agriculture and Rural Development
MOF	Ministry of Finance
MONRE	Ministry of Natural Resources and Environment
MPI	Ministry of Planning and Investment
LNGO	Local Non-Government Organization
NDC	Nationally Determined Contributions
NGO	Non-Government Organization
NPV	Net Present Value
PC	People's Councils

PDARD	Provincial Department of Agriculture and Rural Development
PDOF	Provincial Department of Finance
PDPI	Provincial Department of Planning and Investment
PHMS	Provincial Hydro-Meteorological Station
PLS	Projection to Latent Structures
PPC	Provincial People's Committee
PSP	Participatory Scenario Planning
SEDP	Socio-Economic Development Plan
USD	United States Dollar
VIP	Variable Importance in the Projection
VMHA	Vietnam Meteorological and Hydrological Administration
vs.	versus
VSLA	Village Saving and Loan Association
ZEF	Center for Development Research
°C	degree celsius
%	percentage
$	United States Dollar

Chapter 1: Introduction

1. What are agro-climate services?

Agriculture is increasingly affected by weather, climate variability and climate change. Worldwide, about 32–39 % of the variation in yields of major crops has been attributed to climate variability, with large differences across geographical areas (Ray et al., 2015). Global climate change impacts on crop yields vary across regions, yet impacts tend to be negative more often than positive (FAO, 2016; IPCC, 2014; Rosenzweig et al., 2014). Therefore, supporting farmers and other decision-makers in incorporating weather and climate information in their decisions (e.g. on what to plant and when to harvest) is fundamental to reducing farmers' vulnerability and safeguarding their farm productivity and securing their income (Hansen et al., 2022; Machingura et al., 2018; WMO, 2015, 2019a). Agro-climate services (ACS) offer support for improving input efficiency, increasing yield, generating associated socio-environmental benefits and supporting farmer empowerment (Ferdinand et al., 2021; Hansen et al., 2022).

Agro-climate services include the provision of information about weather and climate (e.g. weekly weather forecasts, seasonal outlooks and climate projection) and agricultural advice for farmers and other intermediary users (i.e. policy decision-makers and agricultural extension workers) (FAO, 2021; WMO, 2019a). However, to my understanding, while a definition for climate services exists, no specific definition applies to a thematic focus like agriculture. Therefore, in the studies outlined in this dissertation, I use the definitions of both the Climate Services Partnership (Climate Services Partnership, 2019) and the World Meteorological Organization (WMO, 2019b) and adapt the definitions to the context of agriculture. Accordingly, I have defined agro-climate services as the provision of weather, climate information and associated agricultural advice that assist individuals and organizations in society in making improved agricultural decisions.

Based on the definition by the Climate Services Partnership (Climate Services Partnership, 2019), I further interpret ACS as a value chain that comprises four main components: (1) production of information on weather and climate, (2) translation of weather and climate information into agricultural advice, (3) transfer of weather information, climate information and agricultural advice to agricultural users and (4) use of weather information, climate information and agricultural advice by intermediary users (i.e. policy decision-makers and agricultural extension workers) and end users (i.e. farmers). The prefix "agro" signifies that advice is both targeted towards an agricultural audience and that it refers specifically to agricultural decision-making. In addition, ACS also include other integral parts: (1) capacity building of actors engaging across the value chain, (2) gender integration to promote gender balance in the value chain and gender equality in accessing and benefiting from agro-climate services among end-users, (3) ensuring good governance of the ACS value chain, (4) monitoring and evaluation of the inputs, outputs and impacts of the ACS.

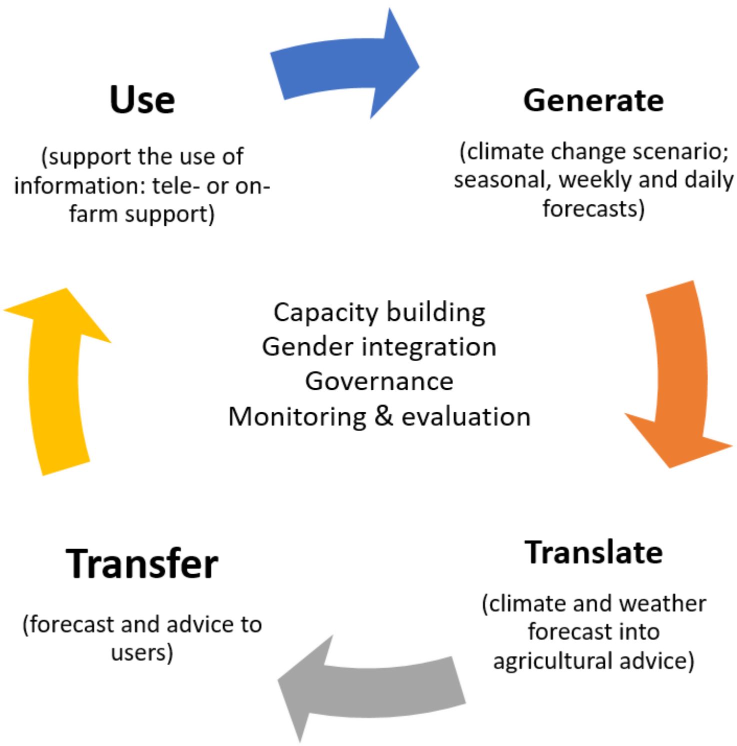

Fig. 1. Components of the agro-climate service value chain

To guarantee actionability, ACS must respond to farmers' needs, including information demand and requirements related to the delivery of climate services. This helps to ensure that relevant information is provided smoothly to both intermediary- and end-users.

2. Relevance of agro-climate services

Smallholder farmers produce 30-34% of the global food supply and play an important role in safeguarding agricultural biodiversity (Ricciardi et al., 2018). However, smallholder farmers, particularly in the Global South, are among the groups experiencing the most direct impacts of weather variability and climate change (Morton, 2007; WMO, 2019a). The direct impacts of climate variability and climate change might disrupt or reverse development achievements such as poverty reduction and food security (Beg et al., 2002; Hansen et al., 2022; WMO, 2019a). Meanwhile, climatic conditions (e.g. temperature, rainfall) also serve as a production factor in agricultural systems (O'Grady et al., 2020). Agricultural decision-makers must incorporate climate-related risks and consider the opportunities for agricultural production brought on by arising climatic conditions (FAO, 2019; Nguyen, 2017; O'Grady et al., 2020). In 2009, the World Climate Conference 3 decided to establish the Global Framework for Climate Services (GFCS) to acknowledge the importance of incorporating climate information into decision-making. The framework aims to provide climate information and services to support sensitive sectors. Agriculture and food security is one of the thematic focus sectors of the GFCS (Vaughan and Dessai, 2014). Globally, 100 out of 117 surveyed countries cited climate services as their priority in supporting climate change adaptation in the agriculture and food security sector in their Nationally Determined Contributions (NDC) submitted in 2019 (WMO, 2019a). Yet the operation and scaling of ACS at the last mile face critical challenges in delivering seamless and actionable services to smallholder farmers, especially in developing contexts (FAO, 2021; WMO, 2019a).

3. Challenges in ACS delivery and scaling at the last mile

3.1. Last mile delivery challenges

Despite increased investment in climate services in recent years, there remains a critical gap in last mile delivery to the farmer (FAO, 2021; Ferdinand et al., 2021; WMO, 2019a). From 2015 to 2020, donors (i.e. international donors, philanthropic organizations and governments) invested 1 billion USD in climate-informed advisory services (Ferdinand et al., 2021). Yet climate services that actually reach farmers remain, in most cases, inadequate, fragmented, poorly engaged and misaligned with existing systems and thus unsustainable beyond project cycles (FAO, 2021; Ferdinand et al., 2021; WMO, 2019a). Globally, out of more than 570 million smallholder farmers (i.e. farmers with farmland areas less than 2 ha), about 300 million have limited or no access to climate services (Ferdinand et al., 2021).

Besides limited access, the last mile provision of ACS faces critical challenges in ensuring that information and advice are actionable (J. Hansen et al., 2019; Simelton and McCampbell, 2021; WMO, 2019a). Agro-climate information may be disseminated, but farmers do not necessarily receive or use it. Moreover, information that reaches farmers might not be used effectively (J. W. Hansen et al., 2019; Simelton and McCampbell, 2021). While, in general, the provision of climate services has increased, service providers and users often do not share a common understanding of what constitutes useful information. This difference can be depicted as a usability gap (Lemos et al., 2012). Thus, the realized value of information/advice at the end-users might fall far below the value expected by investors or information producers.

3.2. Barriers to scaling

3.2.1. Challenges to scaling up ACS pilot experiences

While national programs exist in a few countries of the Global South (e.g. Ethiopia, India, Mali), ACS pilot projects are often supported by international finance (Ferdinand et al., 2021; Tall et al., 2014). Often such funding is project-based and provided in a piecemeal manner (FAO, 2021; Ferdinand et al., 2021; Tall et al., 2014; WMO, 2019a). While these pilot projects have been able to demonstrate the success of ACS to some degree, they also often grapple with the socio-economic complexities of implementing ACS (Tall et al., 2014). Upscaling experience from pilot projects is challenging for different reasons (Woltering et al., 2019). First, the design of ACS in resourceful and tightly managed pilot projects leads to uncertainty in predicting the capacity to provide the services at a large scale and in a complex environment. Often, human resources in the pilot projects include highly qualified staff, which might not be available for large-scale deployment of similar services (Daniels et al., 2020; FAO, 2021; Tall et al., 2014; WMO, 2019a). In addition, such projects are often shielded from the complexity of involving multiple stakeholders. While climate services operate in a highly complex landscape of sectors and administrative levels, stakeholder involvement in pilot projects might be focus only on solving specific issues within projects or contributing with particular services to the projects (Daniels et al., 2020; WMO, 2019a; Woltering et al., 2019). Stakeholders' participation might be considered as an additional task rather than being viewed as the main mandate and core responsibility (Woltering et al., 2019). Without an inclusive co-design approach, scaling initiatives might risk aiming at "low-hanging fruits" by benefiting the better-off, easy-to-reach farmers while leaving the most vulnerable behind (Ferdinand et al., 2021). Such dynamics might pose a challenge in real-world partnerships aiming to operate at scale.

Moving from pilot project to scale also struggles with finance, particularly for interventions targeting the last mile (J. W. Hansen et al., 2019; WMO, 2019a). The project expenditure might not correspond to the locals' cost norm (i.e. predefined and standardized cost structures or rates that are used for payment in a particular context) and financial capacities (Woltering et al., 2019). Therefore, most predictions of financial needs are uncertain, making it difficult to secure finance for scaling. Furthermore, since monitoring and evaluating the societal benefits of climate services is one of the weakest areas within the multiple components (e.g. governance, user interface, monitoring and evaluation, basic forecasting systems, provision and application of climate service, capacity development) of climate service value chain, the benefits of investment in climate services are realized inadequately. Therefore, the mobilization of human and financial resources for scaling faces critical questions of effectiveness (WMO, 2019a).

The scaling challenges suggest that moving from pilot to scaling requires a transition process to unpack and define scaling approaches and to forecast the scaling impacts in the real-world context (Daniels et al., 2020; Woltering et al., 2019).

3.2.2. Challenges to valuing and justifying ACS scaling

Given the lack of scaling approaches, robust evidence of the societal benefits of ACS scaling is inevitably limited. Therefore, analyzing the impact pathways of ACS with a focus on societal effects must be a priority (Ferdinand et al., 2021; WMO, 2019a). However, valuing ACS is associated with uncertainty and complexity, particularly for interventions targeting the last mile (J. W. Hansen et al., 2019; Perrels et al., 2013; WMO, 2019a, 2015). High levels of uncertainty are related to different aspects, including the frequency of extreme climate events, the reliability of weather forecasts, variations in climate projections, agricultural advice and subsequently, the economic, socio and environmental impacts of ACS on agricultural production and society (Born et al., 2021; Lowry and Backus, 2021; WMO, 2015). High complexity arises from technical, social, financial and political interactions.

Furthermore, the valuation of ACS suffers from data scarcity (Perrels et al., 2013; WMO, 2015) as most robust scientific approaches, such as controlled field experiments, require expensive, continuous, short-term (e.g. hourly, daily and weekly) and long-term monitoring (e.g. seasonally, yearly, decennially) to collect substantial amounts of data and observe ACS impacts. Additionally, in seasonal farming systems, researchers have to wait at least one season that features extreme weather events in order to observe the effectiveness of ACS under such extreme events. Apart from climate and farming factors, setting up controlled experiments that also account for technical, social, economic and political aspects is quite challenging. Consequently, data scarcity is among the most common issues in valuing climate services (Daniels et al., 2020; Woltering et al., 2019). Nevertheless, decision-makers have to make decisions even in the face of considerable uncertainty. Thus, analysts have been using different approaches in providing recommendations to decision-makers.

Certain ACS valuation methods rely on assumptions and rough estimations to generate data inputs (Ferdinand et al., 2021; WMO, 2019a). A recent study estimating the finance needed to ensure last mile delivery to smallholders globally acknowledged that it faced limitations since the authors relied on a small number of samples to derive overall financial requirements (Ferdinand et al., 2021). Climate services have often been part of a large project, with donors lacking the ability to distinguish the specific impacts of climate services from those of other project activities (Ferdinand et al., 2021).

Previous studies have also used expert and user knowledge (e.g. willingness to pay, stated preference and constructing assumptions) to value ACS (Ferdinand et al., 2021; WMO, 2015). However, such methods are subject to potential biases of the experts and users (WMO, 2015). In one of my interviews in Vietnam, one stakeholder shared that they could not provide a meaningful valuation of their climate services since their projects were usually too short to assess impacts. This meant they could not collect impact data if some weather events did not occur during the project. Thus, the project had to make assumptions about the events and the potential impacts of their solutions. As a consequence, they were unconfident with the quality of the findings and thus, their report remains unpublished. While the most commonly used approach to valuing ACS is deterministic, probabilistic methods have recently been recommended to provide evidence on agro-climate service cost and benefit, reflecting the uncertainty and complexity of ACS interventions and impacts (WMO, 2015).

4. Challenges to translating evidence into planning decision-making

In case the evidence on scaling approach and cost-benefit analysis are produced, the expectation is that decision-makers will incorporate such evidence into policy formulation. However, such an integration process often struggles with multiple challenges, including the characteristics of evidence, the nature of the decision-making process, and the biases and barriers to rational organization decision-making.

Previous studies suggest that scientific evidence might retain a low chance of being included in rational decision-making if it fails to ensure some critical characteristics. Those features are credibility (i.e. accuracy, plausibility and trustworthiness of information), legitimacy (i.e. “fairness” and “unbiasedness” level of information and the sources of information) and salience (i.e. relevant and timely information to decision-making) (Cash et al., 2003; Haigh et al., 2018). Furthermore, in a complex governance system, evidence might need to go through a multi-stage, multi-sector and multi-level development planning process (Strauch et al., 2018). Thus, in terms of process, there is a challenge to ensure the evidence is consistently considered during the whole planning. If ACS evidence fails to be included in any critical step in the policy discourse, agenda setting and policy formulation process, the incorporation of ACS into planning may experience disruption.

In addition, inconsistent participation of ACS stakeholders may create challenges or present planners with conflicting views. Some stakeholders may be unaware of ACS, but they may be able to influence and dominate other stakeholders during policy formulation. If stakeholders who are knowledgeable about ACS and can confidently engage in constructive debates and reflections are absent, the dynamics of ACS discussions might be detrimental to policy formulation.

At the organizational level, decision-makers still face other barriers to rational decision-making (Hatch, 1997). Uncertainties, imperfect information and complexity involved in decision issues can introduce a barrier for decision-makers due to their limited time available for decision-making and their insufficient capacity to process complex information (Hatch, 1997). Furthermore, organizational decision-making might suffer from organizational biases such as the priority or preference toward some specific solutions (short-term vs. long-term, infrastructure vs. soft measures, response vs. anticipatory actions) (Hatch, 1997; Lindegaard, 2013).

Therefore, integrating scientific evidence into policy decision-making requires an approach that addresses challenges related to evidence quality and availability as well as other obstacles involved in the policy integration processes.

5. Model last mile delivery and scaling

5.1. A need for process-based modeling of last mile delivery

In development contexts, climate service design is largely modeled following traditional development project design, generally based on the logical framework, a tool that is often used to define the key hierarchical changes following the project interventions (Bong, 2014; Springer-Heinze et al., 2003). Intervention inputs, such as fostering data availability and capacity building, are expected to create outputs (e.g. number of agro-climate bulletins). These outputs are then assumed to generate outcomes (e.g. a particular number of innovation adopters). However, strong assumptions about the linear causality behind the logical framework that is not backed up by scientific evidence can be problematic in complex contexts (Springer-Heinze et al., 2003). When the project impact pathway remains implicit, essential processes triggering or blocking expected and unexpected changes may be neglected (Bong, 2014; Springer-Heinze et al., 2003).

A better understanding of the causal pathways by which farmers access and adopt ACS may help design and adjust ACS interventions. Adoption studies have primarily employed variance theory, attempting to determine important factors that can influence the success of innovation adoption. The typical approach is to use regression models to reveal correlations between (hypothesized) independent and dependent variables (Geels and Schot, 2010). Such studies have mostly answered questions such as “what factors/variables affect the adoption? Is it statistically significant?” but not “how did the adoption process happen and how did it evolve?”. Consequently, variables related to the adoption process are assumed static and the history and dynamics of intervention delivery processes may not be reflected (Geels and Schot, 2010). As delivery and adoption pathways evolve and grow in complexity (Haigh et al., 2018), the importance of understanding the dynamics of these pathways increases.

Impact pathways offer a flexible approach to understanding the processes behind agricultural innovations by explicitly including the logical and ordered sequence of events leading to outcomes. Thus they provide the opportunity to elucidate the potential outcomes of changes to processes (Springer-Heinze et al., 2003). Links within these impact pathways represent hypotheses that can be further validated (Springer-Heinze et al., 2003; Vogel, 2012). Findings from the validation can serve as important guides for improving development interventions (Vogel, 2012).

5.2. Unpacking and modeling agro-climate service scaling decisions

Decision analysis (DA) has been introduced as a methodology to engage stakeholders in designing and forecasting impacts to support decisions in complex systems in the face of uncertainty and data scarcity. While Howard and Abbas (2015) have established the foundations for the methods, the Applied Information Economics framework (Hubbard, 2014) provides the key ingredients for decision analysis approach described in this study. DA aims to create system understanding by integrating stakeholder knowledge with system thinking (Luedeling and Shepherd, 2016). Traditional research has often focused on eliminating uncertainties of specific interactions within a system without considering system dynamics and evaluating alternative decision options (Shepherd et al., 2015). Such an approach provides a limited understanding of complex decision impacts and is restricted by the capacity to collect data. DA acknowledges that quantifying every interaction within a system is challenging and resource-intensive. Therefore, within DA, uncertainties are acknowledged and accounted for by applying methods and tools to integrate them into the decision-making process (Luedeling and Shepherd, 2016). One of the key tools in DA to account for uncertainty is to calibrate stakeholders using calibration training (Hubbard, 2014). A critical improvement of calibration training compared to other conventional stakeholder knowledge elicitation approaches is that stakeholders realize their own biases beforehand, often reducing these before eliciting their knowledge and uncertainty for subsequent DA steps (Hubbard, 2014). DA offers many advantages in engaging stakeholders to generate system knowledge to support decision-making in various contexts (Do et al., 2020; Fernandez et al., 2022; Lanzanova et al., 2019; Luedeling et al., 2015; Ruett et al., 2020). However, the rationale for including particular stakeholders in the process has rarely been explicit. Furthermore, throughout the complex planning processes, how, by whom and to what degree this knowledge is integrated into decision-making is often unclear.

5.3. Stakeholder engagement in agro-climate service planning

A consistent recommendation emerging from previous research on climate services was to use “co-” approach in all phases of service design, planning, implementation and monitoring and evaluation (Daniels et al., 2020). Such an approach implies that stakeholders co-explore, co-design, co-create, co-learn, co-manage, and co-integrate ACS (Born et al., 2021; Daniels et al., 2020; Vincent et al., 2018; Warner et al., 2022; Yegbemey and Egah, 2021). The argument of the co-approach is that the current supply driven approach in designing and implementing climate services fail to acknowledge the complexity of the service landscape and thus cannot stimulate necessary policy and action (Daniels et al., 2020). Therefore, a tandem approach (i.e. science informed policy and policy informed science) to engage stakeholders in the design of ACS is needed (Daniels et al., 2020).

While acknowledging the importance of a co-approach, previous studies have had three main limitations concerning stakeholder engagement in ACS. First, prior research did not focus on methods to handle stakeholders' legitimacy, richness and diversity. Stakeholders concerning ACS are often numerous and not homogenous. These actors may have different attributes relating to varied motivations for engagement in ACS knowledge generation and decision-making processes. Therefore, it is necessary to have a strategic approach to their engagement in different but relevant roles throughout the process. Understanding stakeholder characteristics may inform such a strategic approach. The objective is to effectively coordinate and enhance the engagement of relevant stakeholders in ACS processes.

Second, ACS scaling approaches and valuation are complex, uncertain and lack of data. Therefore, without a decision-oriented and stakeholder-coordinated approach, the participation of numerous stakeholders may risk grappling with the complexity and the paramount socio-technical-political-economic challenges when discussing and defining ACS approaches and impacts.

Third, ACS research has a strong focus on stakeholder engagement during the design and implementation process but there is usually little mobilization of stakeholders during the pre-financing stage. This limitation is a critical gap since the dynamics of stakeholders during the pre-financing and post-financing stages may differ. For example, stakeholders who advocate for integrating ACS in local planning have their primary role during the pre-financing phase to search for evidence of ACS impacts and influence other stakeholders. Meanwhile, once the finance is approved, their part is to implement and document the ACS impacts. Nevertheless, ACS cannot enter the implementation phase without the planning and budgeting stage.

Therefore, a transdisciplinary approach, explicitly focusing on the collaboration of stakeholders in addressing the uncertainty, complexity and data scarcity in ACS knowledge generation and in integrating knowledge into planning decisions, is necessary to support the last mile delivery of ACS.

6. Background information of the case study in Dien Bien, Vietnam

Dien Bien, a District in Vietnam, experiences most of the challenges that complicate last mile delivery of ACS. A patchy meteorological observation network in the District associated with mountainous topography restricts the quality of weather forecasts, especially for rainfall. While the meteorological station at the provincial level releases seasonal, weekly and daily forecasts and early warnings, dissemination of weather forecasts to Dien Bien District has been mainly restricted to daily or 3-day forecasts and early warnings. The language used in the forecasts often contains technical terms and uncertainties, which are difficult for agricultural staff and farmers to understand.

Divisions under the Provincial Department of Agriculture and Rural Development must buy specialized information that can be used for a specific purpose in agriculture (e.g. for disease forecasts and plant protection). However, finance to purchase all information for all Divisions is unavailable, and Divisions do not necessarily share information among themselves. The limited access to information and lack of guidance and finance prevent agricultural workers from translating ACS weather and climate forecasts into more locally relevant agricultural advice.

Besides, none of the communication channels provide full coverage of the District. While internet service is available, the signal remains weak in some locations and not all farmers can afford the top-up for an internet package. Similar limitations apply to the loudspeaker system, where a primary network of loudspeakers has been set up. However, there are still places where farmers cannot hear these loudspeakers (i.e. due to the far distance from their home to the loudspeaker). Some farmers do not understand the forecasts and advice since the information is not translated into their local languages.

Since 2015, the Non-Governmental Organization "Cooperative for Assistance and Relief Everywhere" (CARE) in Vietnam (CVN), provided ACS to smallholder farmers on a limited scale in two communes in Dien Bien District, Vietnam. CVN's projects aim "to enhance livelihoods and increase the resilience to effects of climate change and variability of poor ethnic minority women and men in rural areas". CVN facilitates better interactions between weather forecasters and agricultural staff to align service provision with information needs on the ground and to transfer ACS forecasts and advice to farmers. However, until 2019 only two of Dien Bien's 23 communes were covered by the project. The project was expected to end in early 2022 and without the continuation of project support, it is quite unlikely that the services will continue. CVN advocates for upscaling ACS in Dien Bien, but a large-scale roll-out could potentially strain the government's financial and human resources.

Understanding the delivery and adoption process will help CARE design an effective outscaling approach that can reach the end-users. Decreasing uncertainty about the potential costs and benefits of upscaling may increase the government's interest and willingness to make the investments necessary to sustain ACS in Dien Bien. However, planning and budgeting for ACS may need to get through a multi-stage, multi-level and multi-sector and multi-actor planning and budgeting process. Thus, generating and translating scaling evidence need a transdisciplinary approach to produce ACS and integrate them into Dien Bien's socio-economic development planning.

7. Objectives

A major challenge in delivering ACS at the last mile is understanding the environment's complexity which would be time-consuming and expensive. Therefore, the overall objective of my research is to apply and further develop methods that can capture the current state of system understanding while acknowledging the uncertainty and dynamics in the system. I also aim to develop recommendations supporting decision-making in the ACS last mile delivery and scaling. My research, therefore, includes three sub-objectives with a focus on testing ACS delivery and adoption pathways, forecasting ACS scaling impacts and engaging stakeholders in ACS knowledge generation and integration into planning.

7.1. Testing impact pathway in agro-climate service delivery and adoption

The first objective of my dissertation is to develop a method to understand the hypothesized causal pathways during the ACS delivery and adoption process (Chapter 2). The results of this understanding are expected to support development projects in monitoring, designing and adjusting their interventions in ACS last mile delivery.

To this end, I conducted group discussions to construct the conceptual impact pathways reflecting the assumptions in ACS delivery. My co-authors and I also developed a method to explore the validity of hypothesized causal relations. I developed a matrix to interpret the confidence interval (CI) value, which can help show the directions and quantify the strengths of relations (McBride et al., 2013). These relations are interpreted for both statistical and practical implications (Brosi and Biber, 2009; McBride et al., 2013; Sim and Reid, 1999). The practical implications aim to provide immediate support to decision-making in ACS interventions. We intend to move away from the traditional research approach relying on large sample sizes. Instead, we use the probabilistic approach to quantify the possible relations with more moderate resource requirements.

7.2. Modeling agro-climate service scaling decisions

Understanding adoption dynamics is crucial to reveal insights about the effectiveness of ACS interventions within the scope of the project's interventions. However, scaling ACS requires understanding the impacts of adoption within and outside the project's locations and beyond the project timeline. Such requirements imply extrapolation from a pilot project to different spatial and temporal scales, considering uncertainty, changing risks, data scarcity and system complexity (Woltering et al., 2019).

In my research, I used decision analysis (Hubbard, 2014; Shepherd et al., 2015) to capture our current understanding of the possible ACS scaling decisions and impacts (Chapter 3). To this end, I worked with a team of experts to identify decision-makers and potential decisions (Luedeling and Shepherd, 2016) that decision-makers have to make to scale ACS. Using a participatory modeling procedure (Whitney et al., 2018), experts characterized possible scaling options and developed graphical and conceptual impact pathways representing decision impacts. This conceptual model is expected to include all important model variables without concerns about data measurement constraints (Lanzanova et al., 2017). The conceptual model was subsequently converted into a mathematical model. The decision analysis approach does not aim to quantify all variables precisely, as this is often impossible. Instead, it seeks to capture the current state of knowledge on all model variables using secondary literature and expert knowledge while considering the explicit uncertainty associated with knowledge (Luedeling and Shepherd, 2016). Based on secondary data and expert inputs, expected decision outcomes are computed by using the mathematical model to run probabilistic simulations (Lanzanova et al., 2017). The decision analysis approach allowed me to initiate recommendations on the possible options for ACS scaling, despite remaining uncertainty.

7.3. Transdisciplinary approach to engaging stakeholders in agro-climate service knowledge generation and planning

Throughout my study, stakeholders repeatedly asked how and by whom the scientific evidence would be integrated into policy to facilitate its implementation. In my work, I highlight the need to engage stakeholders in decision analysis process and translate the outcomes of decision analysis into policy formulation. However, the roles of stakeholders may vary over time. Chapter 4, therefore, focuses on identifying and analyzing stakeholder characteristics to realize their potential roles corresponding to different stages of knowledge generation and integration. To my knowledge, no approaches comprehensively deal with stakeholder attributes and use such attributes to inform stakeholder engagement strategies in both knowledge generation and knowledge integration processes. Instead, I found two pieces of this puzzle – decision analysis (Lanzanova et al., 2017; Shepherd et al., 2015b) and stakeholder engagement (Reed et al., 2009) – which may constitute a possible solution. While both puzzle pieces may still have room for improvement, they appeared to have complementary potential as the foundation of a powerful transdisciplinary approach to support complex decision-making. I, therefore, proposed an integrated approach relying on decision analysis and stakeholder engagement approaches and tested the method in the case study area in Dien Bien. The new approach primarily focuses on identifying different attributes of stakeholders and using stakeholder categorization and synthesis to recommend suitable roles for stakeholders during knowledge generation and translation.

In addition to the above objectives, I also engaged in other activities to enrich my knowledge of agro-climate services and innovation from different perspectives.

I conducted a study to review CVN's approaches and experiences since the beginning of their work on ACS in Vietnam. In addition, I also participated in a joint study with the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT), the World Agroforestry Centre (ICRAF) Vietnam and CVN to map out an initial country profile of Vietnam's climate services in agriculture. The study aimed to provide recommendations for improving ACS in Vietnam.

I have tried to follow the development of the innovation agenda and efforts in different contexts. I have followed (e.g. subscriptions to updates, joining webinars) the innovation activities of the institutions such as Food and Agriculture of the United Nations (FAO) and The International Fund for Agricultural Development (IFAD). I have also been participating in the activities (e.g. participating in webinars and summer school) of The Sustainability Transitions Research Network (STRN) – an international network of researchers focusing on understanding and analyzing innovation and the long-term societal transitions to a more sustainable world. Additionally, watching the Shark Tank television shows has enabled me to understand the perspective of innovation design and scaling in a business context. Currently, I am joining some other early- and mid-career researchers from different countries to work on a collaborated research on Equity Principles in Agricultural Innovation Systems. While time is a limiting factor to follow and engage in various networks closely, intentional observation (when having time) has enabled me to realize and narrow my knowledge gaps. Such activities outside my PhD project, combined with my self-reflection, have helped improve my dissertation.

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Chapter 2: How to bridge the last mile in agro-climate service adoption? The importance of farmers' needs, attitudes and interpersonal relations

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Abstract

Climate services can support multiple Sustainable Development Goals. However, in agricultural contexts, the last mile delivery of agro-climate services (ACS) struggles with numerous barriers that prevent smallholder farmers from receiving crucial information. We sought to assess the processes by which farmers adopt ACS in order to support the scaling of ACS. We developed a procedure to serve as a rapid test to provide an overview of impact pathway relations in ACS adoption. We generated ACS adoption pathways through focus group discussions, quantified the overall adoption rate and tested relationships between factors and their causal influence on adoption. To showcase our method, we used the case study of CARE in Vietnam (CVN), a non-government organization attempting to improve the provision of ACS to smallholder farmers since 2015. In CVN's projects, ACS were co-generated and subsequently delivered to farmers through structured meetings or on an ad-hoc basis in village meetings. We found that farmers who participated in structured groups were very likely to demand, access, read, discuss, understand, positively perceive and adopt ACS and recommend it to peers. About half of the farmers in non-structured groups continued to have difficulties understanding ACS. Nevertheless, these farmers still had a positive attitude towards ACS. While different impact pathways were attributed to the two groups, they still shared similar adoption rates (98%). The results suggest that adoption of ACS at a critical mass might be sufficient to trigger systemic changes within social groups and interactions between its members. Employing a pathway approach can be beneficial for designing and evaluating development interventions.
Keywords: Agriculture, climate services, development, innovation, scaling, decision-making

1. Introduction

Smallholder farmers, particularly in developing countries, are among the groups experiencing the most direct impacts of climate change (Morton, 2007; WMO, 2019). These direct impacts might disrupt or reverse development achievements such as poverty reduction and food security (Beg et al., 2002; J. Hansen et al., 2022; WMO, 2019). Climate services are essential for the implementation of almost all Sustainable Development Goals (Griggs et al., 2021; Machingura et al., 2018). In agriculture, agro-climate services (ACS) can provide support to SDG1 (i.e. ending poverty) and SDG2 (i.e. ending hunger) by better informing farmers' decision-making and therefore reducing their vulnerability and safeguarding their farm productivity and income (J. Hansen et al., 2022; Machingura et al., 2018; WMO, 2019). For example, ACS can provide information about local climatic conditions and support strategic agricultural planning. ACS can also provide medium to short-term climate and weather information to support daily to seasonal agricultural decisions (Born et al., 2021; FAO, 2019; J. Hansen et al., 2019; Loboguerrero et al., 2017). Depending on the context, the returns on investment generated by investing in ACS may vary. Nevertheless, the benefits often outweigh the costs (Ferdinand et al., 2021; Luu et al., 2022; WMO, 2015). Typical benefits of ACS include increased harvests, efficient use of agricultural inputs, reduced harvest and input losses, farmer empowerment, improved food security, gross domestic product growth, cleaner water and reduced Greenhouse Gas (GHG) emissions (Ambani & Percy, 2014; Ferdinand et al., 2021; Luu et al., 2022; WMO, 2015). In the context of climate services, last mile delivery of information is considered one of the strategic priorities for improving climate change adaptation in the agriculture sector at scale (FAO, 2019; Ferdinand et al., 2021; J. Hansen et al., 2019; J. W. Hansen et al., 2019; WMO, 2019).

The last mile provision of ACS, however, faces critical challenges regarding the delivery of actionable advice to smallholder farmers, especially in developing countries (J. Hansen et al., 2019; Simelton & McCampbell, 2021; WMO, 2019). Agro-climate information may be disseminated, but it is not necessarily received or used by farmers. For example, a recent project in Myanmar aimed to provide agricultural advice and emergency alerts to 150,000 subscribers of the Site Pyo app. While the project actually met this target, the share of active users was below 20% (Simelton & McCampbell, 2021). Moreover, information that reaches farmers might not be used effectively. While, in general, the provision of climate services has increased, there is often a mismatch between service providers and users about what constitutes useful information. This difference can be depicted as a usability gap (Lemos et al., 2012). Related to this gap, Perrels et al. (2013) and Pilli-Sihvola et al. (2014) highlight the risk of decaying value of climate information services, leading to a gradual decline of potential benefits during information delivery and uptake (i.e. from forecast generation and accuracy → user orientation → users' access to information → users' comprehension → users' ability to respond → effectiveness of users' response). For example, if the value of the climate information was mainly dependent on the accuracy of a forecast, very high potential benefits might be realized. However, as the climate information value might be dependent on the appropriateness of the information to different user groups, moderately high potential benefits may remain. Furthermore, when the realization of the final benefits is also dependent on uptake dynamics, including access to information, comprehension of information, application of advice and effectiveness of the application by users, the realized benefits may fall far short of the initial potential (Perrels et al., 2013; Pilli-Sihvola et al., 2014).

The use of diffusion of innovation theory often fails to recognize the dynamic and complex nature of innovation processes in dynamic real-world contexts. Oversimplified and linear views in innovation diffusion theory hinder understanding of adoption processes (Geels & Schot, 2010). ACS innovations, especially digital ACS, can suffer from the use of a narrow, supply-driven approach (Daniels et al., 2020). Simelton and McCampbell (2021) reveal the weaknesses in designing digital climate services, which may fail to effectively involve farmers and thus overlook the needs and social settings of farmers adopting new technologies. In development contexts, climate service design is largely modeled after traditional development project design, generally based on a logical framework, a framework often used to define the key hierarchical changes given the project interventions (Bong, 2014; Springer-Heinze et al., 2003). Intervention inputs such as fostering data availability and capacity building, are expected to create outputs (e.g. number of agro-climate bulletins). These outputs are then assumed to generate outcomes (e.g. a particular number of innovation adopters). However, strong assumptions about the linear causal mechanisms behind the logical framework can be problematic in complex contexts (Springer-Heinze et al., 2003). When the project impact pathway is not explicit, important processes that might trigger or block expected and unexpected changes may be neglected (Bong, 2014; Springer-Heinze et al., 2003). In consequence, influencing factors in the intervention delivery processes may not be reflected and addressed (Bong, 2014; Springer-Heinze et al., 2003; Vogel, 2012). As delivery and adoption pathways evolve and grow in complexity (Haigh et al., 2018), the importance of understanding the dynamics of these pathways increases.

Previous studies on last mile delivery and adoption have outlined important factors that can influence the success of climate services. Examples of these factors include meeting farmers' need for information, supporting access and use of information, co-production of climate services and capacity building for climate service stakeholders (Alexander & Dessai, 2019; Born et al., 2021; J. W. Hansen et al., 2019; Nkiaka et al., 2019; Rossa et al., 2020; Simelton & McCampbell, 2021). However, last mile delivery and adoption studies have generally had a limited focus on adoption pathways. A better understanding of the causal pathways by which farmers access and adopt ACS may help in designing and adjusting ACS interventions. They may also reveal the social dynamics of climate service adoption, delivering answers to critical questions: Do farmers find their needs satisfied by ACS? Do they dis-adopt ACS? Do farmers recommend ACS to their peers? Is there a critical mass within a social group that supports the outscaling of interventions?

Impact pathways offer a flexible approach to understanding the processes behind agricultural innovations by explicitly including the logical and ordered sequence of events leading to outcomes. Thus they provide the opportunity to elucidate the potential outcomes of changes to processes (Springer-Heinze et al., 2003). Links within these impact pathways represent hypotheses that can be further validated (Springer-Heinze et al., 2003; Vogel, 2012). Findings from the validation can serve as important guides for improving development interventions (Vogel, 2012).

In this study, we apply the impact pathway approach to improve our understanding of farmers' decisions for or against receiving and adopting climate services. We assess a case study on the implementation of co-produced ACS for two different farmer group settings in Muong Phang and Pa Khoang communes in Dien Bien District, Vietnam. We demonstrate a novel approach that integrates a desk review with participatory exploratory discussions to map out impact pathways of farmers' decision-making and to reveal insights about the delivery and adoption of ACS. Based on a farmer survey, we validate and determine the strength of relationships between components of the impact pathways and draw recommendations to improve ACS interventions in a development context.

2. Materials and methods

2.1. The agro-climate service projects in Dien Bien District

The study took place in Dien Bien District where eight ethnic groups live together (Dien Bien People's Committee, 2009). The District has a high poverty rate of 17.1% (Dien Bien People's Committee 2019) and the majority of residents are rice farmers, known for producing high-quality rice (Agrifood Consulting International, 2006). In recent years, the region has been experiencing major changes in climate and weather patterns. According to data from the Vietnamese Institute of Meteorology, Hydrology and Climate Change, the average annual temperature in Dien Bien increased by 0.74°C between 1961-1990 and 1991-2018. Farmers reported increased occurrence of cold spells, flash floods, landslides, drought, hailstones, floods, erratic rainfall, frost, extended heavy rain and early start of the rainy season (Luu et al., 2022).

In our study, we rely on three multi-stakeholder projects led by CARE in Vietnam (CVN), which provided ACS in Dien Bien District from 2015 until 2021. These ACS interventions aimed to support farmers with information about adapting rice farming systems to changing climatic conditions to improve system outputs and reduce farmers' vulnerability to climate change.

In an attempt to address the last mile delivery, CVN's projects focused on the co-generation of weather forecasts and agricultural advice through seasonal Participatory Scenario Planning (PSP) workshops (CARE, 2018). The stakeholders that CVN engaged in PSP workshops included weather forecasters from the Provincial Hydro-Meteorological Station, agricultural planners and agricultural extensionists from the Provincial and District Departments of Agricultural and Rural Development, Non-Government Organizations - NGOs/Women's Unions and farmer champions (CARE, 2018; Simelton et al., 2019). Farmer champions included village leaders and the head of the Village Saving and Loan Association (VSLA). The VSLA was a self-selected group of 20-30 women (CARE in Vietnam, 2018) who met almost every week in each project village. Based on the PSP outputs, CARE released a printed seasonal bulletin containing indigenous and scientific seasonal forecasts, analysis of the climate impacts on rice farming and advice on the seasonal calendar and farming practices. Since 2018, weekly bulletins were produced by weather forecasters, agricultural extensionists and NGOs without the participation of farmer champions.

The project shared ACS interventions through two different methods, including non-structured/conventional and structured processes. In the non-structured/conventional ACS intervention, printed seasonal bulletins were distributed at conventional village meetings to both VSLA members and non-members. In the structured-processes ACS intervention, meetings with VSLA group members included additional and structured communications and discussion to explain and exchange the ACS bulletin contents in detail. Weekly bulletins were also sent to VSLA members via text messages **(Table 1)**.

Table 1. Type, generation and communication of agro-climate services (ACS) to Village Saving and Loan Association (VSLA) and conventional farmer groups (non-VSLA) in Muong Phang and Pa Khoang communes, Dien Bien District, Vietnam

ACS type	Generation of ACS	Intended users	Method of communications
Seasonal bulletin containing indigenous and scientific forecasts, analysis of the climate impacts on rice farming, and advice on the seasonal calendar and seasonal farming practices (2015-2021)	Participatory scenario planning workshop Participants: weather forecasters, agricultural extensionists, NGOs, Women's Unions and farmer champions	All farmers in the villages (VSLA + non-VSLA farmers)	Distributed paper bulletins at conventional village meetings in all project villages. No other structured communications
		VSLA farmers	Additional and structured communications of the bulletins to explain the bulletin contents
Weekly bulletins containing weekly weather forecasts, analysis of impacts on farm activities, recommendations on specific sowing dates, fertilizer and pesticide application, water management (2018-2021)	Face-to-face or online meetings Participants: Weather forecasters, agricultural extensionists, NGOs	VSLA farmers	Conventional phone text messages, discussions at weekly VLSA meetings

CVN also integrated gender activities into its projects. These activities included training on gender equality for participants engaging in the PSP. In the VSLA groups, activities such as gender norm realization, reflection and norm change dialogues were also integrated into the groups' activities.

2.2. Adoption pathway development

We conceptualized an impact pathway for CVN's project based on the project's design, the project's logical framework, innovation diffusion literature and personal communication with key informants from the project. We held one focus group discussion (FGD) with 12 VSLA farmers and another with

12 non-VSLA farmers to capture their views on possible impact pathways of ACS. During these focus group discussions, we asked farmers to individually reflect on their experiences in accessing and applying ACS. After that, we encouraged farmers to share their views in group discussions. We then synthesized the information provided by the farmers and integrated it into the previously drafted version of the pathway to derive a consolidated impact pathway model.

The resulting model comprised interacting factors and their relationships in the form of nodes and arrows. Each arrow connecting two interacting nodes represents one sub-hypothesis. One sub-hypothesis consists of a hypothesized causal and a resulting event (e.g. Read → Understand), both binomially distributed (causal event [yes/no] → resulting event [yes/no]). The aggregation of sub-hypotheses constitutes the larger system hypothesis (e.g. Access information → Read → Understand → Adopt). We tested each sub-hypothesis to construct the overall understanding of the system hypothesis, using a farmer survey and our proposed testing procedure.

2.3. Farmer survey

After developing the impact pathway, we developed a household questionnaire (see supplementary information) with questions about farmers' rice production, the impact of weather and climate on farming and farmers' access and practice of ACS. We organized household surveys in all 41 CVN project villages and collected information from 41 VSLA and 41 non-VSLA groups. These groups included 977 VSLA farmer households and 1541 non-VSLA farmer households. We randomly selected 82 rice farmer households (41 from VSLA and 41 from non-VLSA households) out of this population. Since members of VSLA groups were all women, we selected women as the respondents for both VSLA and non-VLSA households. The survey, therefore, reflects women's perceptions of the adoption of ACS in their households. We collected additional information during surveys on contextual variables such as age, gender, household size and income **(Table 2**).

We employed six local enumerators to conduct surveys. We trained them in data collection including sampling, interviewee identification, questionnaire content, gender sensitivity and techniques to avoid potential interference from other respondents or peers. We used KoboToolbox (Harvard Humanitarian Initiative, 2020) to gather data on phones and tablets directly or from notes written in the field and checked the collected data for consistency and completeness at the end of each day. If necessary, we followed up with the respondents.

Table 2. Socio-economic characteristics of 41 Village Saving and Loan Association (VSLA) and 41 non-VSLA households in Vietnam's Muong Phang and Pa Khoang communes in Dien Bien District

Description	VSLA	non-VSLA
Total household population	977	1541
Total surveyed groups	41	41
Total surveyed households	41	41
Average members/group	23	37
Gender of respondents		
Female	41	41
Male	0	0
Respondents who were household heads	3/41	6/41
Household size: Mean	4.78	4.53
Ethnicity		
Thai	30/41	29/41
Khmu	6/41	7/41
H'mong	5/41	4/41
Kinh	0/41	1/41
Illiteracy (Kinh language)		
Wife	5/41	7/39*
Husband	1/39*	1/34*
Poverty status		
Poor	7/41	11/41
Near poor	1/41	5/41
Others (average/better-off)	33/41	25/41
Main income		
Agriculture	41/41	40/40*
Rice cultivation as the main income	38/41	38/41
Average rice area/household (m^2)	2845	2097
Seasonal labor	20/41	17/40*
Others	6/41	5/40*

** not all farmers responded*

2.4. Testing relationships in the adoption pathway

We used the survey data to validate the relationships in the adoption pathway identified before and during the workshop. We quantified the overall "success" rate in terms of the adoption aspects for every node of the adoption pathway. We further tested each relationship between sets of two nodes by comparing the success rate in terms of adoption aspects in the presence and absence of the hypothesized causal event. For example, we wanted to test if understanding would lead to a positive perception (Understand → Perceive ACS positively). We then tested the difference in positive perception rates (successful event [yes]) among farmers who understood (hypothesized causal event [yes]) and did not understand ACS (hypothesized causal event [no]).

To implement the test, we first calculated the two probabilities p_1 and p_2 of the successful event [yes] attributable to [yes] and [no] observations of the hypothesized causal event. We calculated p_1 as the probability of observing successful event [yes] together with hypothesized causal event [yes] observations and p_2 to be the probability to observe successful event [yes] occurrence together with hypothesized causal event [no] observations. The response rates p_1 and p_2 were estimated from the sample proportions x_1/n_1 and x_2/n_2, in which

n_1: Number of [yes] observations of the hypothesized causal event

n_2: Number of [no] observations of the hypothesized causal event

x_1: Number of successful event [yes] attributable to [yes] observations of the hypothesized causal event

x_2: Number of successful event [yes] attributable to [no] observations of the hypothesized causal event

Since the occurrence of all events was binomially distributed, we quantified the 95% confidence interval (CI) for the difference between the two success rates p_1 and p_2 ($\delta = p_1 - p_2$) using the ciBinomial function of the gsDesign package (Anderson, 2021) for the R programming language (R Core Team, 2020). All the data, functions, tests and scripts are provided in a public repository (https://github.com/ThiThuGiangLuu/ACS-adoption-decision-pathway). The CI served as the hypothesis test and also displayed the probability of the population's parameter with a specific level of confidence (Sim & Reid, 1999). This practice moves beyond the traditional strategy of testing for statistically significant differences, which is often based on a null value (Sim & Reid, 1999). The interpretation of the CI value should be considered in practical contexts. For example, when comparing two ratios, the statistical test might indicate a statistically significant difference between the two ratios. Nevertheless, the CI value may reveal that the probable difference is too small to be meaningful. In that case, the difference might not be important in a practical context. In contrast, the CI might indicate a non-statistically significant difference. However, due to the large range of the CI, we would be reluctant to conclude that it was not important (Sim & Reid, 1999). Based on that premise, we interpreted the relationship by comparing the width of the 95% CI with a pre-defined range of practical indifference, i.e. the reference range used to infer, by comparing its quantitative value with the 95% CI, if the difference between two ratios is practically important or not. If the CI lay completely within the range of practical indifference, the difference was considered practically irrelevant or trivial. In this study, we chose a lower and upper limit of the practical indifference at -20% and 20% to interpret the CI value. We also considered other possibilities of the CI value when compared with the range of practical indifference that might lead to other possible interpretations. Depending on the range of the CI, we considered the hypothesized causal and resulting events to have no, potential, weak, moderate or strong relationships. We adapted the matrix of the strength of evidence by McBride et al. (2013) and proposed our interpretation of the CI for the difference between the two proportions as in **Fig. 1**.

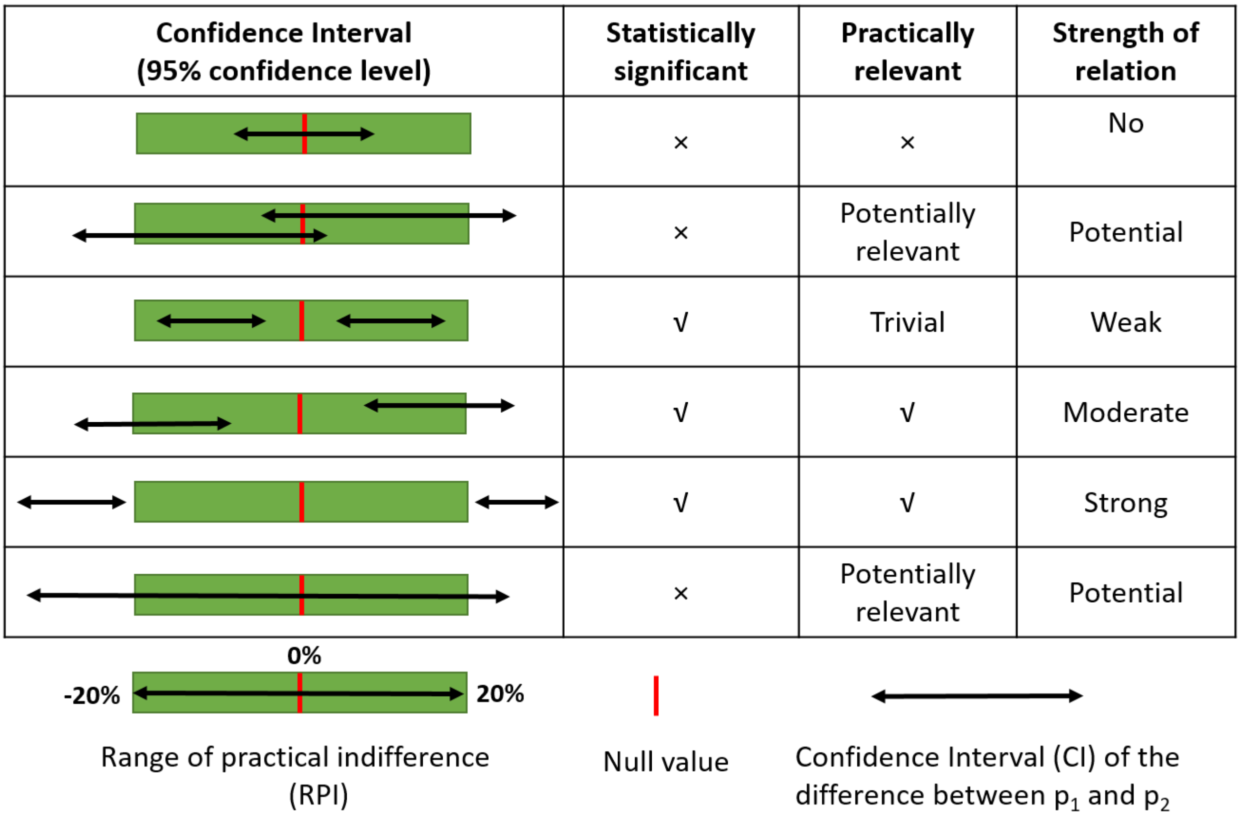

Fig. 1. Quantification of the strength of relationships between binomially distributed (hypothesized) causal and resulting events. The quantification is based on the interpretation of a 95% confidence interval (CI) for the difference of the probabilities p_1 and p_2 of the "successful event" [yes] attributable to [yes] and [no] observations of the hypothesized causal event. The width of the CI is compared with a pre-defined range of practical indifference. Depending on the range of the CI, we considered the hypothesized causal and resulting events to have no, potential, weak, moderate or strong relationships. Source: Adapted from McBride et al. (2013)

The modeled events are generally binomially distributed. However, there were cases where the number of [yes]/[no] observations of the hypothesized causal event in the sample size returned 0 (n_1=0 or n_2=0). In that case, we could not calculate the ratios x_1/n_1 or x_2/n_2 and were unable to test the relationship.

3. Results

3.1. Agro-climate service delivery and adoption impact pathway

Our hypothesized impact pathway of the ACS delivery and adoption decision processes **(Fig. 2a)** illustrates the most important interacting factors that influence the uptake of ACS. The impact pathway shows how occurrence of climate risks motivates farmers' risk perception (Risk occurrence → Perceived risk). This increased perception of climate and weather risks raises the likelihood that they will see a need for access to ACS (Perceived risk → Need). Having this need leads farmers to access ACS (Need → Access ACS). As a result of accessing ACS, farmers are presumed to read/listen to ACS (Access ACS → Read/Listen). After reading/listening, farmers are expected to understand the forecasts and advice (Read/Listen → Understand). Farmers will then have a positive perception of ACS (Understand → Perceive ACS positively). Positive perception is expected to trigger the intention to adopt ACS (Perceive ACS positively → Intend to adopt ACS) and then the adoption of ACS (Intend to adopt ACS → Adopt ACS).

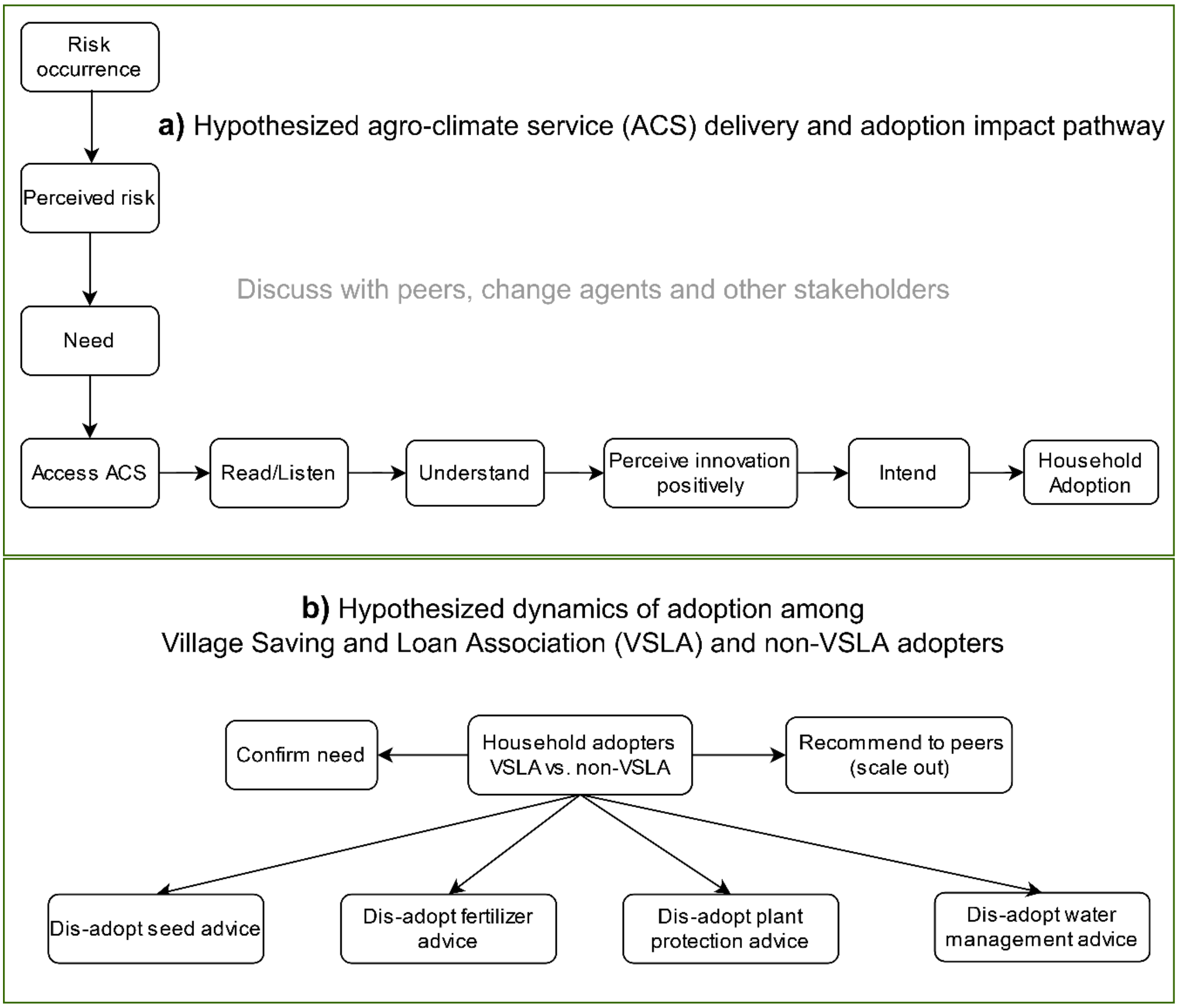

Fig. 2. Hypothesized agro-climate service (ACS) delivery and adoption impact pathway (a) and dynamics of ACS adoption in Village Saving and Loan Association (VSLA) and conventional farmer groups (non-VSLA) (b) in Muong Phang and Pa Khoang communes, Dien Bien District, Vietnam

After the initial adoption, farmers may decide whether they would recommend ACS to peers (Adopt ACS → Recommend to peers) and if they confirm their continued need for ACS in the future (Adopt ACS → Confirm continued need) or decide to dis-adopt (Adopt ACS → Dis-adopt ACS). Since we are interested in understanding the dynamics of recommending, confirming need and dis-adopting among adopters, we test the relationships between VSLA vs. non-VSLA adopters and the possibility to recommend ACS, to confirm the need for ACS and to dis-adopt ACS **(Fig. 2b)**.

During the whole process, farmers may discuss with peers, change agents and other stakeholders to share and exchange information at any time. Due to our limited resources (i.e. we relied on the enumerators to collect data during the Covid-19 pandemic), we did not collect data to test all the relations of "Discuss" with all other observed events, only the relations between Read/listen → Discuss → Understand **(Fig. 3)** were selected for testing.

3.2. Impact pathway validation

The household survey served to validate the hypothesized ACS delivery and adoption impact pathway **(Fig. 3)**. The results show that the adoption impact pathways vary in VSLA and non-VSLA groups **(Fig. 3a)**. For VSLA groups, tests indicate potentially relevant relations for six connections (Perceived risk → Need; Need → Access ACS; Read/Listen → Discuss; Discuss → Understand; Understand → Perceive ACS positively; Intend to adopt → Adopt).

In non-VSLA groups **(Fig. 3b)**, five of the tests show potentially relevant relations for five connections (Risk occurrence → Perceived risk; Perceived risk → Need; Need → Access ACS; Access ACS → Read/Listen; Read/Listen → Discuss). In two cases, tests indicate moderate relationships (Understand → Perceive ACS positively; Intend to adopt → Adopt). In two other cases, tests reveal strong relationships (Discuss → Understand; Perceive ACS positively → Intend to adopt).

Detailed results of all the tests, including the sample, observation and success rates are available in a public repository (https://github.com/ThiThuGiangLuu/ACS-adoption-decision-pathway).

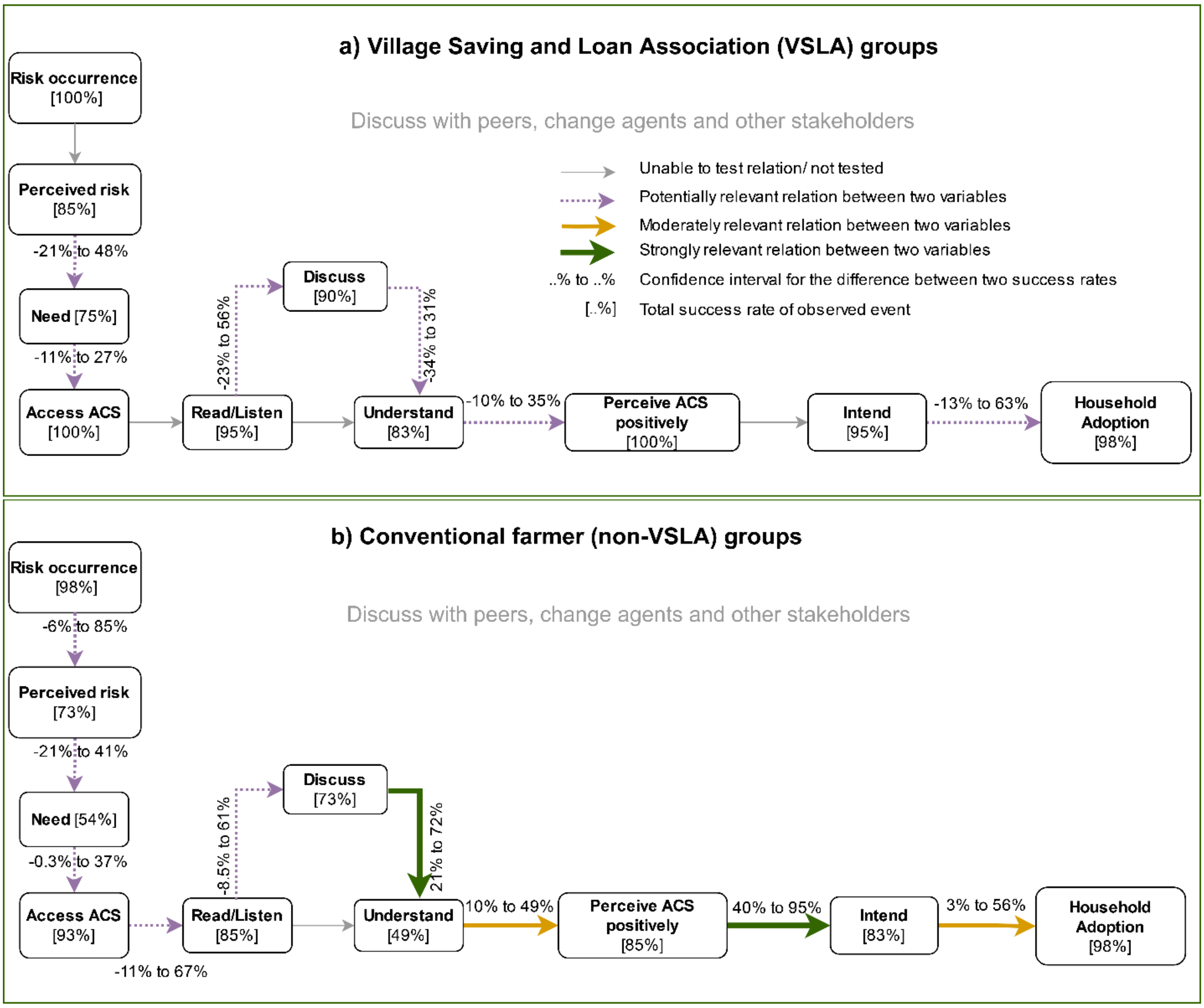

Fig. 3. Testing results of an impact pathway describing the farmer's decision-making processes in adopting agro-climate services in Muong Phang and Pa Khoang communes, Dien Bien District, Vietnam

3.3. VSLA vs. non-VSLA adopters

In addition to the adoption impact pathway results, our survey also revealed some differences in attitudes and behavior between VSLA and non-VSLA adopters, including the confirmed need for continued ACS, peer-to-peer scaling and intention to dis-adopt ACS (i.e. seed, fertilizer, plant protection and water management advice) **(Fig. 4).** Our tests indicate no potentially relevant relations for two connections (VSLA vs. non-VSLA adoption → Confirm need; VSLA vs. non-VSLA adoption → Dis-adopt plant protection advice), one moderately relevant relation for the connection between VSLA vs. non-VSLA adoption → Scale out (recommend to peers), and three potentially relevant relations (VSLA vs. non-VSLA adoption → Dis-adopt seed advice; VSLA vs. non-VSLA adoption → Dis-adopt fertilizer advice; VSLA vs. non-VSLA adoption → Dis-adopt water management advice).

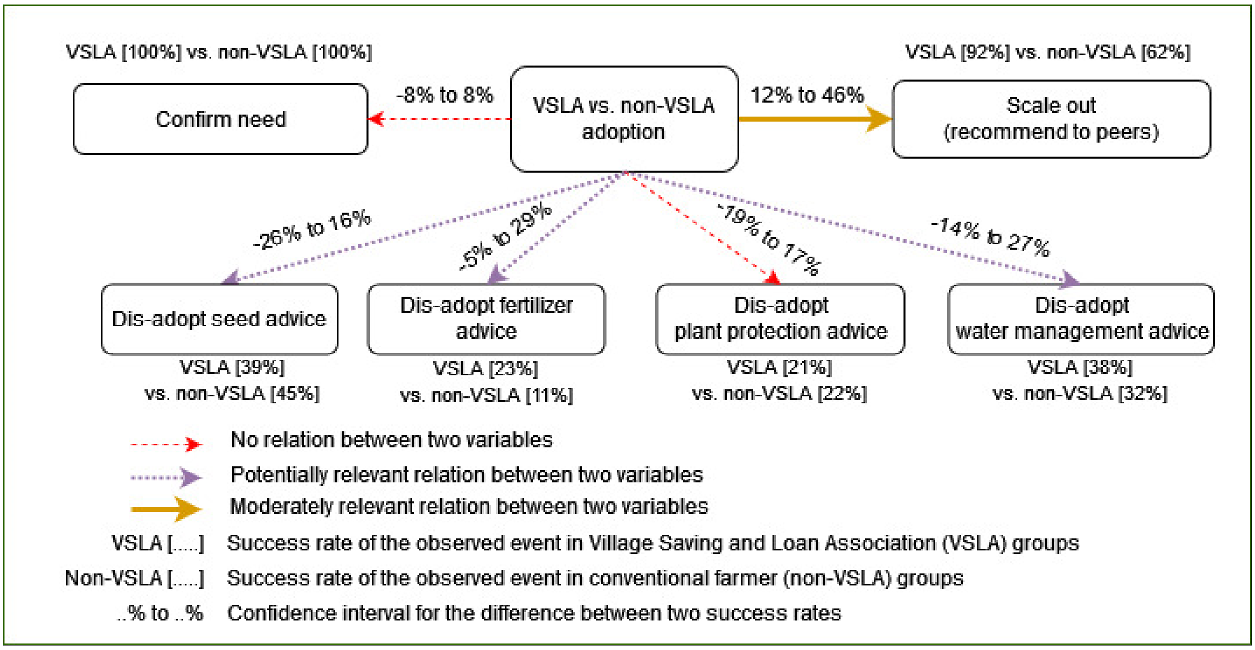

Fig. 4. Testing results of the dynamics of agro-climate service adoption among Village Saving and Loan Association (VSLA) groups and non-VSLA groups in Muong Phang and Pa Khoang communes, Dien Bien District, Vietnam

Our survey revealed some further insights regarding the scaling out among households as well as the reasons for dis-adoption of seed, fertilizer, plant protection and water management advice.

Regarding scaling out, among 79 VSLA and non-VSLA households that responded to the scaling question, 61 households stated that they recommended ACS to other farmers. In total, VSLA and non-VSLA households shared ACS with at least 263 others. Altogether, 36 out of 39 VSLA households recommended ACS. They shared the advice with at least 176 other farmers, of which 169 reportedly followed the recommendation. Among non-VSLA households, 25 out of 40 recommended ACS advice to other farmers. They reported sharing with at least 87 other farmers. As a result, 92 farmers (i.e. it might include adopters who got indirect recommendations) were reported to have applied the recommendation. The number of recommendations ranged from 0 to more than 5 other farmers per household. In both groups, most recommendations went to neighbors (i.e. people living near or next door to the interviewee), followed by neighboring farm households (i.e. people having farms near or next to the farm of the interviewee), relatives and close friends. Farmers did not report recommendations to any other groups. Regarding dis-adoption, some farmers reported their intention to dis-adopt seed, fertilizer, plant protection and water management advice, citing various reasons **(Table 3).**

Table 3. Reported reasons for the dis-adoption of some agro-climate advice among Village Saving and Loan Association (VSLA) and non-VSLA households in Vietnam's Muong Phang and Pa Khoang communes in Dien Bien District

Type of advice	Reasons for dis-adoption
Seed advice (i.e. regarding seed amount, seed type, sowing time, sowing technique)	Farmers were used to existing routines Farmers were concerned that seeds would not germinate as expected Farmers were concerned that cold weather or heavy rain required more seeds Advice was not appropriate for farmers' farm conditions Farmers' preference for new varieties with higher yield Farmers' inability to apply advice
Fertilizing advice (i.e. rate, type, timing/weather and place of fertilizer application)	Farmers lacked the money to buy the right rate Farmers were concerned that fertilizers were not enough Rice did not grow well with recommended fertilizer Recommended fertilizer was not available in local shops Fertilizer advice was not appropriate for the local farms
Plant protection advice (i.e. right type, right rate, right time/weather, right place)	Recommended pesticides were not available in local shops Farmers were unsure if they bought the right type from the recommended pesticide substance Farmers did not have money to buy the pesticide Farmers followed the advice but it was not effective
Water management (i.e. coordinated irrigation, pumping water during floods, droughts, shifting crops, regulating water at critical rice growth development stage, saving water)	Field locations were far from the canal system Farmers could not arrange a time for regular farm visits There was no water during some drought stages and farmers were unable to apply some advice Farmers had no money to buy pumps

4. Discussion

The results reflect the complexity of the social processes in response to the impacts of climate change and its implications for decision-making in development interventions (Morton, 2007; Rickards & Howden, 2012; Wise et al., 2014). Our impact pathway and test results offer several insights into the decision-making process involved in adopting ACS in different farmer group settings. The results show a relatively similar "starting" point (i.e. level of perceived risk occurrence before the project) followed by similar levels of "adoption" (i.e. level of ACS adoption after 5 years) in VSLA as well as non-VSLA groups **(Fig. 3)**. However, analysis of the delivery and adoption pathway indicated different dynamics in the two group settings. VSLA farmers were more likely to perceive risks of climate, have a perceived need for and access, read/listen to, discuss and understand ACS, perceive ACS positively, intend to adopt and ultimately adopt ACS. In the non-VSLA groups, farmers had a lower need and were less likely to understand ACS. Nevertheless, the likelihood to adopt was surprisingly high and similar (98%) between the VSLA and non-VSLA groups. These results support indications that the linear assumption often involved in innovation diffusion models (Geels & Schot, 2010; Hoffmann, 2007) and the conventional use of a logical framework (Springer-Heinze et al., 2003) may be oversimplifications. Our results highlight the importance of understanding the processes behind adoption including interpersonal relationships and the influence of pioneers within societies implementing innovations (Springer-Heinze et al., 2003; Vogel, 2012). Our method for testing these processes offers a novel approach to identifying and quantifying the relationships between events in an impact pathway. Our findings on causal relationships yield insights about the triggers of and barriers to adoption along the impact pathway. These insights can help innovation projects in complex contexts (e.g. development projects) to reflect, learn and adjust their interventions. They also offer an understanding of possibilities and implications for the critical mass needed for outscaling.

The results from our survey reveal a difference in farmers' perceived needs before and after experiencing ACS. Before CVN's project implementation, farmers' perceived need for ACS in VSLA and non-VSLA groups was 75% (30/41) and 54% (22/41), respectively. After experiencing ACS, all households in the two groups stated a need for ACS (39/39). Our findings support previous findings highlighting the importance of realizing the needs of farmers as a critical factor in supporting the last mile delivery of ACS (J. W. Hansen et al., 2019; Nkiaka et al., 2019; Simelton & McCampbell, 2021). However, our results also suggest a potential difference between the stated and the revealed need. Farmers might have a real need for agro-climate information, but may not communicate it or even be aware of it. This might be true in contexts where farmers have limited access to information about climate change. The low need for ACS among farmers may also imply that climate services might not have been clearly defined and communicated to farmers (Lourenço et al., 2016). Awareness-raising on the concept of ACS might be needed to fill the gap between stated need and revealed need. In this case, CVN did create awareness and demand, reaching almost all non-VSLA farms, yet the initial need remained at 54%. Scaling efforts therefore should aim at understanding farmers' revealed needs.

The high level of comprehension of ACS among VSLA farmers (83%) suggests that structured communications in VSLA groups are effective in supporting farmers' comprehension of ACS. This finding supports Hansen et al. (2019), who showed that structured communications supporting farmers' understanding enabled them to relate complex information to their specific contexts and decisions. This was not the case among non-VSLA farmers (i.e. the level of comprehension remained at 49% after five-year project implementation), who did not have frequent contact with project activities and stakeholders. The non-structured communications they received were less effective in increasing their understanding of ACS. This may be explained by the ACS bulletins often featuring technical language and expressions of uncertainty, which may not be easily understood by the remaining 51% of non-VSLA farmers without additional explanation. Past studies have pointed out the difficulties in communicating technical information about weather, climate, uncertainties and other agriculture-related terminologies and principles to farmers (Duong et al., 2020; Lourenço et al., 2016; Simelton & McCampbell, 2021; WMO, 2019). Illiterate people found it particularly challenging to understand the bulletins if they were not supported by others. Ethnic minority farmers may face additional barriers, since they may have to interpret the bulletins in their local languages (CARE in Vietnam, 2013; Nguyen et al., 2021). The results highlight the importance of peer-to-peer learning (Tran et al., 2017). Such personal exchange might be able to address the barriers to understanding ACS partially.

Lack of comprehension, however, does not necessarily prevent the subsequent up-taking process. For example, while the understanding rate remained at 49% in the non-VSLA groups, 85% of those farmers still held a positive perception of ACS. This positive attitude appears to have an important influence on the intention to adopt ACS. The strong relationship between 'Perceive ACS positively → Intend to adopt' (Fig. 2) among non-VSLA farmers, might be attributed to the influence of stakeholder involvement in ACS production, peer exchange and opinion leaders. The ACS production and delivery mechanism may effectively make the information 'credible, salient and legitimate'. ACS is co-produced with credible and legitimate agencies, which have a clear legal mandate to provide such information and local NGOs that have operated in the community for a long time and have gained the farmers' trust. Contacts of those involved in developing the bulletin are provided, along with their phone numbers. The perception of ACS could be further strengthened through peer exchange and the influence of opinion leaders, such as the heads of the villages and VSLAs. Involvement of village and VSLA leaders might enhance the salience of provided information since these people are close to villagers and they might potentially reflect farmers' needs and concerns in ACS provision. Those aspects of credibility, salience and legitimacy are crucial in enhancing the use of climate information in decision-making (Cash et al., 2003; Vincent et al., 2018). All this may enhance the odds of farmers using the advice to take appropriate action. Development efforts should consider farmers' attitudes and perceptions in designing and monitoring ACS interventions.

The equally high adoption rates between VSLA and non-VSLA groups despite different levels of understanding have multiple implications. *First*, valuing ACS benefits might not fully follow a gradual decay process as suggested in the studies by Perrels et al. (2013) and Pilli-Sihvola et al. (2014), i.e. we cannot confirm that the ultimate benefits of ACS adoption are always low if the comprehension level is low. *Second,* scaling out is likely to be possible given that farmers can learn or simply imitate climate-informed actions through social networks (Tran et al., 2017). In this study, each VSLA household recommended ACS services to at least 4.5 peers, resulting in at least 4.3 new applications of ACS. A typical non-VSLA household recommended ACS to at least 2.2 peers, resulting in at least 2.3 new applications of ACS (i.e. it might include adopters who got indirect recommendations). *Third,* the high adoption rate, especially when farmers do not understand information, might lead to over-adoption or misunderstood and mistaken adoption. For example, farms in different regions might experience different drought risks. Thus, simply imitating the drought response of another farmer might not be a good strategy. *Fourth*, adoption rates are promising in both VSLA and non-VSLA groups, suggesting the important roles of interpersonal relations and a potential role of a critical mass in outscaling ACS. The high adoption rates also suggest the continuation of such interventions within CVN's projects. Yet it is still impossible to know at this stage if either the farmer group setting is ideal for scaling out and scaling up beyond CVN's project context. Monitoring the quality and consequences of adoption is necessary to understand the overall impacts of innovation and its diffusion (Rogers, 2003). Recommendations on scaling would be more comprehensive if it is preceded by a socio-economic valuation of such ACS interventions.

We found the chance of dis-adoption for fertilizer and plant protection measures to be low, while it was fairly high for some specific advice on seeds (43%) and water management (34%). The reasons for the dis-adoption of seed and water management advice are mostly related to the mismatch between advice and the households' traditional practices, interests, and resources. Smallholder farmers are diverse, and services are not usually formulated to cater to all the different needs of farmers (Simelton & McCampbell, 2021; VNIFIP et al., 2018). Resources should be invested in understanding the typology of farmers (Cruz et al., 2021; Shukla et al., 2019) and adjusting the interventions accordingly.

Previous adoption studies on agro-climate services have largely been rooted in variance theory, in which the adoption variable is explained by a linear combination of independent variables. The limitation of the variance approach is the neglect of history and time ordering of events (Geels & Schot, 2010), even though these may have important implications for adoption outcomes. The impact pathway testing approach that we used offers us the chance to understand the dynamics of the hypothesized causal processes, as well as potential blockage or trigger points. The impact pathway insights also offer a concrete way to support reflections on the process from inputs to outputs and outcomes in development interventions. These insights are important in identifying and prioritizing further development research and interventions. Thus, impact pathway testing is crucial in supporting ACS design, monitoring, reflection and learning, and ultimately for creating sustainable impacts.

The use of the CI value and interpretation in both statistical and practical contexts provides various advantages (Brosi & Biber, 2009; McBride et al., 2013; Sim & Reid, 1999). Even with the limited sample size of 41 for each type of farmer group, the CI value still offers a lot of insights into the relationships between the events. This differs from the traditional variance approach, which requires a large sample size (Geels & Schot, 2010). Thus, using the CI interpretation approach is helpful, especially when resources are limited. The traditional interpretation of statistical tests for significance can make it difficult to apply results in decision-making. The interpretation of the CI in a practical context, on the other hand, gives concrete meaning to support decision-making (Brosi & Biber, 2009; Sim & Reid, 1999).

Although we have made efforts to understand the impact pathway in ACS adoption, some limitations and caveats should be considered. For example, we did not provide a concrete definition of ACS to the respondents. The interviewees stated whether they mostly understood or did not understand ACS bulletins. There may have been varying interpretations of ACS and the level of understanding may not have been fully captured. Second, while all the variables in the impact pathway are binomially distributed, there may have been some more qualitative information (e.g. the level of detail in understanding) that could have provided further insights. In the results of the impact pathway testing, inferences on causal relations should also be interpreted with caution. Rather than being accepted as proven, they should be treated as improved hypotheses for continued learning, reflection and improvement (Vogel, 2012).

5. Conclusions

Understanding the dynamics of last mile delivery and adoption of ACS is critical for decision-making in sustainability-oriented development interventions. Impact pathway development and testing is a novel approach to generating an explicit overview of the impact pathway relationships in ACS adoption processes. The testing procedure developed in our study offers a robust and rapid tool to validate hypotheses for development interventions. These hypotheses might otherwise be overly simplistic and remain largely untested and unvalidated. The testing procedure also allows for quantifying the strength of relationships, which can be useful in formulating recommendations to support resource prioritization in decision-making. The impact pathway development and testing method may be useful to support filling in the ACS adoption gaps. Our case study shows that structured communications in farmer groups, demand awareness creation, enhancing peer-to-peer exchange and influencing farmers’ attitudes appear to be crucial in delivering and spreading ACS effectively. Efforts to scale out ACS should consider these important aspects. Future research may focus on studying the impacts of ACS adoption, possibly using this impact pathway testing procedure combined with other ACS impact evaluation methodologies, to support further scaling of ACS. The use of the impact pathway development and testing approach is not limited to adoption or ACS contexts. We expect it to find successful applications in a host of other cause-and-effect processes as well as in outscaling of sustainable development interventions and innovations.

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Statement and declarations

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Data availability

Data are available at this public repository:
https://github.com/ThiThuGiangLuu/ACS-adoption-decision-pathway

Material availability

All supplementary documents are available at this public repository:
https://github.com/ThiThuGiangLuu/ACS-adoption-decision-pathway
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Code availability

Code is available at this public repository:
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Author contributions

Conceptualization: TTGL., EL., LBF., and CW.; Data curation: TTGL.; Formal analysis: TTG.L; Funding acquisition: TTGL. and EL.,; Investigation: TTG.L.; Methodology TTGL., EL., LBF., and CW.; Software: E.L. and TTGL.; Supervision: EL., CW. and LBF.; Validation: TTGL; Visualization: TTGL.; Writing - original draft: TTGL; Writing - review & Editing: CW., EL., LBF., and TTGL.

Declaration of interest statement

The authors declare that we have no conflicts of interest

Ethics approval

We followed ethical standards and guidelines of the Center for Development Research (ZEF), University of Bonn and CARE in Vietnam. Informed consent was obtained from all individual participants of the interviews.

Consent to participate

All respondents were briefed about the purpose of the research before deciding whether they wanted to take part in the focus group discussion and survey. Respondents' consent for participation was obtained from all individual participants included in this study. Respondents were free to stop the conversation at any time during the survey. The names and identifying information about respondents were kept anonymous. The information provided was used solely for research purposes.

Consent for publication

The authors affirm that consent was gathered for the publication of all information used in this study.

Supplementary information

All the supplementary information is available at this public repository:
https://github.com/ThiThuGiangLuu/ACS-adoption-decision-pathway

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Chapter 3: Decision analysis of agro-climate service scaling – A case study in Dien Bien District, Vietnam

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Abstract

Farmers' agricultural practices in Vietnam are highly sensitive to weather, climate variability and climate change. The lack of timely and actionable climate-informed agricultural advice leads to significant input and yield losses, which can render investments in farming unprofitable. Development organizations in Vietnam have provided agro-climate services (ACS) to smallholder farmers on a limited scale. They advocate for the government to consider upscaling the provision of ACS, but a large-scale roll-out could strain the government's financial and human resources. Evaluating the merits of climate services is challenging, because weather and climate risks, as well as the benefits that information services may provide, cannot be derived from robust existing datasets or predicted with certainty.

CARE in Vietnam, a non-government organization, has provided ACS in two communes in Dien Bien District since 2015 and they expect to upscale their intervention. In this study, we used a decision analysis approach to develop conceptual models and probabilistic simulations to conduct an ex-ante cost-benefit analysis of four candidate interventions aiming to scale ACS in Dien Bien District, Vietnam. Our analysis was conducted in collaboration with CARE in Vietnam's project staff, Dien Bien government staff and other experts. Our simulation results indicated a very high chance (98.35-99.81%) of the ACS interventions providing net benefits. With 90% confidence, investments in ACS would return benefits between 1.45 and 16.02 USD per 1 USD invested. Our framework offers a foundation for the design, implementation and evaluation of ACS. The cost-benefit analysis provides support to the government's potential decision-making process and suggests replacing deterministic with probabilistic approaches when analyzing uncertain and complex decisions in development planning.
Keywords: Cost-benefit analysis, uncertainty, probabilistic modeling, decision analysis, agriculture, climate change

Practical implications

Agricultural practices and outcomes are strongly impacted by past and present weather and climate.

Future climate change is expected to raise the frequency and intensity of weather extremes and increase climatic variation. Climate services support the agricultural sector in coping with increasing uncertainty about production conditions, yet such services require financing. To justify the investment, there is a need for scientific evidence to help demonstrate the chance that the benefits of agro-climate services (ACS) to the public and investors outweigh their costs. Such evidence is needed as a basis for development planning. However, the valuation of ACS has been challenging due to a lack of usable data and considerable uncertainties and risks.

We employ decision analysis, which is an interdisciplinary approach aiming to support decision-making in an uncertain, complex environment, to analyze the costs and benefits of four ACS scaling investment options in Dien Bien District, Vietnam. The results from our simulations show, with very high certainty (98.35-99.81%) that the benefits will outweigh the costs in four investment scenarios. Our model outcomes indicate that the four ACS interventions could provide net benefits in a range from 0.23 to 4.90 million USD (90% confidence interval). This means that per 1 USD of additional investment, ACS will accrue additional benefits ranging from 1.45 to 16.02 USD over a five-year planning horizon. The benefits include economic returns of improved farm production practices, environmental impact and gender equality. The government should go ahead with any of the four investment scenarios.

From the design and analysis of these interventions, we have drawn some key lessons and recommendations to policy-makers regarding planning, investing in and managing ACS. We have also outlined key principles that should be considered by practitioners when designing, implementing, monitoring and evaluating ACS.

For policymakers

- There is a mismatch between real-life uncertain, complex agricultural system challenges and the legally mandated and dominant use of deterministic and disciplinary approaches in development planning.
- Traditional agricultural research largely relies on agricultural problems and observations without direct analysis of decision-making. This practice potentially leads to a critical knowledge gap in decision-making processes.
- Decision analysis offers various advantages in supporting agricultural decision-making in variable weather and climate contexts. Governments and donors should consider using this probabilistic approach, which is suitable for decision-making and investment planning under uncertain and complex conditions.
- ACS requires partnership with multiple stakeholders, including researchers, farmers, agricultural input suppliers, traders and media, as well as inter-sectoral cooperation and inter-government-level cooperation. Ensuring good governance of ACS will facilitate the establishment and effective operation of ACS.
- Relatively high up-front costs in the first year(s) of investment and expenses for weekly and seasonal deliveries of ACS advice suggest that ACS are resource-intensive in terms of human

and financial capital, particularly at the beginning. Yet once the system is in place, the follow-up investments are low. Decision-makers should consider the long-term outlook of investments.

- ACS can help farmers respond to variable weather and climate conditions. However, some losses and damages are beyond the scope of ACS. The government should also invest in infrastructural solutions, social protection, sustainable agriculture development and market linkage.

For practitioners

- Systemic nature: ACS should not be singularly focused on climate and agriculture but also consider and address social and environmental aspects to generate multidimensional benefits.
- Effectiveness: Reaching the last mile requires strong partnership along the value chain and the removal of economic and social barriers (e.g. language, communication and inputs) to ensure that the information produced is actionable. Ex-ante evaluation of ACS is needed. However, ex-post evaluation of ACS has also rarely been done. Therefore, stakeholders should also prioritize this area of work.
- Adaptiveness: ACS might require adaptation for specific households and local contexts. The aim of ACS should not just be to improve the quality of the forecasts and advisories but also to raise the capacity to manage the uncertainty of forecasts and advisories.
- Probability: The expert calibration technique is feasible and beneficial to supply reasonable estimates in data-scarce, highly uncertain and risk-prone environments. Value of information assessments can indicate where research efforts to close knowledge gaps may be most efficiently directed to high-value variables.

1. Introduction

Agricultural practices are affected by extreme weather events, climate variability and climate change (FAO, 2015; Gornall et al., 2010; IPCC, 2014). In developing countries, the agriculture sector has been estimated to suffer losses around 25% through the impacts of droughts, floods, hurricanes, typhoons and cyclones (FAO, 2015). Worldwide, about 32-39% of the variation in yields of major crops has been attributed to climate variability, with large differences across geographical areas (Ray et al., 2015). Global climate change impacts on crop yields vary across regions, yet impacts tend to be negative more often than positive (FAO, 2016; IPCC, 2014; Rosenzweig et al., 2014). Climatic conditions (e.g. temperature, rainfall) also serve as a production factor in agricultural systems. It is thus crucial for agricultural decision-makers to incorporate climate-related risks and to consider the opportunities for agricultural production brought by climatic conditions (FAO, 2019; Nguyen, 2017; O'Grady et al., 2020).

One important solution that has been applied to make climate and weather information available to agricultural users (e.g. farmers, extension workers and policy makers) is the provision of agro-climate services (ACS). In our study, we refer to definitions of both the Climate Services Partnership (2019) and the World Meteorological Organization (2019a), interpreting ACS as a value chain that comprises four main components: (1) production of information on weather and climate, (2) translation of weather and climate information into agricultural advice, (3) transfer of weather information, climate information and agricultural advice to agricultural users and (4) use of weather information, climate information and agricultural advice by agricultural users. The prefix “agro” signifies that advice is both targeted towards an agricultural audience and that it refers specifically to agricultural decision-making. In addition, the ACS also include other integral parts: (1) capacity building of actors engaging across the value chain, (2) gender integration to promote gender balance in the value chain and gender equality in accessing and benefiting from agro-climate services among end-user farmers, (3) ensuring good governance of the ACS value chain, (4) monitoring and evaluation of the inputs, outputs and impacts of the ACS.

Agro-climate services provide benefits for agricultural planning and management (Nabati et al., 2020; Nguyen, 2017; WMO, 2003). Agro-climatic zoning, for example, can support selection of climate-adjusted crops and management practices (Higgins and Kassam, 1981; Nabati et al., 2020; WMO, 2003). Rainfall, temperature and solar radiation resources, to a certain extent, can be managed and used properly to support optimal agricultural production (FAO, 2019; Nguyen, 2017; O’Grady et al., 2020). The effective operation of ACS, however, requires climate services to provide timely, fine-grained and reliable communication of weather information, climate forecasts and advice, including associated uncertainties (CARE, 2018; Mullins et al., 2018; Simelton et al., 2019; WMO, 2013). Implementation of ACS requires awareness and integration of social, environmental, cultural, technological, market, gender and governance aspects (CARE in Vietnam, 2020; Duong et al., 2020; FAO, 2019; McKune et al., 2018; WMO, 2019b, 2019a, 2013), which can either hinder or facilitate ACS operation. Ensuring the effective operation of ACS in a complex and dynamic system may require high investment costs that might outweigh the benefits, which are difficult to quantify. This concern is exacerbated by the challenge that Vietnam’s state resources can only provide 30% (estimation for 2021-2030) of the finance needed for climate change adaptation (The Socialist Republic of Vietnam, 2020). Given the limited resources and the uncertainty in the costs and benefits of ACS, comprehensive social cost-benefit analyses of the services are crucial to supporting ACS investment decisions.

Despite its importance and recent progress, valuing the socio-economic impacts of climate services is still the weakest area across the climate service value chain, particularly at the local level (Clements et al., 2013; Perrels, 2020; WMO, 2019b). Key weaknesses that remain in valuing climate services and particularly ACS are a lack of usable, unbiased data on economic, social and environmental benefits of climate services (Clements et al., 2013; Perrels, 2020), as well as ways to estimate residual damage that cannot be prevented by climate services (Stern, 2007). Evaluating the merits of climate services requires recognition of numerous risks and uncertainties linked to, for instance, imperfections in weather and climate forecasts and ambiguity of resulting advice (Ambani and Percy, 2014; Clements et al., 2013; Katz and Lazo, 2011; Nurmi et al., 2013; Perrels, 2020; Pilli-

Sihvola et al., 2014; WMO, 2015). Adoption rates by farmers are difficult to predict due to uncertain effects of information access, market dynamics, availability of agricultural inputs and decision-making processes at the community level and within households (e.g. power relations between men and women) (Ambani and Percy, 2014; Perrels, 2020; Pilli-Sihvola et al., 2014; Rogers, 2003). One of the critical recommendations for future research is to purposefully choose valuation methods that consider the lack of usable data (Perrels, 2020) and incorporate risks and uncertainties (Clements et al., 2013; WMO, 2015).

Decision analysis is an interdisciplinary approach that employs both participatory methodologies and probabilistic modeling techniques to support decisions on complex agricultural systems, in data-scarce, uncertain and risk-prone environments (Lanzanova et al., 2019). While Howard and Abbas (2015) have established the foundations for the methods, the Applied Information Economics principles (Hubbard, 2014) provide the key ingredients for the decision analysis approach taken in this study. Decision analysis aims to integrate knowledge and systems thinking to capture the current state of system understanding, without assumptions of certainty (Luedeling and Shepherd, 2016). Given the state of system knowledge, strategies to identify and prioritize critical knowledge gaps that should be narrowed might be performed until system understanding is sufficiently advanced to support decision-making (Lanzanova et al., 2017; Luedeling and Shepherd, 2016). Compared to in-depth disciplinary and deterministic approaches, the analysis might be rather coarse, in particular where data availability is poor. The level of detail, however, is exchanged for a more comprehensive analysis that includes important factors that are often omitted. Decision analysis therefore constitutes a more reasonable foundation for decision-making than data-driven analyses that only partially capture the system of interest (Luedeling and Shepherd, 2016).

Decision analysis concepts and methods have been used to support decisions in computer science, insurance, business management, natural resource management and other fields (Hubbard, 2014; Luedeling and Shepherd, 2016). Recently, decision analysis has been applied in various ex-ante assessments in development and agriculture contexts, including water supply assessment (Luedeling et al., 2015), reservoir sediment management (Lanzanova et al., 2019), agricultural policy impact assessment (Whitney et al., 2017), agroforestry system valuation (Do et al., 2019), disease management strategies for heather growers (Ruett et al., 2020) and law enforcement (Nascimento et al., 2020).

Here we demonstrate the use of decision analysis in performing ex-ante evaluation of the proposed interventions for scaling agro-climate services in Dien Bien District, Vietnam.

2. Background of the study

2.1. Dien Bien District

Dien Bien District is located in the Northwest of Vietnam. The District has a population of around 100,000 people belonging to seven ethnic groups (Dien Bien People’s Committee, 2015). While the written language in the District is mainly Kinh, local populations usually communicate in several other languages.

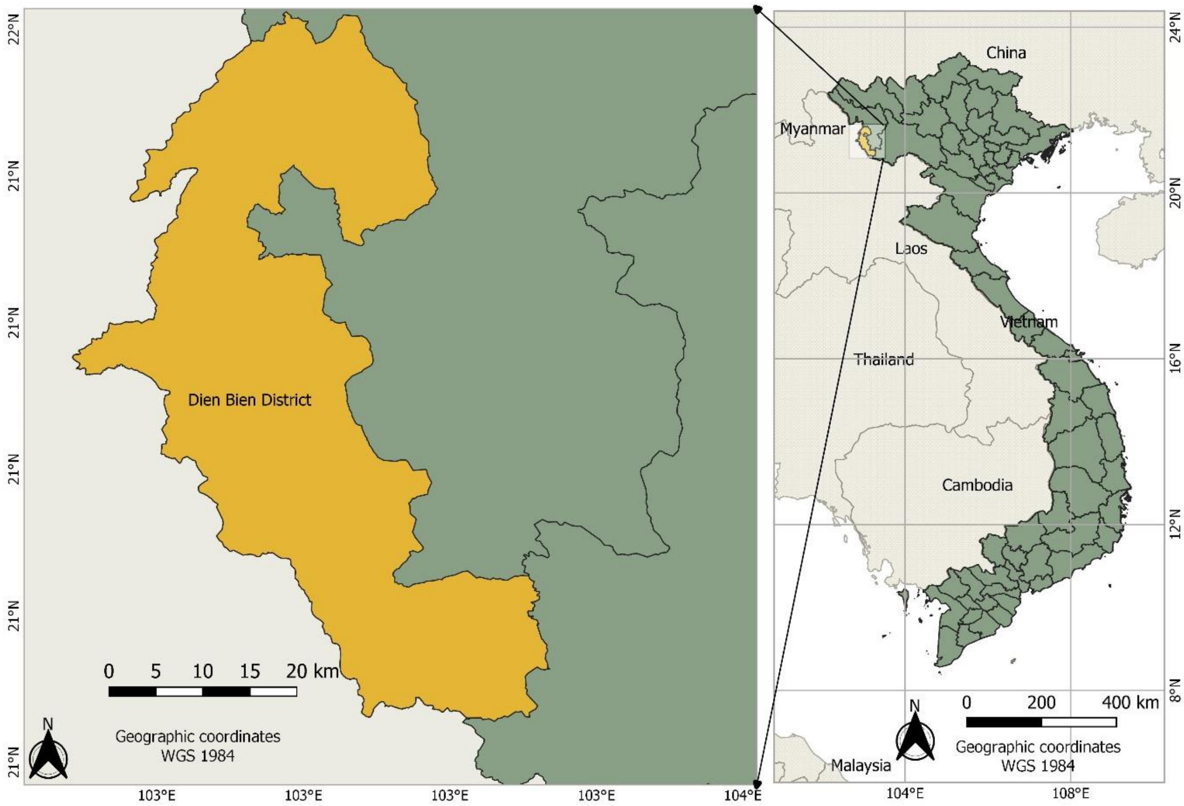

Fig. 1. Map of the agro-climate service research area, Dien Bien District, Vietnam.

Dien Bien has a tropical monsoon climate, characteristic of the uplands of the Northwestern region of Vietnam. While winters are relatively cool, summers are hot and rainy (Dien Bien People's Committee, 2015). According to data from the Vietnam Institute of Meteorology, Hydrology and Climate Change, the average annual rainfall, in the period from 1961-2018, was 1562 mm in Dien Bien District. In that same period, the average annual temperature was 22.17°C, with an increased by 0.75°C between 1961-1990 and 1991-2018. Dien Bien is expected to continue experiencing temperature increases (Tran et al., 2016). According to unpublished baseline data of the ACS project run by CARE in Vietnam, several adverse weather and climate events can be damaging to local agricultural productivity. These adverse conditions include droughts, hailstones, floods, flash floods, whirlwinds, landslides, hoar frosts, cold spells, early onset of the rainy season and extended rainy seasons.

Dien Bien District has two sub-regions, the upland (> 1000m a.s.l./above sea level) and the lowland (400 to less than 1000m a.s.l.) (Dien Bien People's Committee, 2009). The District's poverty rate was 17% in 2018 (Dien Bien People's Committee, 2019). Agriculture is practiced by a majority of households in Dien Bien, constituting a crucial source of income for them (Agrifood Consulting International, 2006). Women in Dien Bien experience gender inequality due to limited access to information, unequal labor division and the general dominance of men in making major decisions (CARE in Vietnam, 2013; Duong et al., 2020).

2.2. Rice cultivation and cattle raising in Dien Bien District

Rice production and cattle raising in Dien Bien are vulnerable to adverse weather and climate events as well as to improper agronomic practices. According to our interviews with representatives from the Dien Bien Division of Agriculture and Rural Development (August, 2019), about 80% of households in Dien Bien grow rice. In the lowland, rice production is mostly market-oriented, while upland farmers often grow rice for subsistence. Farmers experience losses in rice yields and agricultural inputs every year. Seasonal change and extreme weather events often prevent farmers from optimal scheduling of agricultural operations. Early-onset of the rainy season, droughts and cold spells constrain farmers' options when it comes to shifting crops, selecting seeds, determining sowing time and choosing sowing techniques. Erratic rainfall and hot spells cause fertilizer and pesticide losses when farmers apply agricultural inputs shortly before such weather events. Hailstones, flash floods, landslides and heavy rainfall can lead to complete crop failure. On the other hand, farmers apply synthetic fertilizers and pesticides, often overusing these inputs. ACS could help farmers understand and manage weather and climate uncertainties. ACS also provides advice on crop type. For example, if the seasonal forecast shows a high chance of drought, farmers are advised to shift from rice to drought-tolerant crops. ACS can also cover seasonal and weekly forecasts and provide climate-sensitive advice on seed type, sowing time, sowing technique, water management, fertilizer and pesticide use and harvest.

About 30-40% of farm households keep cows and buffaloes, either in stables or free-ranging. Free-ranging livestock is often outside in the rice fields and forests, and they can freeze to death during cold spells, particularly in the upland forests. ACS can advise farmers not to send cattle outside to avoid these losses. Through ACS, farmers are also advised about stable design and protection during winter. Other advice includes recommendations about when to prepare fodder for winter, when to feed, how to ensure nutrition in winter and when and how to treat diseases.

2.3. Agro-climate services in Dien Bien and CARE in Vietnam's interventions

While the meteorological station at the provincial level releases seasonal, weekly and daily forecasts as well as early warnings, dissemination of weather forecasts to Dien Bien District has been mainly restricted to daily forecasts and early warnings. The language used in the forecasts often contains technical terms and uncertainties, which are difficult for farmers to understand. Seasonal and weekly forecasts are not tailored to local agricultural contexts or user preferences, and they are not always available for agricultural planning and practice. This hinders the translation of ACS weather and climate forecasts into actionable agricultural advice.

Since 2015, the Non-Government Organization "Cooperative for Assistance and Relief Everywhere" (CARE) in Vietnam, has provided ACS to smallholder farmers on a limited scale in two communes in Dien Bien District, Vietnam. CARE in Vietnam's projects aim "to enhance livelihoods and increase the resilience to effects of climate change and variability of poor ethnic minority women and men in rural areas". CARE facilitates interactions between weather forecasters and agricultural staff to better align service provision with information needs on the ground and to transfer ACS forecasts and advice to farmers. However, until 2019 only two of Dien Bien's 23 communes were covered by the project. The project is expected to come to an end in early 2022 and without the continuation of project support, it is quite unlikely that the services will be maintained. CARE advocates for upscaling ACS in Dien Bien, but a large-scale roll-out could potentially strain the government's financial and human resources. Decreasing the uncertainty about the potential costs and benefits may increase the government's willingness to make the investments necessary to get ACS sustained and scaled in Dien Bien. Ex-ante valuation of ACS, through the use of decision analysis approaches, can support a better understanding of the costs, benefits, uncertainties and risks involved in investments in ACS. We present such an analysis to compare four potential ACS scaling intervention options in Dien Bien. The work showcases a method for valuing climate services and supporting decision-making for highly uncertain and risk-prone investments.

3. Methods

3.1. Decision analysis for potential agro-climate services in Dien Bien District

In agricultural contexts, Luedeling et al. (2015), Lanzanova et al. (2017), Lanzanova et al. (2019) and Whitney et al. (2018) have provided practical guides and protocols for decision analysis. While there are some variations in the steps (e.g. the number of steps) described in these method guides, they describe a similar process.

The decision analysis procedure typically starts with understanding the decision context and the relevant stakeholders involved in the decision. A decision is understood as a situation where decision-makers have to choose between at least two alternative decision options (Luedeling and Shepherd, 2016). Representatives of stakeholder groups are selected as experts who participate in the decision analysis (Luedeling et al., 2015). Once the decision and the experts have been identified, decision analysis provides tools to support the development of a conceptual model outlining all the possible impacts of a decision. This conceptual framework is expected to include all important model variables, without concerns about data measurement constraints (Lanzanova et al., 2019, 2017; Whitney et al., 2018). Once the conceptual framework is available, it is converted into a mathematical model. Instead of attempting to precisely quantify all variables, which is often impossible, the decision analysis approach aims to capture the current state of knowledge on all model variables using secondary literature and expert knowledge (Lanzanova et al., 2019; Whitney et al., 2018). To improve the experts' ability to express their state of uncertainty, they are subjected to calibration training. This training supports experts in gaining awareness of their potential biases and instructs them in strategies to reduce them (Hubbard, 2014). Calibrated experts provide quantitative model inputs in the form of estimated distributions for all variables. Based on these inputs, expected decision outcomes are computed by using the mathematical model to run probabilistic simulations (Lanzanova et al., 2019). If the expected decision outcomes clearly differ between available decision options, it is often possible to directly recommend a specific decision option with the current state of knowledge. If the decision outcomes are unclear, sensitivity analysis can help to reveal the input variables that are the most important predictors of the variance in simulated outcomes (Luedeling and Gassner, 2012). In case the decision outcomes remain unclear, the Expected Value of Perfect Information (EPVI) is calculated to suggest the monetary value that a decision-maker should be willing to pay to obtain perfect information on a specific variable (Hubbard, 2014; Strong et al., 2014; Thorn et al., 2015).

Our study builds on existing decision analysis methods developed by Luedeling et al. (2015), Lanzanova et al. (2017), Lanzanova et al. (2019) and Whitney et al. (2018). In addition, we further detail the protocol in a seven-step process (Fig. 2). We explicitly add step 3 “Characterize interventions” to the protocol since we find that the decision identification should constitute a separate step, because it is critical to understanding the detailed implications of the decision. Furthermore, since we consider decision analysis as a learning process, we add step 7 “Share results, receive feedback” and acknowledge that iteration and critical reflection will help us improve the approach.

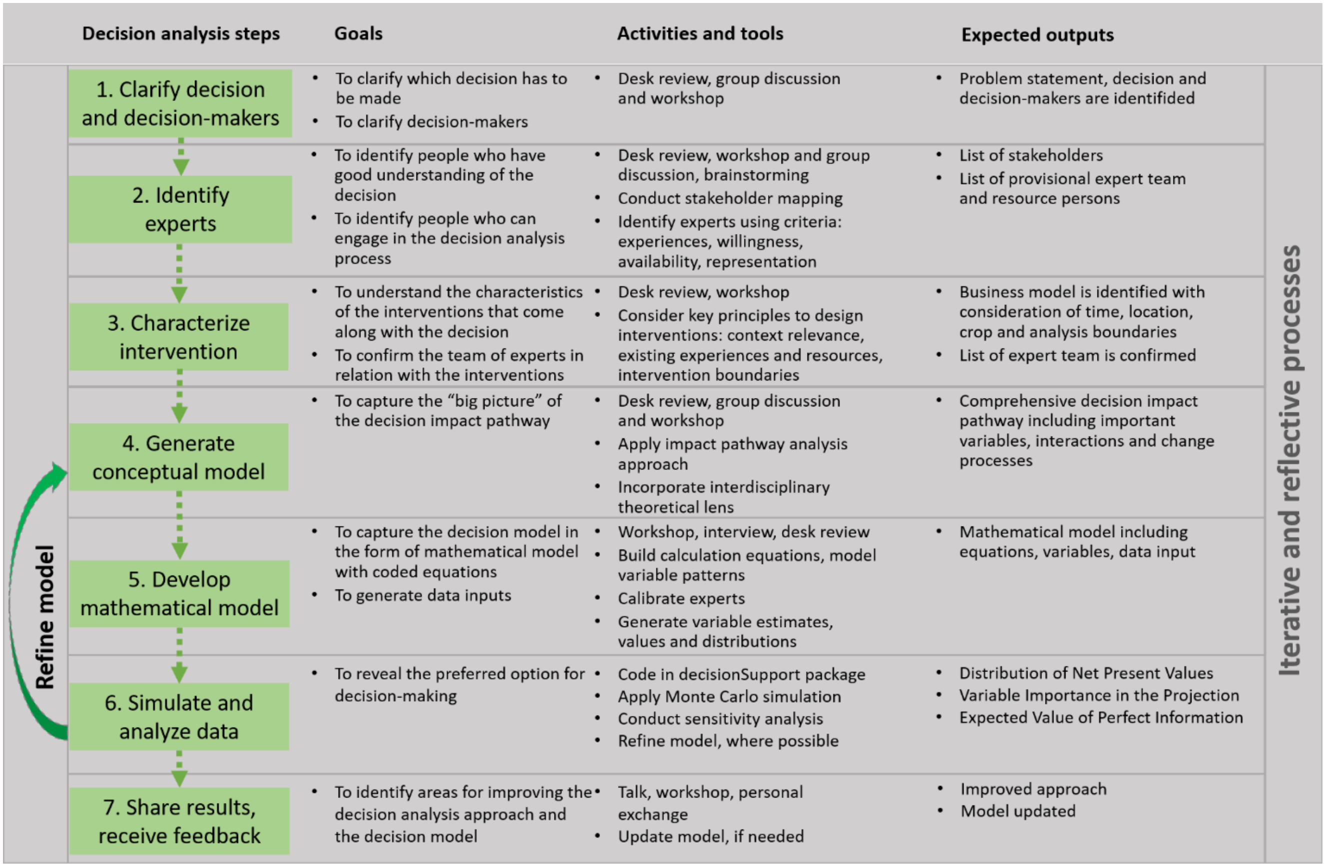

Fig. 2. The seven-step decision analysis approach applied to support Vietnam’s Dien Bien government in a potential investment decision for sustaining and scaling up agro-climatic services (ACS). Adapted from Luedeling et al. (2015), Lanzanova et al. (2017), Lanzanova et al. (2019) and Whitney et al. (2018).

Step 1: Clarify potential decisions and decision-makers

We started the decision analysis process by gathering a general understanding of the problem

related to sustaining and scaling ACS through desk review and discussion with CARE staff. Subsequently, we conducted one inception workshop with 20 participants, recruited from the management board and technical staff of the CARE project, to define the decision problem and decision-makers involved in the process of upscaling ACS. The management board consisted of senior provincial and district government decision-makers and the managers from CARE in Vietnam and the Dien Bien Centre of Community Development (CCD), which was CARE's local non-government organization (NGO) partner.
We also clarified if potential decision-makers would be available to participate in the decision analysis process.

Step 2: Identify experts
We reviewed CARE in Vietnam's project documents and previous studies to understand the organization of the climate service system and the potential stakeholders involved across the value chain. During the inception workshop and two subsequent group discussions in Dien Bien, we used the brainstorming technique (Yang et al., 2011) to identify potential stakeholders. We interviewed stakeholder experts (Yang et al., 2011) who had managerial experiences at the national level to recommend other potential stakeholders.

Stakeholders were identified as individuals or groups who would affect, would be affected by or would have an interest in the scaling of ACS (Bourne and Walker, 2008; Freeman, 2010). Among identified stakeholders, we selected experts to contribute to the decision assessment and model building, based on their experiences related to ACS implementation, as well as their willingness and availability to participate in the analysis process. We also considered the representation of stakeholders across the ACS value chain. We interviewed and consulted with experts, who were willing to participate in the analysis but did not have enough time to participate in workshops as resource persons.

Step 3: Characterize interventions
Agro-climate services can be scaled in various ways, and no specific option for scaling was defined in CARE's project at the time we started our study. We conducted a group discussion with 6 CARE project staff and subsequently held two half-day workshops with 14 experts to characterize and identify possible ACS scaling interventions.

Experts helped to define the business model of the proposed interventions, considering their suitability for the local contexts, including factors such as existing experiences, and local human and financial resources. The boundaries of interventions included timeframe, geographical location, crops and animals. Experts decided not to produce a separate baseline cost-benefit analysis of the current ACS in Dien Bien. Instead, we only calculated new and additional costs and benefits to identify the marginal return of the additional ACS interventions, as indicated below.

Net benefit ACS = New ACS benefit – New ACS investment costs **(1)**

in which

New ACS benefits = New climate damage avoided + New ACS associated benefits **(2)**

After characterizing interventions, the detailed descriptions of service implementation helped us to update the expert team to optimize the team's ability to evaluate the identified service.

Step 4: Generate a conceptual model

We held one focus group discussion with six CARE project staff and a participatory workshop with 13 experts. To develop an impact pathway and determine the costs and benefits of ACS, we used holistic model-building procedures to ensure that the resulting conceptual framework included all variables, interactions and details of the change process that experts and stakeholders considered important (Springer-Heinze et al., 2003; Whitney et al., 2018). We employed value chain analysis to classify costs across the value chain. We considered the triple bottom line approach to comprehensively incorporate social, economic and environmental benefits of the services (WMO, 2015).

Step 5: Develop a mathematical model

In this step, we conducted three key sub-steps to develop a mathematical model. These steps included (1) building equations to calculate costs and benefits and modeling patterns of variables, (2) expert calibration training and (3) generation of data inputs.

Step 5.1: Building equations to calculate costs and benefits

We applied collaborative procedures to build stochastic models that included all variables and interactions considered important regarding the intended outcomes of the potential ACS decision (Lanzanova et al., 2019). We converted the conceptual model into a mathematical model, which was coded using functions of the decisionSupport package in R (Luedeling et al., 2020), to calculate intermediate and final outcomes. All the formulas and scripts are provided in the supplementary files and a separate public repository (https://doi.org/10.5281/zenodo.6426967). During this conversion process, we modeled temporal patterns of variables where needed. Here we showcase an example of how we modeled the adoption pattern, which was vital in determining ACS benefits. We modeled the temporal pattern of ACS adoption according to the diffusion of innovations curve by Rogers (2003) and the Bass model (Bass's Basement Research Institute, 2008). We adapted the prediction of dynamic quantitative innovation adoption over time to the context of ACS. Whereas Bass et al. (2008) originally predicted the adoption of a product that was purchased once, we considered ACS as a free product that was repeatedly produced and used.

Overall, experts expected a relatively high adoption rate in the first scaling phase spurred by mass media, local events and information from change agents. For the second scaling phase, experts predicted more farmers to adopt ACS due to interpersonal communication. There are chances of dis-adoption annually when forecasts are inaccurate or when farmers fail to use ACS effectively. In the third phase, after the majority of farmers have accessed, tried and verified ACS and exchanged feedback with peers, most farmers should have developed an opinion regarding the usefulness of ACS for their agricultural operations. The adoption rate is therefore projected to remain stable, as it reaches the saturation phase. However, not all interventions may reach the saturation phase within five years. Even when an intervention reaches the saturation phase, the adoption of ACS among farmers may fail to reach 100%.

We model the annual adoption rate of an innovation i as a two-step procedure.
The adoption rate in year 1 is denoted as $r_{i(1)}$. For all subsequent years t, the adoption rate $r_{i(t)}$ is then iteratively defined as

$$r_{i(t)} = r_{i(t-1)} + r_{ip} * r_{i(t-1)} - r_{id} * r_{i(t-1)} \quad \textbf{(3)}$$

with r_{ip} being the annual adoption rate due to the interpersonal effect of the intervention i and r_{id} the annual dis-adoption rate of intervention i.
Once the cumulative adoption rate reaches the saturated rate r_{is}, it is assumed to remain at this value.

Step 5.2: Expert calibration training
Experts can play a crucial role in generating knowledge in a data-sparse and uncertain environment (Shepherd et al., 2015). Nonetheless, generating expert knowledge requires consideration of human heuristics and cognitive biases. The intuitive system in the human brain struggles to use statistics when making judgments. People tend to use simple strategies to find solutions to complex problems (Kahneman, 2011; Tversky and Kahneman, 1974). Individuals, including experts, are commonly influenced by their biases when estimating their level of knowledge, especially in quantitative terms (Hubbard, 2014; Kahneman, 2011). For example, experts tend to be overconfident in expressing their knowledge. Their estimates can be anchored by recently observed numbers or influenced by a vocal person (Hubbard, 2014; Luedeling and Shepherd, 2016). As people are not naturally well-calibrated, methods have been developed to support people in stating their uncertainties. Calibration training is a useful technique for supporting experts in de-biasing themselves before generating estimates (Hubbard, 2014).

We used sets of trivia questions to calibrate core experts, aiming for them to accurately state 90% confidence intervals that reflected their state of knowledge. Between and during consecutive rounds of quizzes, experts were introduced to techniques to enhance estimation skills, such as the equivalent bet (Hubbard, 2014), Klein's premortem (Klein, 2007), exclusion of impossible values, asking countering questions (e.g. ask if the opposite answers could be true) and reflection about cognitive biases that can affect estimates. We introduced these key concepts of biases and calibration to all our resource persons.

Step 5.3: Generation of data inputs
After the calibration training, we asked experts to provide their subjective 90% confidence intervals by specifying lower and upper bounds for the input variables of the model. For example, experts were 90% confident that the adoption rate for seed advice in the first year of the intervention Weather station-SMS-Gender would be in the range between 20% and 30%. All experts were also asked to identify the expected probability distribution shapes (i.e. normal, positive normal, uniform) of input variables. Before finalizing the estimates we verified and updated all the data we received from experts by reviewing the literature and secondary data sources and talking with further resource persons where applicable. All input variable descriptions, data values and distributions are available in the supplementary materials and in a separate repository at

https://doi.org/10.5281/zenodo.6426967.

Step 6: Simulate and analyze data

This step aims to convert probabilistic inputs into probabilistic outcomes. To generate probabilistic inputs, we applied Monte Carlo simulation to create large numbers of random data draws (10,000 model runs) (Hubbard, 2014; Lanzanova et al., 2019). In each model run, one possible value for every input variable was fed into the model's mathematical functions (in Step 5) to generate one possible Net Present Value (NPV). Results of all 10,000 model runs represented the plausible outcomes of the decision (Lanzanova et al., 2019), illustrated as the probabilistic distribution of NPVs given the current state of uncertainty. In many cases, the combined outcomes of all model runs help to inform a rational decision even under uncertain conditions. In other cases, the overall outcomes do not provide sufficient information for decision-making due to high uncertainty. In such cases, strategies for collecting additional information can be derived by running a Projection to Latent Structures (PLS) analysis between input and outcome variables and evaluating the results using the Variable Importance in the Projection (VIP) metric (Lanzanova et al., 2017; Luedeling et al., 2015).

The regression coefficient of the PLS model reveals the magnitude and direction of the effect of each input variable (Luedeling and Gassner, 2012). The VIP score shows the significance of a variable in predicting variation in the response variable (Akarachantachote et al., 2014; Wold et al., 2001), meaning the NPV in our study. The value of the VIP score is always greater or equal to 0. VIP score cut-off thresholds, which are used to determine which predictor variables are relevant, vary across studies that have used this metric (Akarachantachote et al., 2014; Chong and Jun, 2005; Cocchi et al., 2018). For our study, we applied the commonly used cut-off threshold of VIP=1 (1 is the average of squared VIP values) (Cocchi et al., 2018). A VIP score greater than 1 implies an important contribution of the predictor variable in explaining variance in the response variable (Akarachantachote et al., 2014; Cocchi et al., 2018).

We also applied the Expected Value of Perfect Information (EVPI), which further supports decision-making by quantifying the amount of money a decision-maker should be willing to pay for perfect information on specific variables (Hubbard, 2014). The EVPI is the difference between the monetary value of the optimal decision, i.e. the decision that would be made by a decision-maker with perfect information on a particular input variable, minus the expected value of the decision given the current state of knowledge on that variable (Lanzanova et al., 2017). Thus, the EVPI value of an input variable shows the sensitivity of a decision to uncertainty about that input variable (Strong et al., 2014; Thorn et al., 2015). In that way, EVPI can help to identify which variables should be prioritized to gain more knowledge (Lanzanova et al., 2019) and the highest price that decision-makers should be willing to pay to obtain perfect information (Hubbard, 2014). The model can be refined by collecting more information on high-EVPI variables.

Step 7: Share results and receive feedback

The results were shared with stakeholders for consultation, where this was possible. We also decided if we needed to revisit the model based on feedback.

The seven steps of the decision analysis were reflective and iterative, including revisiting earlier steps when changes or further information were needed.

4. Results

4.1. Decision context and expert identification

Initially, we identified the potential decision-maker as the Dien Bien Government. Due to the time limitations of the top-level governmental decision-makers, we decided to work with CARE in Vietnam, CCD, and the technical staff/mid-level managers of the local government. Together with stakeholders, we identified the following decision as the basis for this study "Should the Dien Bien Government invest in the implementation of ACS? If yes, which ACS interventions promise the greatest net benefits?". At this stage, we identified core experts and resource persons, including governmental technical staff/mid-level managers, NGO staff, researchers and farmers. The government expert team was comprised of staff from various departments, including crop production, hydro-meteorology, animal husbandry, agricultural extension center, planning and investment, and finance. Experts' main competencies were weather forecasting, crop production, animal husbandry, pest and disease management, planning, finance, agricultural statistics, climate change, policy, management, communication, gender and on-farm practices.

4.2. Intervention characterization

During our workshops, the expert team developed recommendations about the overall ACS scaling intervention and identified four investment options, with the potential engagement of various actors (Fig. 3). These four investment options share some common strategies but each investment option also includes some distinct activities.

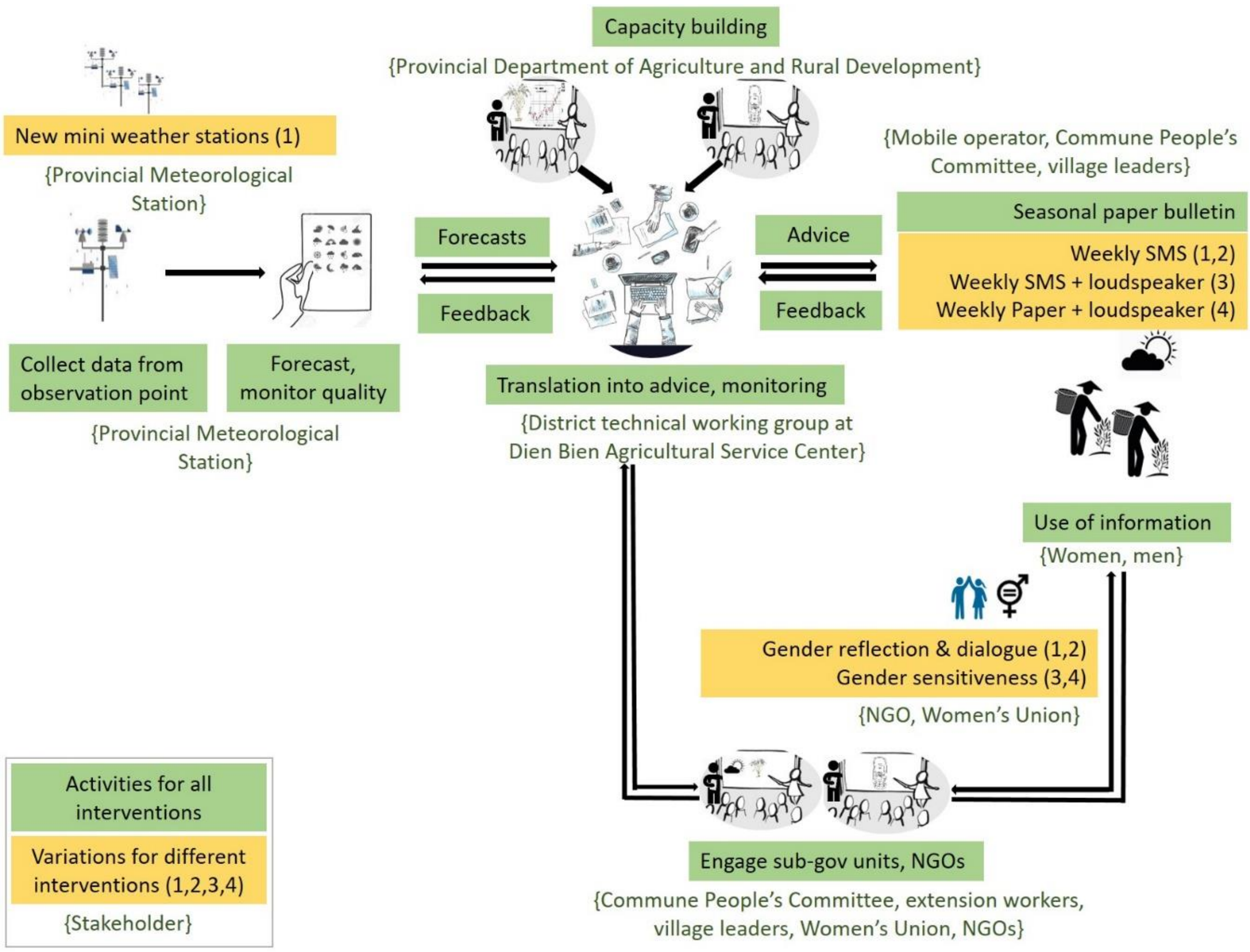

Fig. 3. Overview of four agro-climate service (ACS) interventions in Dien Bien District, Vietnam. The black arrows represent information flows. The green boxes illustrate activities implemented for all four interventions. The yellow boxes with numbers indicate activities that only apply to the corresponding interventions. Stakeholders are listed in winged parentheses.

4.2.1. Common strategies in the four investment options

For each of the four identified interventions, the Provincial Meteorological Center will collect data and use these to produce seasonal and weekly weather forecasts downscaled for Dien Bien District. This information will then be transferred to a technical working group that has been trained in generating agro-climate advice. This group will develop recommendations for a seasonal calendar, seed types, sowing techniques, fertilizer application, pest and disease control, weeding, water management and harvesting. In most cases, the advice will be based on weather forecasts, but it may also be based purely on agronomic considerations. The advice will be presented in seasonal and weekly bulletins. Seasonal bulletins will be printed and delivered to communes and villages in paper format. Weekly bulletins will be communicated to farmers in several ways, using combinations of SMS or paper messages and loudspeakers. Engagement of local organizations (e.g. sub-government units, NGOs and unions) will also be part of the strategy to ensure understanding and smooth delivery of services at the last mile. Farmers can channel feedback on the service to the technical working group, either directly or through local organizations.

4.2.2. Distinct activities across the four investment options

In addition to common strategies, we distinguish between four investment options based on their variation from the common interventions. We name the investment options according to these distinct characteristics.

Option 1) Weather station-SMS-Gender: New weather stations will be set up in different micro-climate zones in addition to the use of existing weather forecasts. Weekly bulletins will be transferred by SMS to mobile operators and then sent to village leaders. Village leaders then pass the information on to farmers via phone SMS.

This investment option addresses several gender aspects in agriculture among Dien Bien farmers, including unequal access to weather and agriculture information, labor division in farming and household chores, and domestic power relations in livelihood decision-making and in controlling income. Gender training will be organized for key facilitators, who then facilitate a series of gender activities following the social analysis and action approach (CARE International, 2018) and the gender action learning system (Oxfam in Vietnam, 2017) with female and male farmers. The social analysis and action approach aims to transform gender norms through individual reflection about and challenging of social beliefs (CARE International, 2018). The gender action learning system promotes gender equality and economic development for smallholder farmers (Oxfam in Vietnam, 2017). These gender approaches offer tools to support women and men in recognizing their own social and gender norms, the root causes of norms and the relation between norms and inequality in families and societies. For example, women and men can reflect separately on gender role differences in accessing agro-climate information and making decisions on livelihood practices and why there are such differences. While women are perceived as suffering more from social and gender norms than men, these approaches also aim to reveal norms that exist for male farmers. Labor division clocks and simulated decision-making situations (related to livelihood and income control) are used to facilitate dialogue between men and women about their norms and the implications of gender inequality. Women and men will also identify what changes they intend to implement in their families. They will be encouraged to share their change stories with other villagers during community events (e.g. through plays, games or sports activities) to create spill-over effects and strengthen a socially enabling environment.

Option 2) SMS-Gender: Weekly bulletins will be transferred by SMS to mobile operators and then sent to village leaders. Village leaders then send information to farmers via phone. Gender norm realization and norm change dialogues and actions will be integrated into the intervention in the same way as in Weather station-SMS-Gender.

Option 3) SMS-Loudspeaker: Weekly bulletins will be transferred by SMS to mobile operators and then sent to village leaders. Village leaders will broadcast the information in their villages using loudspeakers. Local languages will be used wherever possible. Gender balance will be considered by encouraging both women and men to participate in any activity related to ACS implementation.

Option 4) Paper-Loudspeaker: Weekly bulletins will be transferred to communes by email. Village leaders will go to the Commune People's Committee to receive the weekly bulletins as official paper correspondence. Village leaders then broadcast the information in their villages using loudspeakers. Local languages will be used wherever possible. Gender balance will be considered by encouraging both women and men to participate in any activity related to ACS implementation.

4.2.3. Intervention boundaries and analyses

In addition to identifying the overall implementation strategy, the expert team defined the boundaries of investment options and analyses. Intervention advice will focus on rice cultivation and cow and buffalo husbandry, which are the key crop and livestock activities in the District that are sensitive to weather and climate. Our cost-benefit analyses cover a five-year time frame, which corresponds to the regular planning period in the District. The analyses focus on direct and indirect impacts for benefiting households in Dien Bien.

Dien Bien Agricultural Service Centre is proposed as the key project holder given that they have the technical capacity and their works cover agricultural and aquacultural extension services, plant protection and veterinary services. Key risks that the interventions aim to respond to are inter- and intra-annual rainfall and temperature variation, droughts, mild floods and cold spells. Risks that are normally beyond their capacity to respond are hailstones and flash floods. The interventions consider that services will be scaled up across Dien Bien District. Government regulations on the operation of the climate services, as well as the roles and tasks of each stakeholder, will be in place. We confirmed the expert team, including 13 core experts and 12 resource persons after defining the detailed interventions.

4.3. Conceptual model for cost-benefit analysis

Our conceptual framework includes important potential costs, benefits and risks, as well as the discount rate, which is used to express the time preference of investors (Fig. 4). We identified five types of costs along the value chain from forecast generation to putting information to use, as well as for cross-cutting activities, monitoring and evaluation. For benefits, we captured the intermediary benefits and the ultimate economic, environmental, and social benefits at the household level.

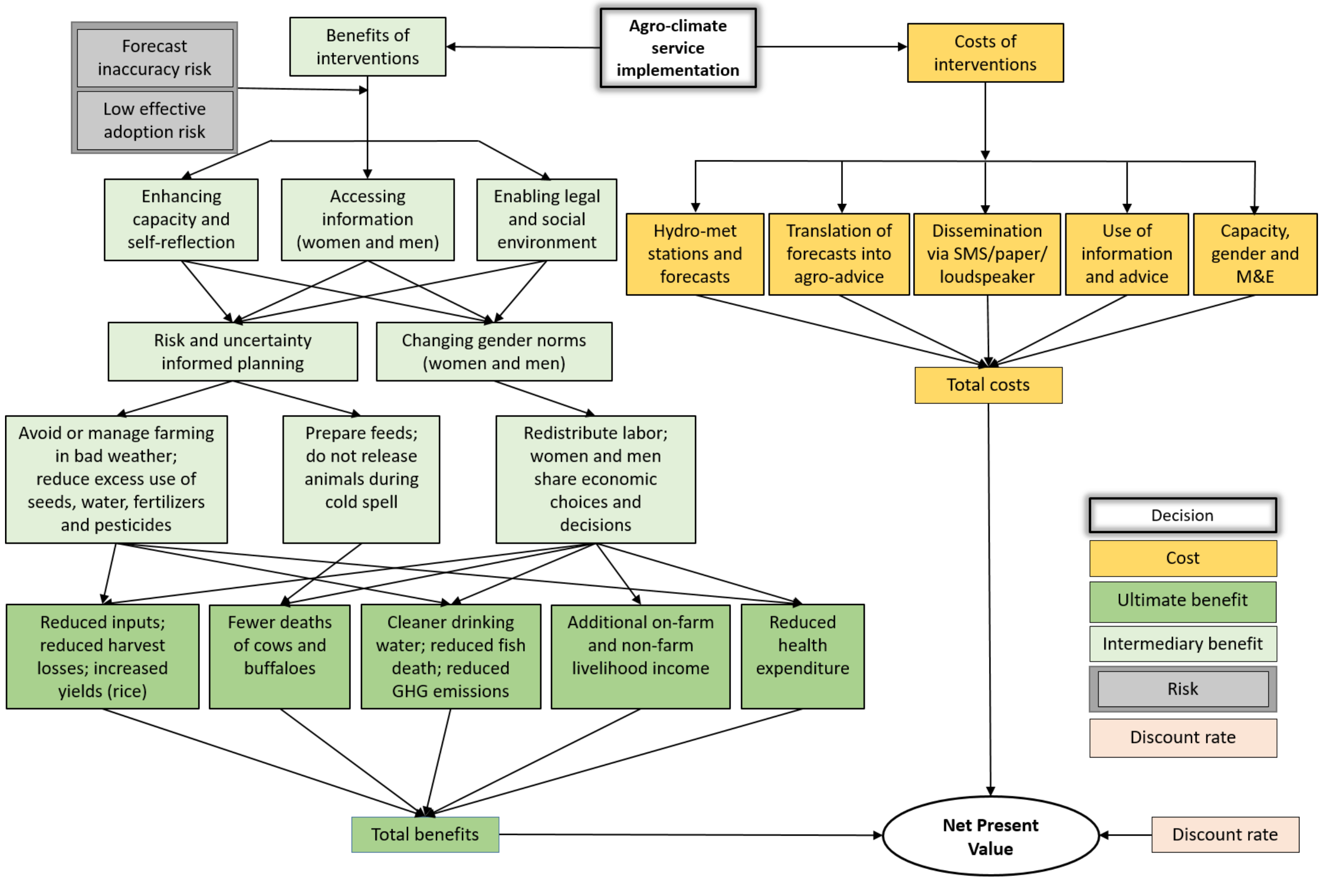

Fig. 4. Conceptual framework for cost-benefit analysis of agro-climate services.

Many of the ultimate benefits result from reductions in agricultural input use, for which there is high potential in Dien Bien due to the current overuse and misuse of seeds, fertilizers and pesticides by farmers. The interventions are also predicted to improve potential yield and reduce harvest losses caused by changing weather and climate conditions.

Advice to protect cows and buffaloes during cold spells is expected to reduce animal deaths in winter. The predicted pesticide use reduction will contribute to lower surface water pollution and consequently to lower fish mortality rates. Reduced application of fertilizer and pesticides has positive impacts on water pollution, leading to cleaner drinking water and improving farmers' health. Reduction in nitrogen fertilization will result in reduced emissions of nitrous oxide (N_2O). However, methane (CH_4) emissions might increase if farmers are advised to use more agricultural residues. The redistribution of housework labor (where needed and possible) coupled with respected, shared economic choice and decision-making between women and men will incentivize households to diversify their income, including additional small farming and non-farm activities.

Key risks identified in the four interventions concern the inaccuracy of weather forecasts and the low effective adoption rate among farmers.
All the costs, ultimate benefits, risks and the consideration of discount rate served as the key components to support quantifying the NPVs of all the potential investment options.

4.4. Converting the conceptual model to a mathematical model

We identified 142 variables to calculate costs, benefits, risks, uncertainties and discount rate (see supplementary data input file). We incorporated all 142 variables with data estimates and fed them into the mathematical model's equations to calculate the outcomes of different interventions (see supplementary mathematical model file).

4.5. Profitability of agro-climate services

4.5.1. Net present value and benefit-cost ratio of agro-climate services

In all of the cost-benefit model runs for the four investment decision scenarios, the results show small chances of loss ranging from 0.19% to 1.65%. Based on a 90% confidence interval (CI), the NPVs (Fig. 5a) range from 0.90 to 4.46 million USD for Weather station-SMS-Gender, from 0.45 to 3.52 million USD for SMS-Gender, from 0.95 to 4.90 million USD for SMS-Loudspeaker and from 0.23 to 2.66 million USD for Paper-Loudspeaker. The optimal choices are to go ahead with any of the interventions.

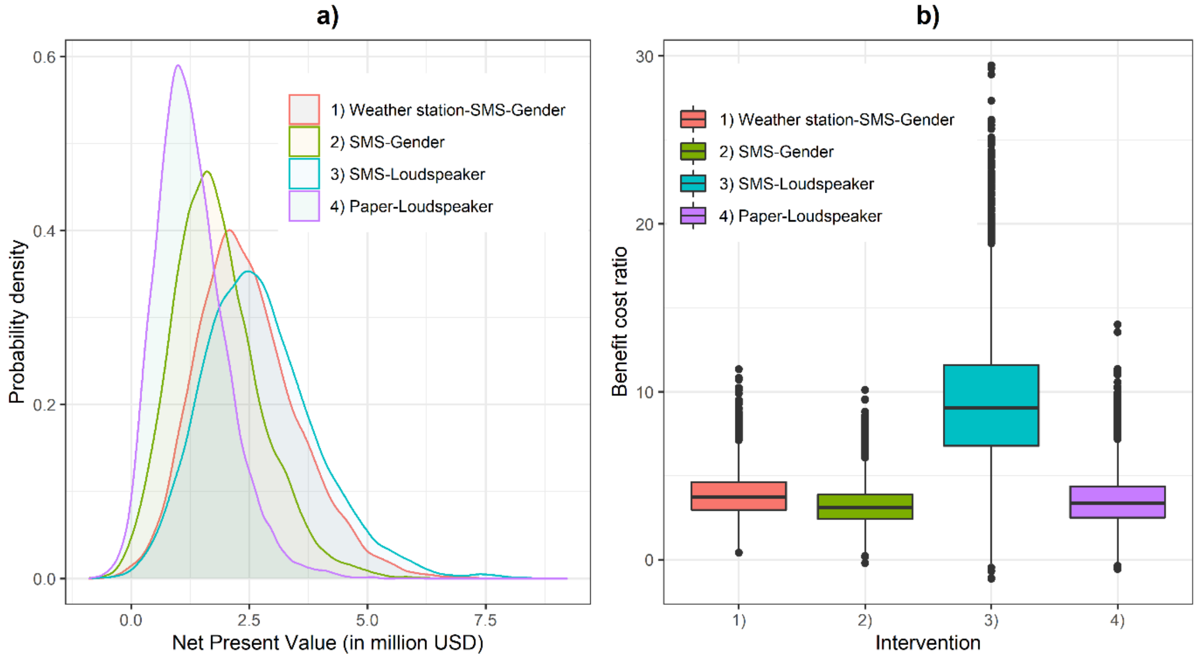

Fig. 5. Net Present Value (a) and benefit-cost ratio (b) of four agro-climate service (ACS) interventions in Dien Bien District, Vietnam. Results were obtained through Monte Carlo simulation with 10,000 runs for each investment scenario.

The benefit-cost ratio (BCR) is the ratio of discounted benefits divided by discounted investment costs. In simple terms, this metric shows how many dollars a project may gain or lose if implementers invest one dollar over a certain period. With 90% confidence, per 1 USD invested over five years, ACS can accrue gains of 2.03-6.17 USD for Weather station-SMS-Gender, 1.55-5.32 USD for SMS-Gender, 3.98-16.02 USD for SMS-Loudspeaker and 1.45-6.22 USD for Paper-Loudspeaker (Fig. 5b).

4.5.2. Importance of uncertain variables and value of information

4.5.2.1. Importance of uncertain variables

Variables with VIP values greater than 1 are considered important (Fig. 6). In all interventions, four similarly important variables are negatively correlated with the NPV. These variables include doses of urea, potassium and seed used by farmers after receiving advice and the discount rate.
For the interventions Weather station-SMS-Gender, SMS-Loudspeaker and Paper-Loudspeaker, VIP scores indicated that rice area lost by severe risks (i.e. complete rice cultivation/harvest failure caused by severe risks such as flash floods, hailstone) was an important variable that was negatively correlated with NPV. For the intervention Paper-Loudspeaker, the dis-adoption rate appears as another important variable, correlated negatively with the NPV.

VIP score analysis revealed ten variables as important and as positively correlated with the NPV for Weather station-SMS-Gender. Similarly, the VIP score indicated twelve variables as important and as positively correlated with the NPV for SMS-Gender. These important variables were related to health expenditure reduction, pollution reduction, rate of farmers applying advice effectively among all adopters, baseline agricultural input use, rate of early fertilizer and pesticide advice adopters, reduction in the frequency of spraying pesticides (i.e. number of applications per year), coverage of gender activity and economic returns of improved gender equality.

VIP score analysis revealed nine important variables that were positively correlated with the NPVs, for both SMS-Loudspeaker and Paper-Loudspeaker. These important variables were related to health expenditure reduction, pollution reduction, baseline agricultural input use, reduction in the frequency of spraying pesticides, rate of farmers applying advice effectively and the rate of early fertilizer and pesticide advice adopters.

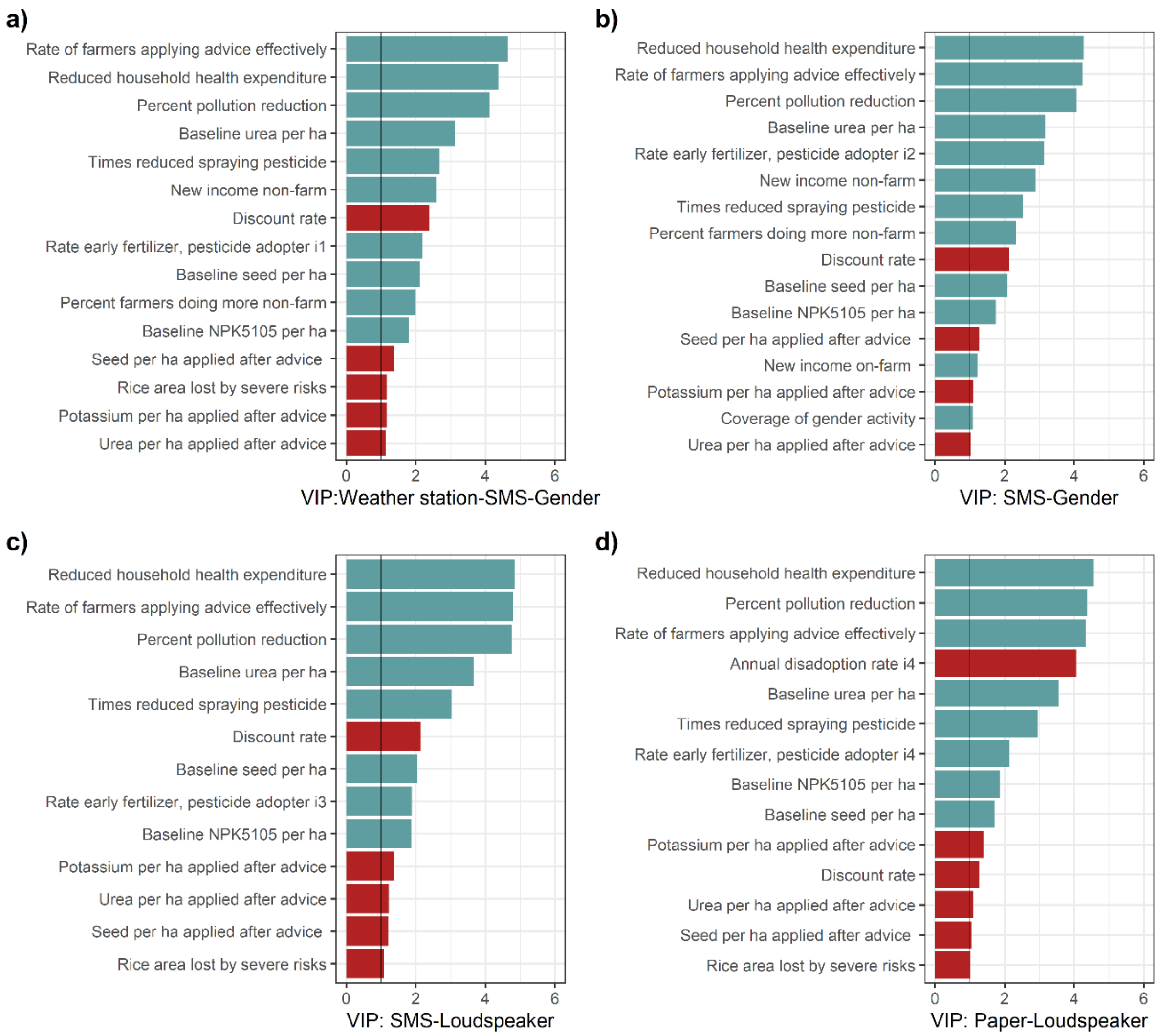

Fig. 6. Variable importance of a Partial Least Squares (PLS) regression model relating uncertain inputs to decision models for four agro-climate service (ACS) interventions in Dien Bien District, Vietnam. The vertical line shows the VIP score threshold at 1, which is used to define if a variable is important or not. Red bars for the VIP score imply a negative correlation with the NPV, while the green color indicates a positive correlation.

4.5.2.2. Value of information

The EVPI assessment returned 0 for all variables in all investment options. These zero values suggest that, despite the uncertainty about ACS benefits, decision-makers do not need to collect additional evidence to determine whether investments in ACS interventions produce net benefits.

4.5.3. Annual costs and investment feasibility

The results show that the annual investment might have implications for annual budget planning in a resource-limited environment. With 90% confidence, the initial cost for the first year will range from 450 to 510 thousand USD (kUSD) for Weather station-SMS-Gender, from 410 to 470 kUSD for SMS-Gender, from 170 to 190 kUSD for SMS-Loudspeaker and from 210 to 240 kUSD for Paper-

Loudspeaker. Costs in the following four years will be significantly lower (Fig. 7).

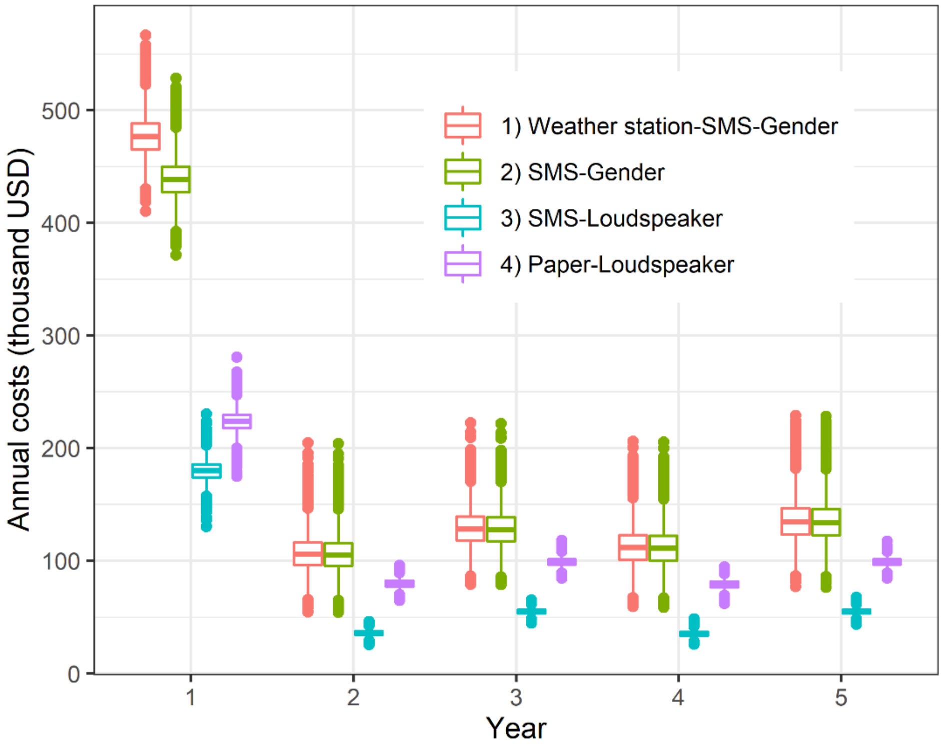

Fig. 7. Simulated annual costs (thousand USD) needed to implement four agro-climate service (ACS) interventions in Dien Bien, Vietnam over five years. Results were obtained through Monte Carlo simulation using 10,000 model runs for each investment scenario.

5. Discussion

5.1. Profitability and investment feasibility of ACS

The NPV results indicate that investing in scaling ACS is a good choice for generating socio-economic and environmental benefits. The government can choose among identified interventions to allocate funding based on realistic financial capacity. The outcomes support the current effort by CARE to promote ACS scaling in Dien Bien District (CARE in Vietnam, 2020). If Dien Bien makes ACS a priority, they will be joining an international trend. Climate services are a top priority for agriculture and food security in the submitted Nationally Determined Contributions of 100 countries (WMO, 2019b). However, the ranges of values in the NPV results of the model indicate considerable uncertainty about the benefits that different interventions may produce. This uncertainty has been highlighted in previous studies (Clements et al., 2013; Nicholles et al., 2012; Perrels, 2020).

The uncertainty of NPVs also implies that the replication of the interventions described in this study to other contexts beyond Dien Bien District needs to consider differences in local contexts. Nonetheless, the principles in designing ACS interventions, the conceptual framework and the mathematical model could be useful references to be adapted in other ACS scaling investment decisions.

Outcome distributions showed almost complete overlap in NPVs for Weather station-SMS-Gender and SMS-Loudspeaker (Fig. 5). These distributions also showed considerable overlap with SMS-Gender. The predicted outcomes for Paper-Loudspeaker identified this measure as likely to produce the least benefits among all interventions. Using paper correspondence to transfer information from commune to village may delay information transmission as well as increase transaction costs, both of which reduce net benefits. This finding highlights the importance of removing communication barriers not just in communications to farmers but also to intermediary actors of the ACS value chain.

For the benefit-cost ratio analysis, our results appear to agree with results from a global review of climate service case studies, which found BCR generally ranging between 1 and 10 dollars gained for each dollar invested. In some other case studies, BCR estimates have even exceeded 10 dollars per dollar invested (WMO, 2015).

First-year investment costs differed greatly across the four interventions. The low initial costs for the SMS-Loudspeaker and Paper-Loudspeaker interventions reflect the advantages of using the existing loudspeaker communication systems. The comparably higher initial investment costs of Weather station-SMS-Gender and SMS-Gender are due to the high costs of the first investments in establishing mini weather stations (Weather station-SMS-Gender) and organizing gender norm reflection and gender dialogue sessions (Weather station-SMS-Gender and SMS-Gender).

In Vietnam, funding for socio-economic development at the district level is provided by the provincial government. In a resource-constrained province, such as the one where Dien Bien District is located, the provincial government might rely on funding from the national budget (National Assembly, 2015; Vu, 2008). In case there are budget restrictions from the national government, SMS-Loudspeaker might be the most preferable and affordable option among the four interventions.

For all interventions, annual costs could be predicted with relatively high certainty. This indicates that the large variation in NPV outcomes mainly derives from uncertainty about the benefits of ACS. This result agrees with findings from Perrels (2020), who noted that uncertainty about benefits is normally higher than uncertainty about costs in valuing climate services.

5.2. Important uncertain variables and value of information

Through variable importance assessments, we were able to identify a number of important variables that introduced uncertainty about the overall decision outcomes. Across all interventions, important variables were related to pollution reduction, health expenditure reduction, agricultural input use, rate of farmers applying advice effectively, rate of early fertilizer and pesticide advice adopters, and discount rate.

Limited knowledge about the proper application of fertilizers and pesticides and the planting of seeds is a common challenge among smallholder farmers (Abhijit and Duflo, 2012; Lamers et al., 2013; Xu et al., 2008). The impact of excessive use of fertilizers and pesticides is not only detrimental to the farm economy but also to the wider environment. Misuse of pesticides can incur health costs for the treatment of headaches, dermatological irritation or even chronic diseases like cancer (Lamers et al., 2013; Nguyen et al., 2018). ACS not only provides regular advice on the use of agricultural inputs under changing weather conditions but also general advice on the use of agricultural inputs. The benefits of ACS, therefore, are largely dependent on the extent to which ACS can reduce agricultural input use, environmental pollution and health expenditure.

Among farmers who access, understand and adopt advice, only a certain group might effectively use and adapt the advice to their specific context (Sen et al., 2021). Studies by Nurmi (2013) and Pilli (2014) point out the gap between using information and using it effectively as part of an information filtering or decay process. Farmers who effectively implement advice will apply fertilizer and pesticides using the combined right time/weather, right type, right rate and right place principles. However, given various uncertainties such as weather accuracy, timely communications, comprehension of users or availability of agricultural input in the local market, the estimation of the effective adoption rate is uncertain.

The rate of early fertilizer and pesticide advice adopters was also identified as an important variable. Early adopters are considered to be farmers who apply the advice in the first two rice seasons. In the early stage of innovation adoption, mass media or community events play an important role in stimulating the early adoption of an innovation. At later stages, the early adopter will play a role in sharing information about the innovation (Everett, 2003). As ACS interventions will be new in 21 communes in Dien Bien District, it is still unclear to what extent farmers will accept it at the early stage.

In our models, the discount rate had an important impact on the NPV in all simulated interventions. This result echoes a similar finding reported by Nicholles et al. (2012). The choice of a value for the discount rate is often a topic of debate in studies about climate change and climate services (Polasky and Dampha, 2021; WMO, 2015). Some economists argue for a zero discount rate or a very low nominal discount rate to value the impacts of a project on the next generation (e.g. climate protection) (Stern, 2007; Weitzman, 1998; WMO, 2015). Others favor a higher discount rate that reflects the real market or the present-day benefit preference (Mendelsohn, 2006; Nordhaus, 2007; WMO, 2015). In Vietnam, the common practice is to refer to the interest rate of a bank. In our study, we took advantage of the probabilistic approach and included a discount rate ranging from 4 to 15%, reflecting a 90% confidence interval of our uncertainty.

In Weather station-SMS-Gender and SMS-Gender, important variables identified were new income from non-farm activities and the percentage of farmers who do more non-farm work. The coverage of gender activities (i.e. the interventions only reach certain groups within the communities) and new income from on-farm activities were also important variables in SMS-Gender. Due to the improved division of labor, information access and decision-making expected under these interventions, families can adopt new livelihood activities such as raising more chickens, planting more vegetables, working as seasonal laborers or running agricultural micro-businesses to diversify their income. Our results partly agree with the findings by Anderson et al. (2021), who suggested that women's empowerment may lead to increased household agricultural productivity and economic returns. However, we find that the economic return does not only derive from the empowerment of women but from improved equality for both women and men. Despite the potential economic returns, benefits from improved and diversified economic activities are uncertain due to the volatile availability of non-farm activities as well as farmers' limited ability to take advantage of economic opportunities.

Due to the uncertainty around the likelihood of severe risks like flash floods and hailstones, rice area lost was an important variable in Weather station-SMS-Gender, SMS-Loudspeaker and Paper-Loudspeaker interventions. This result signifies that there may be residual losses that are beyond the scope of ACS to address (Ambani and Percy, 2014).

Another important variable for the Paper-Loudspeaker intervention was the dis-adoption rate. This finding can be explained by the potential delay in advice transfers caused by uncertain transmission via paper correspondence from commune to village leaders, which may lead farmers to dis-adopt the services.

5.3. Use of decision analysis in planning agro-climate services and development

The use of decision analysis in the context of ACS confirmed distinct advantages of this research approach that have been highlighted in other studies. These benefits include bias reduction as well as enabling credible ex-ante assessment of interventions in a data-scarce, complex, highly uncertain and risk-prone environment (Do et al., 2020; Lanzanova et al., 2019; Luedeling et al., 2015; Rojas et al., 2021; Ruett et al., 2020). Involving stakeholders through a participatory approach created a platform for learning and reflection. Experts gained insights by taking a systems perspective and improving their ability to consider and integrate different sources of knowledge.

Applying decision analysis comes with challenges. Analysts may introduce their own biases in selecting stakeholders and experts, in facilitating the choice of a decision of interest and in converting conceptual diagrams to mathematical models (Luedeling and Shepherd, 2016). It is also difficult to ensure an expert's confidence level at 90% when estimating input variables (Luedeling et al., 2015; Rojas et al., 2021). Model validation is inherently difficult for any ex-ante projection methodology. This challenge, nevertheless, can at least partly be overcome in decision analysis by defining a minimum set of skills for analysts. Longitudinal monitoring and validating of selected decision analysis models can offer greater insights into the value of decision analysis, which might be critical for the long-term diffusion of the decision analysis approach.

Development planning in Vietnam allows very limited flexibility in budget planning, implementation and selecting monitoring indicators by government, donors, research institutes and NGOs. This limited flexibility is particularly acute in developing a socio-economic development plan for projects that rely on a state budget (National Assembly, 2015; Strauch et al., 2018; Vu, 2008). Though our results may reflect a realistic context, there will still be challenges in harmonizing our recommendations with government planning processes. These challenges are the key barriers to scaling ACS in Dien Bien and possibly in other locations in Vietnam.

These reflections of challenges to the decision analysis approach should be seen in the context of available resources and alternative methodological choices. Decision analysis should not be compared with resource-intensive, interdisciplinary research approaches. Admittedly, those approaches may be able to generate more precise results, but they are often infeasible due to budget or time constraints (Luedeling and Shepherd, 2016). The introduction of decision analysis in ACS valuation and development planning offers a chance to debate and reflect on the existing limitations of the deterministic approach. It may constitute a promising strategy to overcome the limitations of purely data-driven analysis approaches that have often struggled to provide convincing support to complex decisions.

6. Conclusions

We use the decision analysis approach to support realizing and valuing potential ACS scaling interventions in Dien Bien. Our results show that investing in ACS is a good option here, with multiple positive socio-economic and environmental impacts. These impacts include improved yield, reduced losses in agriculture, cleaner water, better health, reduced Greenhouse Gas (GHG) emissions, and economic returns from improved gender equality.

We also find that decision analysis offers great potential for ACS valuation. Decision analysis demonstrated its usefulness as a powerful new tool, given the current dearth of methods capable of addressing biases and uncertainties in valuing climate services. Furthermore, decision analysis can provide holistic analysis and serve as a “quick test” to understand complex issues when there are time and financial constraints, which is common in most low and middle-income countries.
The decision analysis approach, however, struggles with a structural challenge. There is a mismatch between real-life complex, uncertain challenges and the legally mandated and dominant use of deterministic approaches in development planning. This barrier, if not removed, may restrict decision analysis from unfolding its potential in this space and prevent government planners from using its results. We therefore recommend that governments, donors and other stakeholders consider adopting this probabilistic approach when engaging in complex and uncertain ACS and development planning and implementation.

Declaration of interest statement

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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Supplementary data

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Author contributions

Thi Thu Giang Luu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Visualization, Writing - original draft, Review & Editing. **Cory Whitney:** Conceptualization, Methodology, Software, Supervision, Visualization, Review & Editing. **Lisa Biber-Freudenberger:** Supervision, Review & Editing. **Eike Luedeling:** Conceptualization, Funding acquisition, Methodology, Software, Supervision, Visualization, Review & Editing.

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Chapter 4: Stakeholder engagement in agro-climate service planning

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Abstract

The severe impacts of weather, climate variability and climate change on agricultural production make actionable agro-climatic services increasingly crucial. Transitioning from supply-driven provision of climate and agricultural information to demand-driven agro-climate services (ACS) at scale cannot be accomplished in a top-down manner but requires the engagement of diverse stakeholders in all phases of ACS development and implementation. This requires methods and tools to handle the diversity and the dynamics of interactions between relevant stakeholders, in particular during the pre-financing stage of the ACS. Our study addresses this methodological gap by proposing a transparent method to identify and engage stakeholders in the ACS planning phase. We demonstrate this method as part of the socio-economic development planning process in Dien Bien, Vietnam. We find that considering stakeholder attributes such as availability, experience, gender, expertise, benefits and costs for each stakeholder, interest, influence, relevance and attitude, combined with insights about the socio-economic development planning processes, is crucial for the engagement of stakeholders. We also find that facilitating collaborative interaction between ACS stakeholders is pivotal in supporting the planning of demand-driven ACS. Our methodology for engaging stakeholders is transferrable to designing and planning other interventions in complex systems.

Keywords: decision analysis, stakeholder attributes, upscaling, complexity, uncertainty

Practical implications

Transitioning from the supply-driven provision of climate and agricultural information to demand-driven agro-climate services (ACS) is a long-term process. The early stages of such a transition often feature uncertainty, scattered knowledge, conflicting views and the challenge of establishing dialogue among relevant stakeholders. Without coordination, such an "incubation" process can take a long time.

Integrating ACS into the government's policy and financial plan during the pre-financing stage of ACS is a prerequisite for implementation. Meanwhile, methods and tools for identifying and mobilizing relevant stakeholders during the pre-financing stage are lacking. We address this methodological gap by proposing a transparent method to engage stakeholders in ACS decision-making as part of socio-economic development planning. We demonstrate a case of ACS intervention in Dien Bien Province in Vietnam. Building on our experience, we draw key lessons and recommendations to policy-makers and practitioners.

For policy-makers

- Existing regimes often feature barriers to innovations that prevent new ideas from penetrating the socio-technical-political systems. Due to path dependencies, many systems are locked into unsustainable patterns that are difficult to overcome. Developing and upscaling sustainability innovations, such as agro-climate services, need windows of opportunity (e.g. supporting policy and finance), to overcome constraints so that innovations can be tried, tested and improved.
- Previous studies have indicated that failure to engage stakeholders in ACS scaling can lead to several risks: inability to meet farmers' diverse demands, lack of timely and seamless delivery, compromised actionability of services and reduced socio-economic impacts. Often, easily accessible farmers benefit from ACS, while marginalized groups are left behind.
- Co-creation from the early stage of planning is suggested to overcome the common barriers in ACS last mile delivery. However, stakeholders are not homogenous. They may have different views and motivations for engaging in ACS. Therefore, a challenge with the co-creation approach is to handle the scattered knowledge, diversity, dynamics and conflicting views of stakeholders.
- We suggest a strategy to deal with the scattered knowledge, diversity and dynamics of stakeholders by gaining insights into the relevant stakeholder attributes (e.g. stakeholders' availability, experience, gender, expertise, interest, influence, relevance and attitude, as well as the cost and benefit profile of each stakeholder). The objective of gaining such insights is to help coordinate and enhance the engagement of relevant stakeholders in ACS knowledge generation and planning processes.
- In situations where reporting lines vary between non-government and government actors regarding climate services, valuable insights from non-government actors may go untapped. To address this, governments should integrate relevant reports and experiences from non-government actors into their specialized reporting systems, such as the agricultural sector report.

For practitioners and Non-Government Organizations (NGOs)

- Transitioning from supply-driven to user-driven climate information often involves complexities and uncertainties. Decisions related to ACS scaling often lack clarity on its best course of action or outcome. ACS scaling effort requires feedback and demand from and active participation of practitioners and NGOs during knowledge generation and from the early stage of ACS planning.

- ACS end-users are diverse (i.e. farmers with diverse farming systems, varying access to information and different languages). During socio-economic development planning, ACS end-users should be organized (i.e. into farmer groups) and coordinated (i.e. participation of diverse groups of farmers) to ensure their collective voices and representation and thus better reflect their demands for ACS in decision-making.
- Governments' oral and written reporting systems for specialized sectors are important channels for practitioners and NGOs to provide feedback and communicate essential aspects of ACS interventions.
- NGOs can be an essential catalyst in the promotion of ACS. NGOs and other local actors can play the role of knowledge brokers and support facilitating relationships among stakeholders.

1. Introduction

Agriculture is facing multiple challenges, many of which are related to weather, climate variability and climate change, and to the resulting impacts on yields, pests and agricultural input use (Hansen et al., 2022; Luu et al., 2022a; WMO, 2015). Agro-climate services (ACS) have been suggested as one way to reduce farmers' vulnerability and safeguard their farm productivity and income (Hansen et al., 2022, 2019; Hansen and Sivakumar, 2006; Leal Filho and Jacob, 2020; Machingura et al., 2018; O'Grady et al., 2020). However, ACS delivery often faces a critical gap at the last mile, and considerable effort and capital may be needed to enable widespread access to ACS for farmers from diverse social groups (Ferdinand et al., 2021).

Generating evidence on ACS scaling impacts and integrating such evidence into decision-making is crucial for justifying the investment. Previous studies have suggested that scientific evidence may have a high chance to be considered in decision-making if it fulfills certain criteria, including credibility (i.e. accuracy, plausibility and trustworthiness of information), legitimacy (i.e. "fairness" and "unbiasedness" of information and sources of information) and salience (i.e. relevant and timely information for decision-making) (Cash et al., 2003; Haigh et al., 2018; Wagner et al., 2023). However, generating ACS evidence on scaling and impacts at the last mile is characterized by high uncertainty and complexity (Hansen et al., 2019; Luu et al., 2022a; WMO, 2019). This uncertainty is due to a lack of proven scaling approaches, unreliable climate information and agricultural advice, data scarcity and biases concerning the economic, social and environmental impacts of ACS on society (Born et al., 2021; Lowry and Backus, 2021; Luu et al., 2022a; WMO, 2015). Additionally, valuing ACS impacts is complex since analysts must consider the interactions of socio-technical-economic systems to forecast the scaling benefits (Born et al., 2021; Lowry and Backus, 2021; Luu et al., 2022a; WMO, 2015). Due to these challenges, monitoring and evaluating the societal benefits of ACS are regarded as one of the weakest components across the ACS value chain (WMO, 2019).

Regarding the integration of evidence during ACS scaling, previous experiences have highlighted additional challenges. In many developing contexts, investments are made through international development aid with the expectation that local resources will sustain and scale the introduced ACS approach (Ferdinand et al., 2021; Simelton and McCampbell, 2021; WMO, 2019). However, experience in integrating pilot projects into local planning and budgeting to support upscaling is very scarce. A mismatch often exists between pilot project design and the roll-out of ACS in the real complex socio-economic scaling landscape (Woltering et al., 2019).

Challenges related to the complexities of and uncertainties about ACS delivery and ACS cost-benefit valuation provide barriers that may prevent decision-makers from investing in ACS (Luu et al., 2022a). A top-down approach is ineffective in designing and planning for actionable ACS, since it might risk mis-prioritizing resources that are already limited in developing contexts (Daniels et al., 2020; Ferdinand et al., 2021; Lemos et al., 2012). Therefore, transitioning from the provision of conventional supply-driven climate and agriculture information to demand-driven agro-climate services (ACS) requires transdisciplinary approaches that are capable of engaging stakeholders in supporting decision-making related to defining, planning and implementing ACS (Daniels et al., 2020; Hansen et al., 2019). Such an approach must explicitly focus on engaging stakeholders to address the uncertainty, complexity, biases and data scarcity involved in knowledge generation and to support the integration of this knowledge into planning decisions.

Stakeholder engagement and decision analysis can provide valuable insights into supporting decisions on complex systems. Combining these approaches into a coherent analysis framework promises to generate a powerful transdisciplinary approach to support complex decision-making.

Stakeholder analysis aims to identify and understand stakeholders' interests, goals, and influence in a given decision-making process (Reed et al., 2009; Yang et al., 2011). However, while the importance of engaging stakeholders in climate information services has been consistently acknowledged, previous studies have rarely focused on methods to identify and mobilize relevant stakeholders, in particular during the ACS pre-financing planning stage. This limitation highlights a considerable methodological gap since the dynamics of stakeholder engagement during the pre-financing stage can differ from the post-financing stage. For example, stakeholders who advocate for integrating ACS in local planning have their primary role in searching for evidence of ACS impacts and trying to convince other stakeholders. Once the finance is approved, the role of implementation stakeholders, which can be another group of stakeholders, is to implement and document the ACS impacts. Since ACS cannot enter the implementation phase without the planning and budgeting stage, we focus in this study on the important yet often disregarded stakeholder dynamics and diversity during the pre-financing stage.

Luu et al. (2022a) recently applied Decision Analysis (DA) as a methodology to engage stakeholders in designing and forecasting ACS impacts to support investment decisions on complex systems under uncertainty. DA aims to create system understanding by integrating stakeholder knowledge with system thinking (Luedeling and Shepherd, 2016). Traditional research has often focused on eliminating uncertainties of specific interactions within a system, not considering system dynamics and not evaluating alternative decision options (Shepherd et al., 2015). Such an approach can only provide a limited understanding of complex decision impacts and is restricted by the capacity to collect data for each specific system interaction. DA acknowledges that quantifying every interaction within a system is challenging and resource-intensive – and it may often be impossible. Therefore, within DA, uncertainties are acknowledged and accounted for by applying methods and tools to integrate them into the decision-making process (Luedeling and Shepherd, 2016). One of the key tools in DA to account for uncertainty is calibrating stakeholders through a process known as calibration training (Hubbard, 2014). A critical improvement of calibration training compared to other conventional stakeholder knowledge elicitation approaches is that stakeholders are trained to realize their own biases beforehand and often reduce these before their knowledge is elicited for data inputs (Hubbard, 2014).

DA is a way to engage stakeholders to generate system knowledge for supporting decision-making (Do et al., 2020; Fernandez et al., 2022; Lanzanova et al., 2019; Luedeling et al., 2015; Ruett et al., 2020). However, studies have rarely been explicit about how decision analysts select the stakeholders involved. Furthermore, it is often unclear, how, by whom, and to what degree knowledge gathered throughout the complex planning processes is integrated into decision-making.

Acknowledging the potential benefits of stakeholder engagement in decision analysis to support complex decision-making, we propose a method to (1) integrate stakeholder analysis into DA and (2) explore the roles of stakeholders in ACS planning using their specific characteristics.

2. Background of the study

ACS pilot projects and their upscaling challenges

We use the case study of CARE in Vietnam (CVN) to showcase the application of DA and the steps of stakeholder analysis. CVN is funded by external sources and has implemented several ACS projects in Dien Bien since 2015 to reduce the vulnerability of rural communities to adverse climate change impacts (Luu et al., 2022a). When we began our study in July 2019, CVN was developing a plan to sustain and upscale ACS interventions, especially after 2022, when CVN’s project was expected to end. This plan aimed to get the local government to support the upscaling processes. This was challenging, given the limited financial resources available to the provinces and the government’s traditional approach to development interventions, which includes little stakeholder involvement. Despite these challenges, the need to provide reliable information to farmers appeared obvious, and CVN needed a strategy to guide the advocacy process.

An effective advocacy strategy has to serve multiple purposes, including guidance for the upscaling process and participation of various stakeholders relevant to the decision-making process. A further goal of the strategy that CVN was developing was to support the decision-making process through a business model justifying the upscaling of ACS. In a previous study, Luu et al. (2022a) evaluated the costs and benefits of four alternative ACS investment options using a probabilistic approach. These investment options share some common interventions but are also distinct in terms of implementation, including outreach measures (via paper, SMS or loudspeaker) and consideration of gender issues in accessing and applying ACS information. Results of the study suggested a high probability of a positive net benefit for investments in ACS across all intervention options (Luu et al., 2022a).

Investment decision-making in Dien Bien, Vietnam

Decision-making on investments in climate and agriculture in Dien Bien operates within the overall administrative structure and nested budget system that is commonly used in Vietnam (**Fig. 1**). The higher administrative levels include the budget of the subordinate levels. The Central Government and People's Committees at local levels prepare respective budget plans (Asian Development Bank, 2017; World Bank, 2015). One of Vietnam's most crucial guiding policies in development is the 5-year Socio-Economic Development Plan (SEDP). The implementation of SEDP is conditional on the approval of the budget by the National Assembly and the respective People's Councils (Asian Development Bank, 2017; Strauch et al., 2018; World Bank, 2015). Therefore, any ACS scaling initiative would have to integrate the ACS plan and the respective budget into the Dien Bien Provincial SEDP, considering the complex administrative and nested budget system.

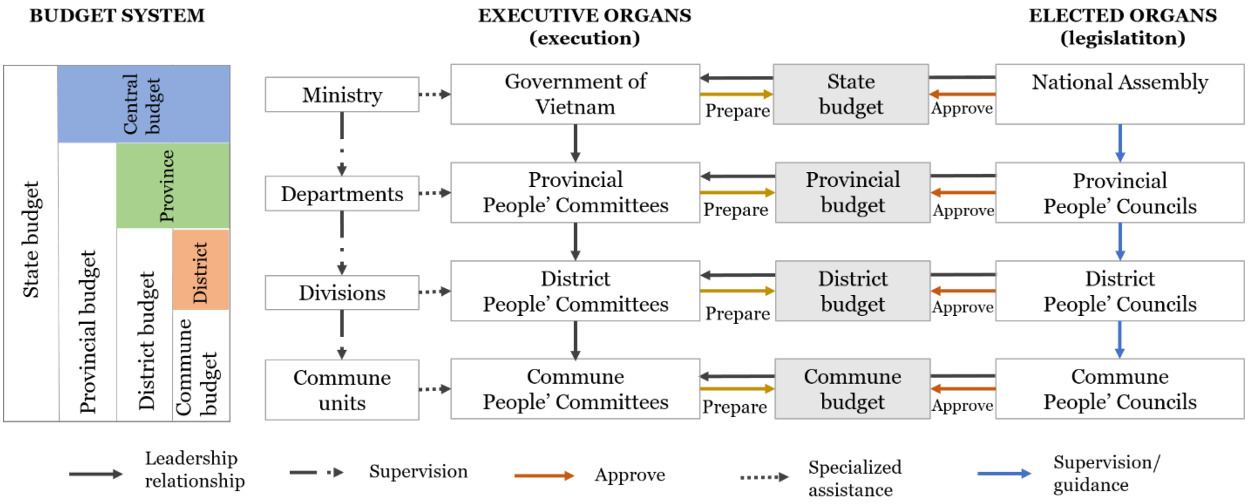

Fig. 1. Administrative structure and nested budget system in Vietnam. Adapted from Asian Development Bank (2017) and Strauch et al. (2018)

3. Methods

We integrated stakeholder identification and stakeholder analysis with decision analysis - a method combining participatory and modeling techniques to identify ACS decisions and to analyze the implications of decision outcomes (Luu et al., 2022a). We further identified potential windows of opportunity for stakeholder participation in the ACS knowledge generation and decision-making processes (**Fig. 2**).

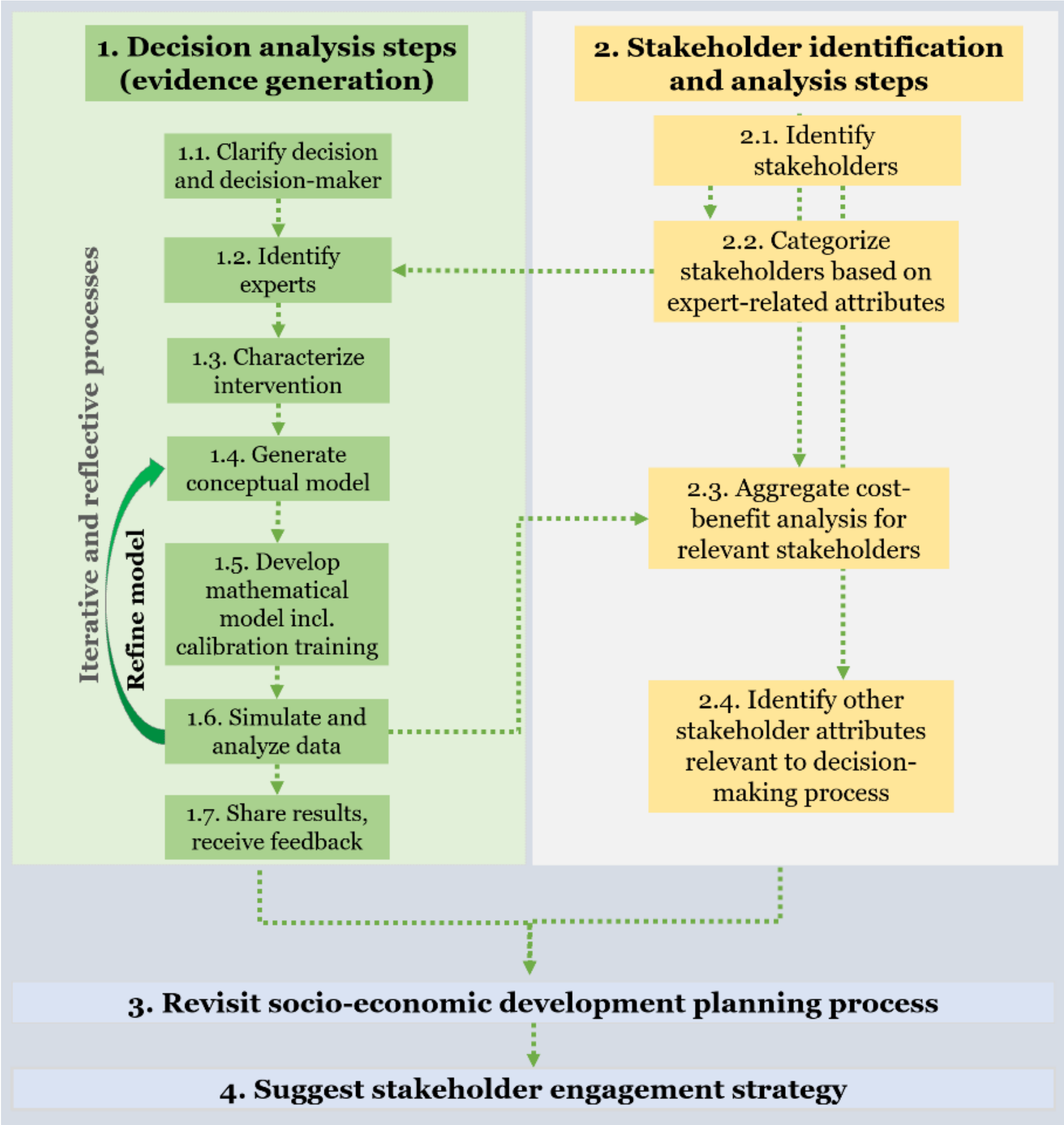

Fig. 2. Approach to engage stakeholders in agro-climate service planning. The methodological steps of decision analysis in the context of ACS are based on Luu et al. (2022a).

3.1. Stakeholder identification

Building on various definitions (Bourne and Walker, 2008; Carroll and Buchholtz, 2009; Freeman, 1984; Luu et al., 2022a; Yang et al., 2011), we define a stakeholder (step 2.1 in **Fig. 2**) as any individual or group who has an interest in a decision or who can affect or is affected by a decision.

We conducted a desk review to identify potential stakeholders for the design and implementation process of ACS projects. To this end, we reviewed several documents outlining the Vietnamese Government's organizational and decision-making structures to understand and capture the representation of different stakeholders in the process (Asian Development Bank, 2017; Strauch et al., 2018; World Bank, 2015). During this process, we also identified stakeholders across the information value chain of ACS, using CVN's project reports and other studies on ACS in Vietnam.

To validate and refine our results, we organized a focus group discussion in Vietnam with six CARE employees who were involved in the management and implementation of ACS in Dien Bien. The group participants shared their knowledge about stakeholders who are relevant to CVN's efforts to implement ACS.

Due to time and resource limitations, we could not engage all identified stakeholders. Therefore, we identified a shorter list of key stakeholders in collaboration with a technical working group that was in charge of implementing CVN's climate service project. For the selection of key stakeholders, we considered (i) the representation of stakeholders across the whole information value chain, (ii) the inclusion of stakeholders with experience in the provision and use of climate information and agricultural advice in Dien Bien, (iii) national stakeholders who already had established a partnership with CVN, (iv) the inclusion of actors who were not yet involved in a CVN project but with the potential to play a direct role in the upscaling process of ACS in Dien Bien (e.g. departments working on animal husbandry, finance and socio-economic development planning). This set of key stakeholders served as a pool for identifying experts involved in the subsequent steps of the ACS planning process.

3.2. Stakeholder categorization and analysis

Expert identification among key stakeholders

We identified experts (step 2.2 in **Fig. 2**) from the pool of key stakeholders to characterize specific scaling options and assess the impacts of these options. For this purpose, we grouped stakeholders based on their time **availability** and **experience** into core experts and resource persons. Together with CVN's technical working group, we evaluated the availability and expertise of each key stakeholder by scoring them on a scale from 0 to 5 for these traits. We characterized those with an availability score and an experience score greater than 2.5 as 'core experts' and those with availability lower than or equal to 2.5 and experience higher than 2.5 as 'resource persons'. We did not involve stakeholders with experience and availability scores below 2.5 as experts. However, they might still play a role during the planning process (see section 4.5). We considered the **gender** of stakeholders to support the constitution of a gender-balanced team of experts. Furthermore, we mapped out the **expertise** (i.e. knowledge and skills related to ACS) of stakeholders to help us identify experts with representative expertise across the value chain. We used the ggplot2 package (Wickham et al., 2022) in R (R Core Team, 2020) to visualize stakeholder attributes.

Cost-benefit profiles for relevant stakeholders

Luu et al. (2022a) used decision analysis to forecast the overall outcomes of different options to invest in agro-climate services. In this study, we argue that the benefits and costs of decisions might not be uniformly distributed across different stakeholders and that such an uneven distribution has the potential to create ambiguous incentives for stakeholders to engage in the ACS decision-making process. Therefore, in the present analysis, we explicitly analyzed the costs and benefits for each institutional stakeholder and for each decision option (step 2.3 in **Fig. 2**) and subsequently considered this specific **cost-benefit profile** as a relevant stakeholder attribute.

With the support of key experts (identified in step 2.2), we were able to assign potential costs and benefits to each stakeholder. While these were obvious for some stakeholders (e.g. rice and animal-raising farmers benefitting from the information provided), we experienced some challenges in defining costs and benefits for others. For example, for the Agricultural Service Centre and Women's Union involved in the implementation step of the intervention, we defined the benefits as the funding they receive for implementing the services. For the Provincial People's Committee (PPC), ACS implementation and upscaling would reduce their available funds, which we defined as their costs. Meanwhile, some other stakeholders, such as farmers and implementing stakeholders, will most likely benefit. To gain an overview of all the investment costs and impacts, experts weighed all funds invested by the PPC against all benefits (i.e. benefits for all other stakeholders), to calculate the nominal cost-benefit for the PPC. Furthermore, while agricultural input suppliers do not incur any direct cost for implementing ACS, the farmers' potential reduction in fertilizer and pesticide use may reduce their revenues from agricultural input sales. We therefore considered the farmers' reduced expenses for fertilizer, pesticides and seeds as the "cost" of agricultural input suppliers.

Perceived interest, influence, relevance and attitude of stakeholders

Stakeholder attributes can change over time (Reed et al., 2009); therefore we conducted three focus group discussions (FGDs) with the expert team in 2019 and three in 2020 to map out the perceived attributes of stakeholders that are relevant in ACS planning (step 2.4 in **Fig. 2**). We categorized stakeholders according to four main attributes, including interest, influence, relevance of ACS to the stakeholders' mandates, and attitudes. **Interest** implies attention to or curiosity about ACS decisions. **Influence** refers to stakeholders' relative power over a decision (Smith, 2020). Here, we relate the influence attribute to stakeholders' authoritative power and knowledge relevant to the government's ACS decision-making system. **Relevance** relates to the alignment between the stakeholders' mandates or core business objectives and their potential roles in implementing the ACS solutions. **Attitude** represents ways of thinking or feeling about the possible ACS decisions and their potential impact. Due to limited resources, we could not assess the stakeholders' "soft" power, which may manifest, for instance, where a stakeholder may not have strong authoritative power but can use personal relations to influence the decisions of other actors. Together with the expert team, we gave a score to each stakeholder with a value ranging from 0 to 5 for interest, influence and relevance and labeled the stakeholder's attitude as positive, negative or unknown (no information). We categorized stakeholders using a four-dimension matrix using the ggplot2 package (Wickham et al., 2022) in R (R Core Team, 2020).

3.3. Develop recommendations for stakeholder engagement

We conducted one meeting with the expert team in 2020 to revisit (step 3) the socio-economic development planning process (as described in section 2 on investment decision-making in Dien Bien). In this meeting, experts integrated stakeholder knowledge of ACS (outcome from step 1.1 to step 1.7), stakeholder attributes (outcome from step 2.1 to step 2.4) and insights into the ACS design and planning process to develop recommendations (step 4) on the stakeholder engagement strategy in Dien Bien's SEDP decision-making process **(Fig. 2)**.

4. Results

4.1. Stakeholder identification

We identified 35 key stakeholders based on the outlined selection criteria. We categorized these stakeholders into different groups **(Table 1)**.

Table 1. Most relevant stakeholders to be considered in knowledge generation and planning for ACS upscaling.

Type of organization/ group/ individual	**Stakeholder and abbreviation**
Local authorities of the State	People's Councils (PC) at the provincial, district and communal levels
National administration	Ministry of Natural Resources and Environment (MONRE) Vietnam Meteorological and Hydrological Administration (VMHA) Ministry of Agriculture and Rural Development (MARD) Ministry of Planning and Investment (MPI) Ministry of Finance (MOF)
Local administration	Provincial People's Committee (PPC) District's People's Committee (DPC) Provincial Department of Planning and Investment (PDPI) Provincial Department of Finance (PDOF) Provincial Department of Agriculture and Rural Development (PDARD) District Division of Agriculture and Rural Development (DDARD) Project communes Non-project communes Project village leaders
Weather forecast provider	Provincial Hydro-Meteorological Station (PHMS)
Political-social organization	Women's Union
Public non-business service units	District Agricultural Extension Centre (DAEC) District Agricultural Service Centre (DASC) – a potential new entity in the government system formed by merging DAEC and some other public service units
Private service providers	SMS service providers Agricultural input suppliers

Type of organization/ group/ individual	**Stakeholder and abbreviation**
Civil society organizations	CARE in Vietnam (CVN) Dien Bien Center for Community Development (CCD)
Farmer groups	Village Saving and Loan Association (VSLA) – direct beneficiaries in CVN's project villages Other conventional farmer groups (non-VSLA) – farmers residing in the same villages with VSLA. They do not engage directly in CVN projects, but they benefit from accessing ACS provided to CVN's project villages
Other individuals	Other individuals within key organizations and groups

4.2. Expert identification

We classified stakeholders based on their expertise, availability, experience and gender **(Fig. 3)**. We identified 11 organizations and individuals as meeting the experience and availability criteria, which qualified them to serve as core expert stakeholders. We also determined 19 organizations and individuals as potential resource stakeholders due to their highly relevant experience but limited time availability. Among these stakeholders, 26 individuals (10 males and 16 females) ultimately joined our study as the core experts (14 individuals) and resource persons (12 individuals). Five out of 35 key stakeholders did not join us since they were too busy or did not respond to our invitation.

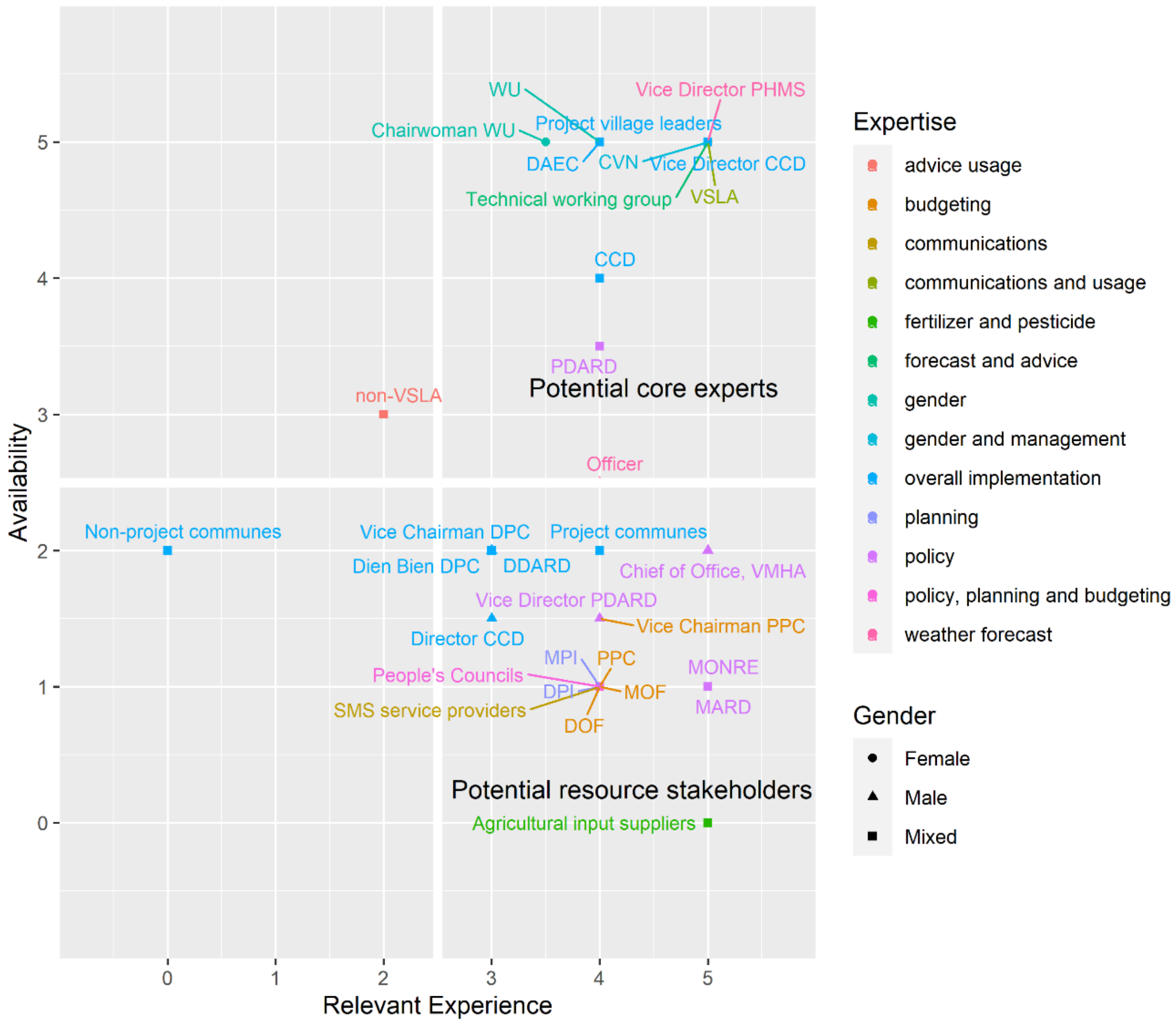

Fig. 3. Categorization of stakeholders to identify potential core experts and resource persons. Criteria for core experts (top right quadrant of the grid): availability score > 2.5 and experience score > 2.5. Criteria for resource persons (bottom right quadrant of the grid): availability score ≤ 2.5 and experience score > 2.5

Stakeholder expertise identified included the stakeholders' knowledge or skill in using climate information, translation of climate information into agricultural advice, budgeting, communication, fertilizer and pesticide use, weather forecasting, gender analysis and gender integration in development interventions, ACS intervention management, ACS implementation, socio-economic development planning and ACS policies. The explicit mapping of expertise helped us identify the overlap between stakeholders. Based on this information, we could identify "backup" experts for each field to attend workshops in case the first expert was unavailable.

4.3. Cost-benefit analysis for ACS stakeholders

We calculated costs and benefits for individual stakeholders (**Fig. 4.**) likely to be directly affected by the implementation of ACS, using data collected by Luu et al. (2022b). In all four investment options, we found similar patterns, with a very high likelihood that the “winners” would be the Provincial People’s Committee (98.3%-99.9%), rice farmers (99.9%-100%) and fish farmers (100%). Service implementers would benefit in those investment scenarios where they have roles in implementation. These stakeholders are the Provincial Hydro-Meteorological Station, the Provincial Department of Agriculture and Rural Development, the District Agricultural Service Centre, SMS service providers, Women’s Union/Local Non-Government Organization-LNGO, and village leaders.

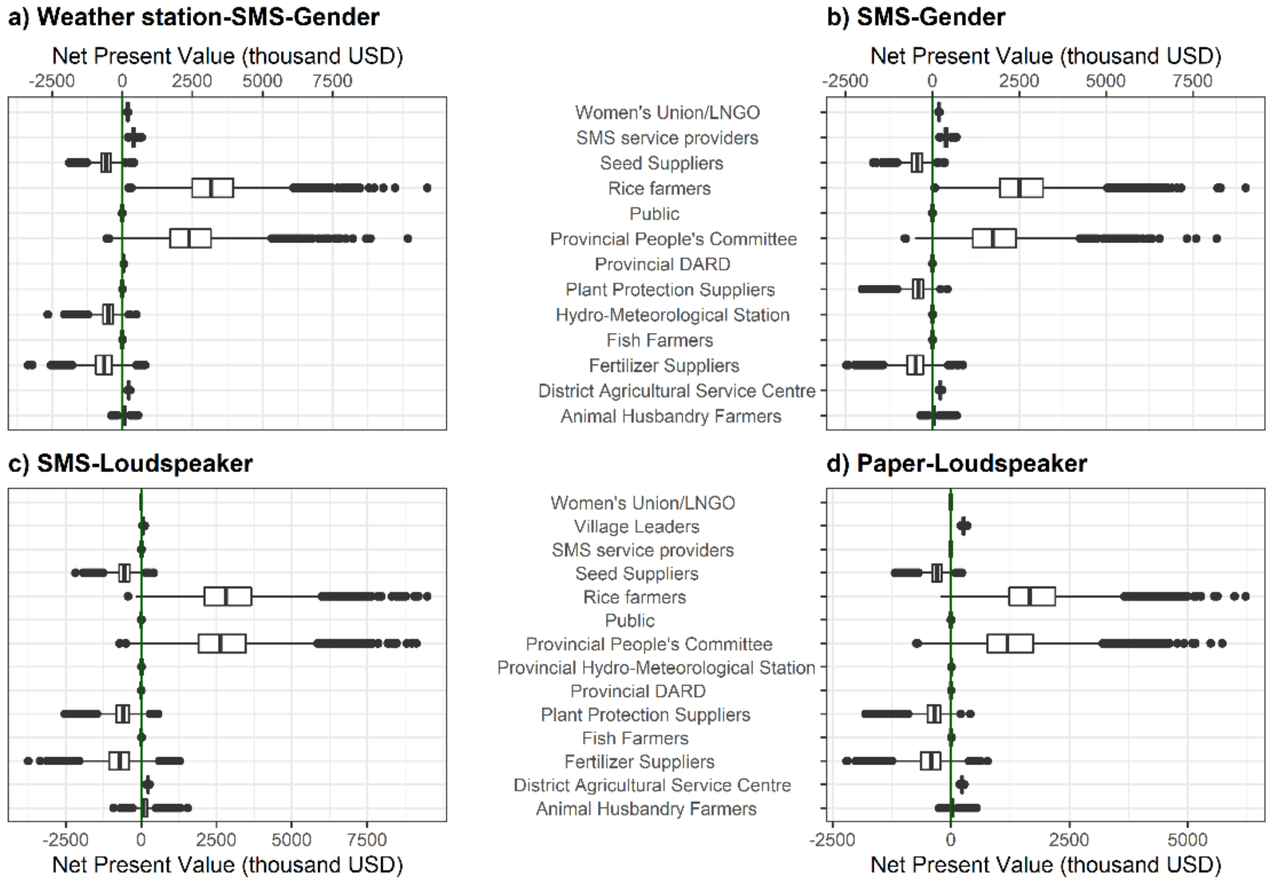

Fig. 4. Net Present Values of four agro-climate service (ACS) interventions in Dien Bien District, Vietnam, aggregated for different stakeholders. Results were obtained through Monte Carlo simulation with 10,000 model runs for each investment scenario.

We found that there is a small chance that animal husbandry farmers and the wider public will become “losers” (i.e. in cases when they experience wrong forecasts and advice) from ACS interventions (17.2%-17.8% and 4.8%, respectively). Meanwhile, there is a very high probability that costs will outweigh benefits for seed (99.4%-99.7%), fertilizer (93.8%-95.5%) and pesticide suppliers (99.0%). A summary of individual Net Present Value results for each stakeholder is available in the Supplementary Material 1.

4.4. Perceived interest, influence, relevance and attitude of stakeholders

Experts categorized all 35 stakeholders into four groups according to their level of interest and influence for 2019 and 2020. Experts also considered their attitude and the relevance of their mandate to the scaling of ACS **(Fig. 5 and Fig. 6)**. These considerations helped us formulate recommendations for the stakeholder engagement strategy.

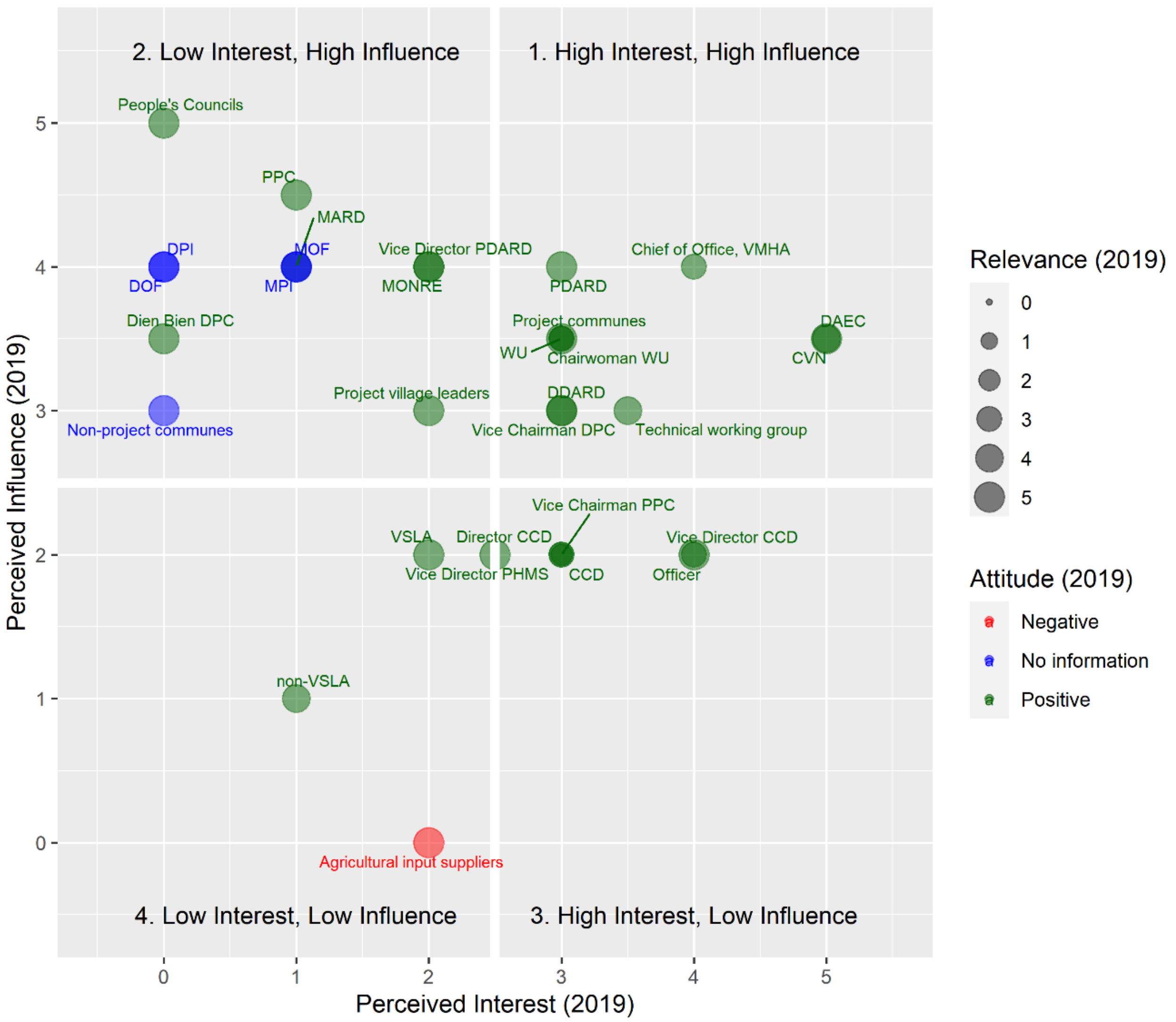

Fig. 5. Perceived interest, influence, relevance and attitude of stakeholders in the decision to scale agro-climate services in Dien Bien District, Vietnam. Results were captured through expert consultation in 2019

Group one: In 2019, ten stakeholders were categorized as having high interest and strong influence. All these stakeholders were perceived as having positive attitudes about the scaling of ACS. Their mandates are highly relevant to the purpose and implementation of the potential interventions. In 2020, thanks to CVN's efforts in engaging with stakeholders, three stakeholders (the Vice Chairman of the PPC, the Vice Director of the Provincial Department of Agriculture and Rural Development and project village leaders) gained higher interest scores. This implies that they may become more likely to support ACS scaling activities. The influence score of the Vice Director of the Provincial Hydro-Meteorological Station also increased, as she became the Director of the same institution during the project. Experts suggested these stakeholders, particularly those who will benefit from implementing the ACS scaling (e.g. women's union, project village leaders, Dien Bien District Agricultural Extension Center), could be key allies in the planning process.

Nevertheless, among all stakeholders in group one, only the VHMA Chief of Office had very high influence and interest scores (i.e. scores of 4) in both years. Most of the other stakeholders did not have very high influence scores. Since opportunities to increase influence are limited, experts recommended a strategy to increase the interest of highly influential stakeholders with low-interest scores (from group 2).

Group two: In 2019, twelve stakeholders were categorized within group two (strong influence and low interest). In 2020, the Vice Director of the Provincial Department of Agriculture and Rural Development and Project village leaders moved to group one, thanks to the project's continued stakeholder engagement. At the same time, the Director of the Provincial Department of Agriculture and Rural Development, a vacant position in 2019 when we conducted our study, was newly appointed and joined group two (strong influence but little interest). Nine of the stakeholders in this group had very high influence potential and high relevance (i.e. influence and relevance scores at 4 to 5 in 2020). Among them, PPC was identified as one of the most important decision-makers for ACS scaling, since PPC is in charge of connecting the demand from the local level to support at the national level. Experts pointed out the importance of increasing the interest and support of influential stakeholders, keeping them informed and engaging them during the preparatory work and the actual planning processes.

In 2019, experts could not identify the attitudes of the Provincial Department of Planning and Investment, Provincial Department of Finance, Ministry of Planning and Investment, Ministry of Finance and non-project communes (group two), since they had not interacted with them before on ACS scaling. In 2020, thanks to the engagement of different stakeholders as part of this study, interactions could be initiated between the Provincial Department of Planning and Investment and the Provincial Department of Finance to introduce the scaling ideas. While these stakeholders did not object to any planned ACS intervention and signaled their willingness to review the scaling proposal as part of the planning and budgeting process, they were also cautious about signaling support for the interventions. Thus, in 2020, experts still ranked them as neutral in their attitude toward scaling decisions.

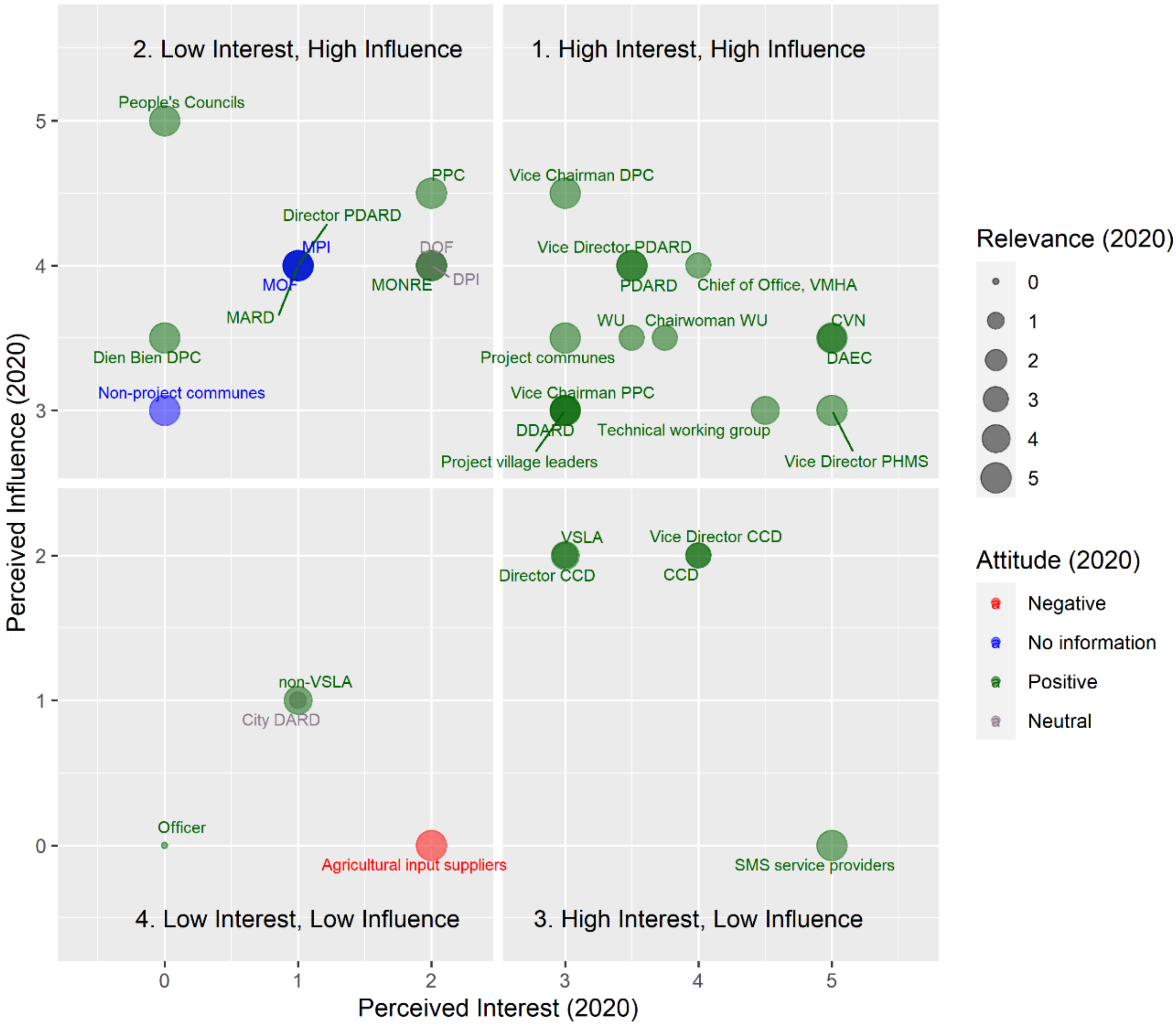

Fig. 6. Perceived interest, influence, relevance and attitude of stakeholders in the decision to scale agro-climate services in Dien Bien District, Vietnam. Results were captured through expert consultation in 2020

Group three: In 2019, five stakeholders were members of group three (high interest but low influence) and one stakeholder, the Vice Director of the Provincial Hydro-Meteorological Station, was positioned by the experts on the verge between groups three and four. Among these, the Vice Chairman of PPC and the Vice-Director of the Provincial Hydro-Meteorological Station moved from group three to group one in 2020, indicating an increase in influence. The Village Saving and Loan Associations (previously in group four) and the SMS company (experts did not have information about them in 2019) joined group three in 2020. These stakeholders, some of whom are likely to benefit from ACS (e.g. Village Saving and Loan Associations, SMS Company and Dien Bien Center of Community Development), are particularly relevant regarding upscaling of ACS. Stakeholder engagement efforts can help keep these stakeholders organized (e.g. Village Saving and Loan Associations) to increase their voice or to keep them participating (e.g. CCD, SMS company) during the planning processes.

Group four: In 2019, group four (low interest and low influence) included four stakeholders. The Vice Director of the Provincial Hydro-Meteorological Station was placed on the verge between groups four and three. In 2020, this number decreased to four, with one senior government officer newly joining group four due to his changed position (i.e. he was in group 3 in 2019). Dien Bien Phu City Division of Agriculture and Rural Development was included as a new stakeholder since some part of Dien Bien District was moved to Dien Bien Phu City in early 2020. Two other stakeholders (i.e. Village Saving and Loan Association and Vice-Director of Provincial Hydro-Meteorological Station) moved out of the group. Stakeholder engagement efforts have the potential to keep stakeholders informed and engaged in the process. For example, non-Village Saving and Loan Association farmers might have low interest due to their low awareness about the scaling initiative. However, they are potential beneficiaries and should be informed during preparation and planning. Dialogue is also needed where stakeholders have a negative attitude (e.g. agricultural input suppliers) about implementing ACS.

4.5. Possible considerations in engaging stakeholders

In this step, experts analyzed all relevant stakeholder attributes and answered the two following questions: (i) Does the stakeholder analysis suggest any substantial modifications in the SEDP decision-making process? and (ii) How do the attributes inform the potential coordination and roles of stakeholders in the decision-making process?

4.5.1. Does the stakeholder analysis suggest any substantial modifications in the SEDP decision-making process?

In principle, the involvement of stakeholders in the SEDP process does not lead to substantial modifications compared to the standard process (illustrated in **Figure 1**). Besides, experts suggested that the composition of stakeholders involved in the SEDP planning remained unchanged. However, experts pointed out the importance of investing in preparatory actions given that many influential stakeholders (e.g. Provincial People's Committee, People's Council and all the relevant Ministry stakeholders) have low interest in ACS. Such preparatory actions aim to increase awareness and thus the interest of stakeholders with the power to support ACS scaling.

4.5.2. How do the attributes inform the potential coordination and roles of stakeholders in the decision-making process?

Experts identified multiple opportunities for stakeholder involvement in ACS planning steps. In the following, we highlight results in the context of these different stages:

Involvement of stakeholders at the policy recognition stage: At present, development projects with external funding, such as CARE's project, usually go through the "administrative" but not the agricultural sector reporting system. We observed a low interest of influential stakeholders in ACS, partly because they were unaware of the insights of CVN's pilot project on agro-climate services. It is thus often difficult to bring up ACS topics in the policy discourse. While critical decision-making is expected to happen at the provincial level with PPC as the key stakeholder, efforts must be supported by specialized departments and governments at the village, commune, district and national levels, as well as by NGOs.

The sensitization of decision-makers supporting the recognition of evidence for the effectiveness of ACS, as well as potential limitations, can be considered the first step towards evidence-based decision-making. Experts point out that stakeholders should provide information and evidence mainly in the existing written and oral reporting systems since this is the only formal reporting line in the government system. This reporting process involves reflections from stakeholders, including Village Saving and Loan Associations and farmers with ACS experience, village leaders, project communes, the District Division of Agriculture and Rural Development, the Provincial Department of Agriculture and Rural Development, the District People's Committee, the Women's Union at provincial, district and commune levels, and NGOs (i.e. CARE in Vietnam and the Dien Bien Center of Community Development). These reports should include information about the application of ACS in Dien Bien and the impacts, opportunities and challenges. This process aims at increasing interest and support from the PPC, which holds a high influence (score of 4.5) and low interest (score of 2.5), as identified in 2020. In addition, the province needed support from upper levels, i.e. from national ministries with a high influence and low interest. MONRE and MARD are expected to signal support for the necessity and feasibility of the interventions given their high influence (score of 4 in 2020), and considering that ACS are well aligned with relevant policies within their thematic domains (e.g. the National Adaptation Plan). The Ministry of Planning and Investment and the Ministry of Finance are expected to advise on the appropriateness of funding acquisition and the potential funding sources according to their relevant mandates (score of 5 in 2020). Considering the local requirement and the legal framework, the PPC could support the scaling plan and start setting the agenda. This support can be materialized in guiding the SEDP planning process, by indicating that it is possible to plan for ACS upscaling.

Involvement of stakeholders during the planning process: Based on the SEDP guidance, specialized departments and governments at the village, commune and district levels can integrate ACS in their SEDP planning. However, some communes did not have any experience (score of 0) using ACS before and thus had low interest (score of 0 in 2020). Therefore, scaling workshops in the project and non-project communes should be organized to record the needs and share experiences between project communes and non-project communes. In this way, the experience attribute of project communes (score of 4) is being used, aiming for increased interest from non-project communes. Furthermore, CARE had rich experience (score of 5) in ACS implementation and a high interest in ACS scaling (score of 5 in 2020). Thus, it is expected that CVN could provide technical support to the District Division of Agriculture and Rural Development to develop a detailed scaling proposal that makes use of CARE's experience and insights about the costs and benefits of the scaling solutions.

Coordinating and facilitating stakeholders: Acknowledging the complexity of the SEDP process (i.e. multi-stage, multi-actor, cross-sector and multi-level), experts also highlighted the importance of having a coordinating body for the whole process. The coordinating actor is supposed to gain an overview and support facilitating the stakeholders' roles in the horizontal (i.e. between departments at the same administrative level) and vertical (i.e. different administrative levels) dimensions of the SEDP planning process. Experts considered the Provincial Department of Agriculture and Rural Development the most appropriate stakeholder for this role due to the alignment of this task with the institution's mandate (score of 5 in 2020) and the department's high influence (score of 4 in 2020). Additionally, the Provincial Department of Agriculture and Rural Development is considered to have the least conflict of interest with other stakeholders in terms of finance and relevant mandate. Experts also suggested that CVN should support the Provincial Department of Agriculture and Rural Development in this process due to their rich experience (score of 5), strong interest (score of 5 in 2020) and relatively strong influence (score of 3.5 in 2020). Besides, CVN is perceived as having the lowest potential for conflicts of interest (i.e. funding for CARE is often from external sources and they do not have a potential financial conflict with other stakeholders in ACS scaling).

Collective organization of stakeholders: Village Saving and Loan Associations, the Dien Bien Center of Community Development and SMS service providers had strong interest (scores of 3, 4 and 5, respectively, in 2020) and low influence (scores of 2, 2 and 0, respectively, in 2020). However, according to the cost-benefit analysis, they are all potential beneficiaries of ACS scaling. Therefore, they can be allies in the process of driving ACS planning. Their low influence can be increased by pooling their voices. For example, the Dien Bien Center of Community Development could support organizing Village Saving and Loan Association farmers and help them collectively provide feedback, opinions and needs to the reporting systems and planning process.

Involvement of individual stakeholders: Even though experts were unable to describe in detail the possible participation of all individual stakeholders, they discussed the critical roles of a few stakeholders at some crucial steps in the SEDP. The Vice Chairman of the PPC and the District's People's Committee (high interest and high influence in 2020) must be involved at all critical decision-making moments in the SEDP (e.g. meetings to decide if ACS will be included in SEDP guidelines, meetings to defend the SEDP). The Vice-Director of the Provincial Department of Agriculture and Rural Development (high interest and high influence in 2020), the Chairwoman of the Women's Union (high interest and high influence in 2020) and the Vice-director of the Provincial Hydro-Meteorological Station (high interest and high influence in 2020) are expected to support collecting evidence and incorporating such evidence into the reporting system of their respective organizations. The Vice-Director of the Provincial Hydro-Meteorological Station and the Chief of Office of the Vietnam Meteorological and Hydrological Administration (high interest and high influence in 2020) are expected to signal support for agro-climate service scaling during consultation and experience-sharing events at the national level. The Vice-Director and the Director of the Dien Bien Center of Community Development (high interest, low influence in 2020) are expected to support mobilizing and organizing farmers collectively during the reporting and planning processes.

Managing the stakeholders' different perspectives: Agricultural input suppliers were identified as the "losers" since they might face a reduction in farm input sales. They are perceived as having a negative attitude towards ACS scaling. This suggests the necessity of managing the different perspectives of these stakeholders. One of the solutions proposed by the experts was to involve them in the SEDP process. Commune and District governments should invite them to the SEDP consultation meetings. In that way, these stakeholders can voice their concerns or proposals. Another suggestion during the potential implementation of ACS is to share agricultural advice with all these stakeholders. In the current situation, some agricultural advice requires agricultural inputs (i.e. drought-tolerant breeds, fertilizer or pesticides) that are unavailable in the local market. By receiving such information, agricultural input suppliers will be better informed about the users' demands in the new context.

We describe and visualize the detailed SEDP process with potential pathways to integrate ACS in the SEDP, and the roles of institutional stakeholders in Supplementary Material 2.

5. Discussion

In the context of climate change, decision-makers are increasingly in need of effective measures to support and invest in transitioning the agricultural sector toward climate-informed agricultural planning and management (Ferdinand et al., 2021; WMO, 2019). A transdisciplinary and probabilistic approach has the potential to support the planning and budgeting processes (Daniels et al., 2020; Luu et al., 2022a). In this study, we propose a comprehensive approach combining decision analysis with stakeholder engagement to generate system knowledge and incorporate it into the decision-making processes. We contribute to the improvement of existing methods by offering comprehensive and transparent guidance for defining stakeholders, identifying experts and assessing relevant stakeholder attributes to explicitly suggest which roles they might play in ACS planning.

Defining stakeholders is essential to supporting a participatory process. However, stakeholder selection is often made on an ad-hoc basis (Reed et al., 2009). This study highlights the importance of a transparent method to identify and strategically engage stakeholders. We believe that this method can be helpful for research and development practitioners working in multi-stakeholder processes. However, when we conducted our study, there was a discussion, mainly on social media, regarding the racist or colonial connotations of the term "stakeholder" in the context of decolonization (Reed, 2022). While it may be necessary to find a new term (Reed and Rudman, 2023), there is no obvious alternative, and rushing towards another term could have unintended negative consequences. Future studies should explore the etymology, the necessity for an alternative term and the potential impacts of these alternatives.

In this study, we argue that stakeholder engagement in the ACS design and planning process would benefit from considering individual stakeholder characteristics, since these may influence the information that stakeholders provide during the decision-modeling process. For example, a stakeholder interested in the scaling of ACS will most likely have a stronger motivation to share favorable information regarding ACS scaling initiatives than those not interested in ACS. While multiple attributes have been suggested to inform the stakeholder engagement strategy (Reed et al., 2009), the most commonly used in previous studies were interest and power or influence in the form of an influence/power interest matrix (Reed et al., 2009; Sperry and Jetter, 2019). We extended this approach by including nine attributes in determining stakeholder roles, from knowledge generation to influencing ACS decision-making. Attributes included in our study, such as relevant experience and availability, help to determine the overall strategy to engage stakeholders as core experts and resource persons. In our study, explicit consideration of gender revealed the gender disparity in the expert team. While it is not always possible to achieve perfect representation of all stakeholders (Reed et al., 2009), such explicit analyses help to inform on the status quo and provide guidance for improvement.

We suggest moving away from the internally-focused, narrow viewpoints in managing stakeholders (i.e. managing stakeholders to achieve specific goals set by some actors) and offering a way to explore opportunities for them to co-create research results by playing an active role in the planning process. Many common approaches for stakeholder analysis remain static in engaging stakeholders (Sperry and Jetter, 2019). Monitoring change in stakeholder roles helps to gain insights into the dynamics between different stakeholders, which can be used to adapt the engagement process over time (Fassin, 2011). In this study, examples of change include a new person taking on a leadership role (e.g. Director of the Provincial Department of Agriculture and Rural Development), changes in interest and influence due to the changing position (e.g. a government officer), or a change in the administrative structures resulting in the emergence of an additional stakeholder (e.g. City Division of Agriculture and Rural Development). Such changes suggest that if projects fail to include stakeholder dynamics in decision-making, they might risk failure of scaling processes and investments (Sperry and Jetter, 2019). Stakeholder engagement, therefore, requires continuous monitoring of stakeholder dynamics (Reed et al., 2009; Smith, 2020).

The DA approach supports decision-making by providing evidence through analyzing decisions (Hubbard, 2014; Luedeling and Shepherd, 2016). In Vietnam's multi-stakeholder, multi-stage, cross-sectoral and multi-level collaboration system, such evidence may need to go through a complex planning process (Strauch et al., 2018; World Bank, 2015). We found that to influence decision-making, it is necessary to engage multiple levels of stakeholders during ACS scaling and planning. Stakeholders at individual, village, communal, district, provincial and national levels all need to be part of the process. Our findings agree with Gonzalez-Porras et al. (2021), who suggested that the contribution of stakeholders from different levels in a nested system helps further sustainability transitions. Moreover, Gonzalez-Porras et al. (2021) argue that collaborative relationships and interactions among stakeholders can be understood as change agencies accelerating sustainability transitions. This finding aligns with our result, implying that coordination and collaboration among stakeholders are crucial in influencing multi-stage and multi-level decision-making processes.

Our transdisciplinary approach addresses the common barriers to rational organizational decision-making. These barriers include information gaps and imperfections, the complexity of the decision problem, human information-processing capacity, the time available for decision-making processes, and potential conflicts between the priorities of different stakeholders and decision-makers (Hatch, 1997). Our approach addresses the issue of imperfect, incomplete information and complexity by mobilizing stakeholder knowledge and secondary data to capture the current state of system understanding. While it may not be possible to obtain perfect information, the current state of system understanding is often sufficient to support decision-making (Luedeling and Shepherd, 2016). On the human information-processing capacity, we acknowledge that ACS systems and the impacts of potential ACS solutions are complex, which is difficult to communicate to time-constrained senior government decision-makers. We found that integrating evidence into the government's periodic oral and written reporting systems may be effective in communicating information to senior decision-makers in an established format.

While asserting the comprehensiveness of our proposed approach, we acknowledge some limitations. We did not evaluate conflicts between the different priorities of stakeholders and decision-makers. ACS requires long-term investment and a focus on "soft" measures (i.e. awareness raising, information interpretation, communication, improved planning, and improved collaboration among stakeholders) (Luu et al., 2022a). However, Vietnam's climate-related investment is biased towards large-scale infrastructure investment as opposed to softer measures (Lindegaard, 2013; Pannier et al., 2020). Therefore, there may be a conflict between prioritizing funding allocation for agro-climate services and other investments. We did not incorporate such prioritization conflicts into our model.

We explored the authoritative power of stakeholders as part of the government's guided SEDP process. We find this helpful for making concrete recommendations about each stakeholder's role in the decision-making process. However, social network analysis, which was outside the scope of this study, may also help clarify the dynamics, opportunities and challenges of stakeholder engagement.

We did not manage to engage the potential "losers" of ACS in our study, which limited the insights we could gain regarding mechanisms to resolve conflicts between stakeholders. While the CVN project established some exchanges, it did not involve an official partnership with the agricultural input suppliers. Due to time and resource constraints, we could not establish contacts and engage with them. Thus, we suggest future studies should focus on more systematic engagement with such stakeholders.

While acknowledging some limitations, our approach to generating and translating system knowledge into decision-making supports the notion of stakeholder engagement as an effective approach to empowering marginal stakeholders to engage in and influence decision-making (Reed et al., 2009). We believe this approach will help increase the credibility, legitimacy and salience of evidence generated and promote a sense of shared ownership in decision-making processes.

6. Conclusions

Sustainability transitions are long-term processes. The pre-stage of transitions often features uncertainty, scattered knowledge, conflicts of different views (i.e. traditional and new perspectives) and the challenge of bringing stakeholders to the same table. Without coordination, such an "incubation" process can take a long time. Our study offers a transparent and systematic method to address critical challenges at this early process stage by engaging stakeholders in generating and translating system knowledge for use in decision-making processes. Using nine different attributes, combined with stakeholders' system knowledge and insights about the decision-making process, we could explicitly recommend where, when and how stakeholders can engage in the socio-economic development planning process in Dien Bien, Vietnam. This transparent approach offers the opportunity to increase the reproducibility of the methods and to support other complex decision-making processes.

Declaration of interest statement

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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Supplementary data

All input data for stakeholder mapping and analysis and supplementary materials are available at this public repository
https://github.com/ThiThuGiangLuu/Stakeholder-Decision-Analysis-ACS/blob/master/Supplementary-material.html

Author contributions

Conceptualization: TTGL., LBF., EL. and CW.; Data curation: TTGL.; Formal analysis: TTGL.; Funding acquisition: TTGL. and EL.; Methodology TTGL., LBF., EL. and CW.; Software: TTGL. and EL.; Supervision: LBF., EL. and CW.; Visualization: TTGL., EL., LBF. and CW.; Writing - original draft: TTGL.; Review & Editing: LBF., EL., CW. and TTGL.

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Chapter 5: Conclusions

I set out on this PhD journey with the ambition to understand the complexity and to provide decision support to the ACS adoption and scaling process at the last mile in the Global South. To fulfill this objective, I developed and used different methodologies and approaches. In my dissertation, I describe a novel method to test the impact pathway using confidence interval (CI) interpretation. I demonstrate the application of decision analysis for valuing ACS to support their scaling and present the combination of decision analysis and stakeholder engagement methods to create an improved integrated approach. I showcase my work with three scientific studies concerning the dynamics of ACS adoption processes, the valuation of ACS scaling, and stakeholder engagement in generating and harnessing system knowledge for ACS planning decision-making. These studies offer both methodological contributions and practical implications for decision-making within and beyond the ACS context.

The case study in Dien Bien on ACS delivery and adoption shows that in two distinct settings, farmer groups experience different pathways to access and uptake ACS while they share a similar high adoption rate. Structured communications in farmer groups, demand awareness creation, enhancing peer-to-peer exchange and influencing farmers' attitudes appear crucial in leveraging the delivery and dissemination of ACS. Structured communications enhance farmers' understanding, exchanging and providing feedback for ACS. The low-stated need for ACS among farmers may imply that climate services were not clearly defined and communicated to farmers. Awareness-raising on the concept of ACS might be needed to fill the gap between stated need and revealed need. Meanwhile, a lack of comprehension does not necessarily prevent the subsequent process of talking up ACS. The strong positive relationship between the positive perception of ACS and the intention to adopt ACS may be attributable to the influence of stakeholder involvement in ACS production, to peer exchange and to the impact of opinion leaders. Development efforts should consider farmers' revealed needs, social learning and attitudes in designing and monitoring ACS interventions.

The newly proposed method contributes to methodologies used to understand the dynamics of the causal relations in ACS adoption and any other causal processes. The testing procedure offers a robust and rapid tool to validate hypotheses underlying the impact pathways of development interventions. These hypotheses may otherwise be overly simplistic and remain largely untested and unvalidated. The application of the impact pathway development and testing approach is not limited to adoption or ACS contexts and might be applicable in many other change processes, especially in upscaling sustainable development interventions and innovations.

My study shows that decision-based analysis provided practical and useful guidance to stakeholders in shaping and sharpening the initial and rather unclear understanding of the scaling process. Stakeholder participation in decision analysis serves as a knowledge generation platform for individual experts and facilitates knowledge exchange and knowledge mapping at the system level. The problem-based approach (i.e. designing a scaling strategy based on problems in delivering and scaling ACS) often struggles with multiple options and a lack of focus on capturing the potential impacts of such options and is thus ineffective in supporting decision-making. In contrast, the decision-based approach often offers straightforward guidance for the decision problem. The cost-benefit analysis can directly support decision-making by governments or development donors aiming to scale ACS or indirectly support through the advocacy effort of civil society organizations. Decision analysis demonstrated its usefulness as a powerful new tool, given the current dearth of methods capable of addressing biases and uncertainties in valuing climate services. Furthermore, decision analysis can provide holistic analysis and serve as a "quick test" to understand complex issues when there are time and financial constraints, which is common in most low and middle-income countries.

For the case of Dien Bien, my study shows that ACS offer multiple socio-economic and environmental impacts. These impacts include improved yield, reduced losses in agriculture, cleaner water, better health, reduced GHG emissions, and economic returns from improved gender equality. The results of the model simulation indicate a very high chance (98.35-99.81%) of the ACS interventions providing net benefits. With 90% confidence, investments in ACS would return benefits between 1.45 and 16.02 USD per 1 USD invested. My study demonstrates that despite intensive resource investment in the initial years and the uncertain range of benefits, the cost-benefit analysis still provides strong positive signals for investment.

Having positive evidence for investment does not imply a direct translation into policy. ACS planning in Vietnam is highly complex since it is a multi-actor, multi-sector, multi-stage and multi-level process characterized by uncertain and scattered knowledge.

My study results show that defining stakeholders' multi-dimensional attributes is important for mobilizing stakeholders' knowledge and engagement. In the case of Dien Bien, gender, availability, experience and expertise attributes helped define expert stakeholders at the early stage of knowledge generation. Meanwhile, other features (i.e. costs and benefits that are specific for each stakeholder, interest, influence, mandate, relevance and attitude) were useful in defining the influencing strategy and roles of stakeholders (e.g. key allies, coordinating bodies) at different stages of ACS planning. While it might be infeasible to constitute a perfect representative and legitimate team of stakeholders, my study presents a transparent selection process based on multi-dimensional attributes. This transparent approach offers an opportunity to increase the reproducibility of the methods. Additionally, the transparent method is also helpful in identifying our potential biases that remained in stakeholder selection and defining the attributes. Our approach can be used directly or adapted to support other complex and multi-stakeholder decision-making processes.

Overall, my work highlights the importance of employing a probabilistic and systemic approach in understanding the complexity of ACS scaling. Additionally, capturing the system complexity should focus on the "what" (i.e. defining ACS scaling interventions and impacts) and also the "how" (i.e. pathways to scaling and impacts) and the "who" (i.e. stakeholder engagement in knowledge generation and integration). Specifically, my research reflects an improved understanding of the dynamics of ACS delivery and adoption at the last mile. I also demonstrate the capability of the decision analysis approach to value and support ACS scaling decisions in an uncertain and complex environment. To further complement the decision support “package”, I suggest and demonstrate an improved approach to engage stakeholders in generating and translating scientific evidence into planning and budgeting decision-making. The studies presented within this dissertation offer a set of different keys to unpack and reflect on the dynamics of ACS adoption and scaling. I expect our methods to be useful for other scientists studying adoption and scaling in ACS and other contexts. I also hope this work will be useful for other stakeholders, especially governments, civil societies and donors, aiming to acknowledge the dynamics, complexity and uncertainty of ACS and use the resulting insights to inform their decision-making in order to support the sustainability transition. I recommend future research focus on exploring ways to promote the adoption of the probabilistic approach amidst the prevalent use of the deterministic approach in decision-making on complex systems.

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