Climate Services 27 (2022) 100313

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

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

Thi Thu Giang Luu [a,*], Cory Whitney [a,b], Lisa Biber-Freudenberger [b], Eike Luedeling [a]

[a] Department of Horticultural Sciences, Institute of Crop Science and Resource Conservation, University of Bonn, Auf dem Hügel 6, 53121 Bonn, Germany
[b] Center for Development Research, University of Bonn, Genscherallee 3, 53113 Bonn, Germany

ARTICLE INFO

Keywords:
Cost-benefit analysis
Uncertainty
Probabilistic modeling
Decision analysis
Agriculture
Climate change

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.

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.

---

* Corresponding author.
E-mail address: luuthithugiang@gmail.com (T.T.G. Luu).

https://doi.org/10.1016/j.cliser.2022.100313
Received 6 August 2021; Received in revised form 13 April 2022; Accepted 25 July 2022

- 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.

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 to 2018, was 1562 mm in Dien Bien District. In that same period, the average annual temperature was 22.17 °C, with an increase 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 (>1000 m a.s.l./ above sea level) and the lowland (400 to less than 1000 m 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-Governmental 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 methods guides, they describe a similar process (Fig. 1).

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.

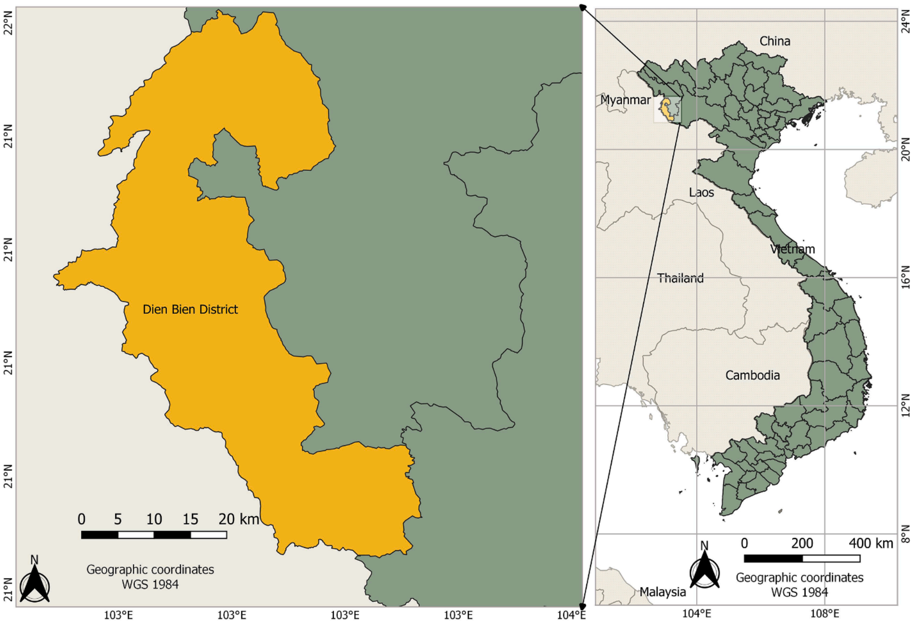
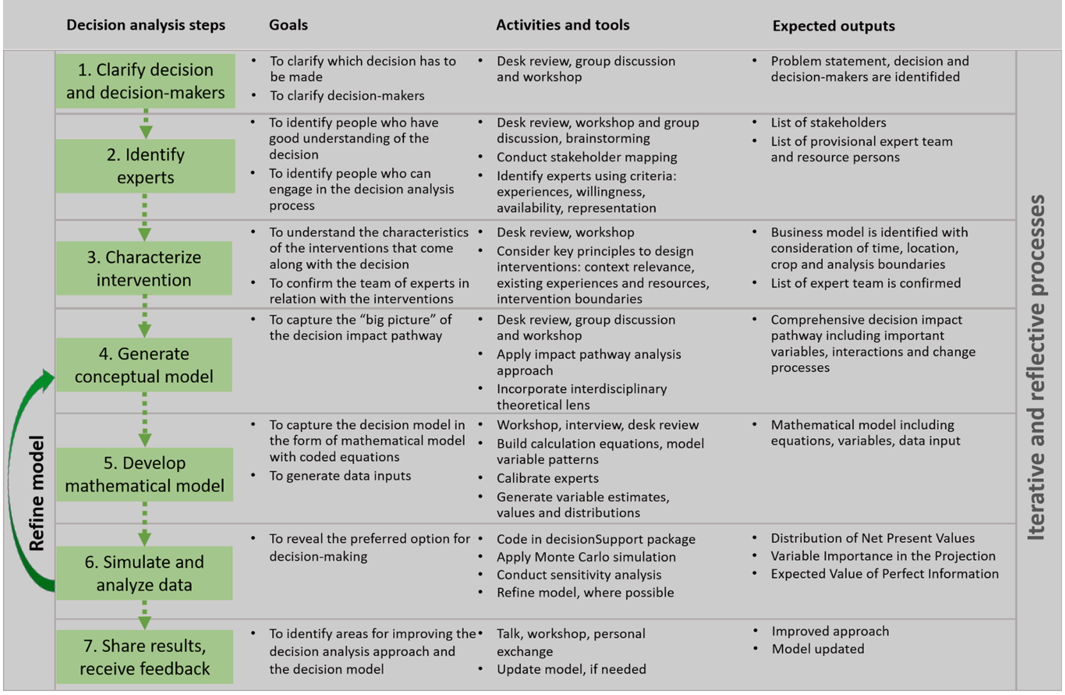


Fig. 1. Map of the agro-climate service research area, Dien Bien District, Vietnam.



Decision analysis steps	Goals	Activities and tools	Expected outputs
1. Clarify decision and decision-makers	• To clarify which decision has to be made • To clarify decision-makers	• Desk review, group discussion and workshop	• Problem statement, decision and decision-makers are identifided
2. Identify experts	• To identify people who have good understanding of the decision • To identify people who can engage in the decision analysis process	• Desk review, workshop and group discussion, brainstorming • Conduct stakeholder mapping • Identify experts using criteria: experiences, willingness, availability, representation	• List of stakeholders • List of provisional expert team and resource persons
3. Characterize intervention	• To understand the characteristics of the interventions that come along with the decision • To confirm the team of experts in relation with the interventions	• Desk review, workshop • Consider key principles to design interventions: context relevance, existing experiences and resources, intervention boundaries	• Business model is identified with consideration of time, location, crop and analysis boundaries • List of expert team is confirmed
4. Generate conceptual model	• To capture the "big picture" of the decision impact pathway	• Desk review, group discussion and workshop • Apply impact pathway analysis approach • Incorporate interdisciplinary theoretical lens	• Comprehensive decision impact pathway including important variables, interactions and change processes
5. Develop mathematical model	• To capture the decision model in the form of mathematical model with coded equations • To generate data inputs	• Workshop, interview, desk review • Build calculation equations, model variable patterns • Calibrate experts • Generate variable estimates, values and distributions	• Mathematical model including equations, variables, data input
6. Simulate and analyze data	• To reveal the preferred option for decision-making	• Code in decisionSupport package • Apply Monte Carlo simulation • Conduct sensitivity analysis • Refine model, where possible	• Distribution of Net Present Values • Variable Importance in the Projection • Expected Value of Perfect Information
7. Share results, receive feedback	• To identify areas for improving the decision analysis approach and the decision model	• Talk, workshop, personal exchange • Update model, if needed	• Improved approach • Model updated

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 for 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

$$\textit{Net benefit ACS} = \textit{New ACS benefit} - \textit{New ACS investment costs} \tag{1}$$

in which

$$\begin{aligned}\textit{New ACS benefits} = {} & \textit{New climate damage avoided} \\ & + \textit{New ACS associated benefits}\end{aligned} \tag{2}$$

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 were 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

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

with $r_{i(t-1)}$ being the adoption rate of intervention *i* in year $t-1$*t-1*, 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 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.

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-

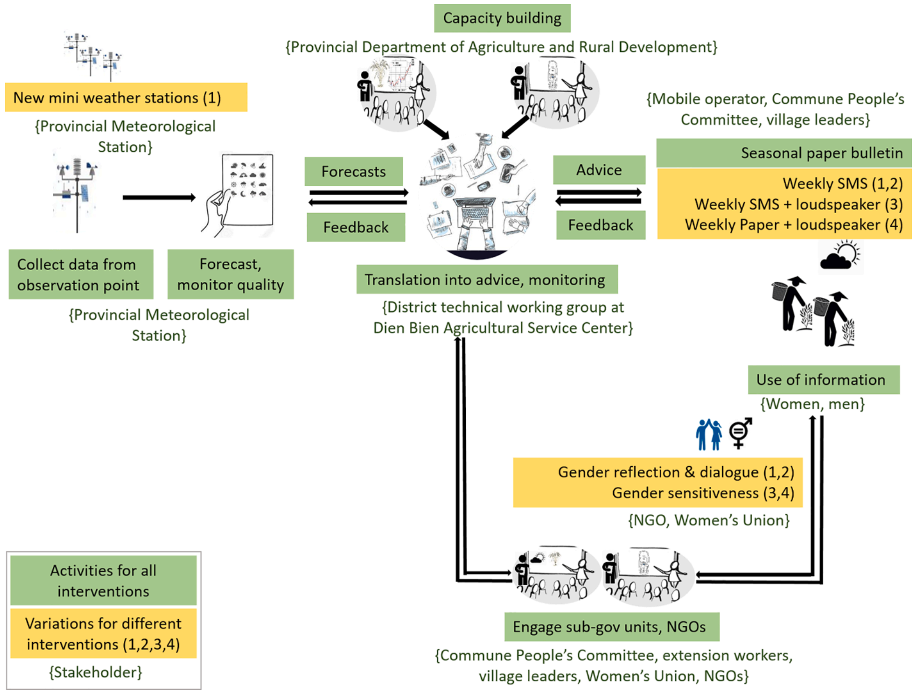


Fig. 3. Overview of four agro-climate service (ACS) interventions in Dien Bien District, Vietnam. The black arrows represent information flows. The green boxes illustrate activities implemented for all four interventions. The yellow boxes with numbers indicate activities that only apply to the corresponding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

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 accross 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.

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

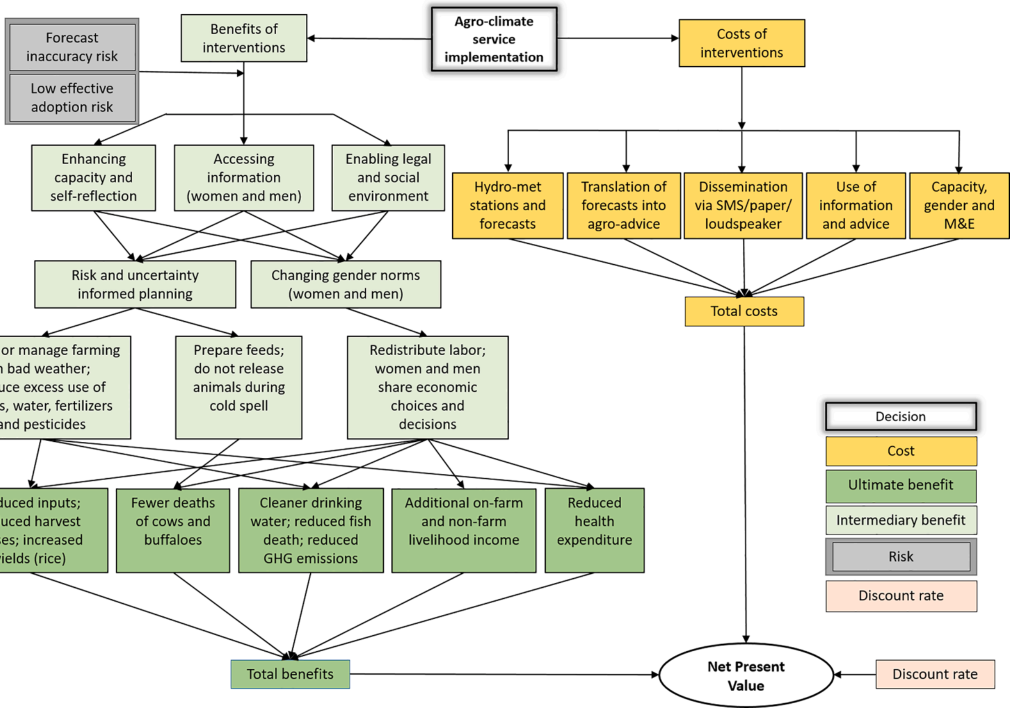


Fig. 4. Conceptual framework for cost-benefit analysis of agro-climate services.

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.

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

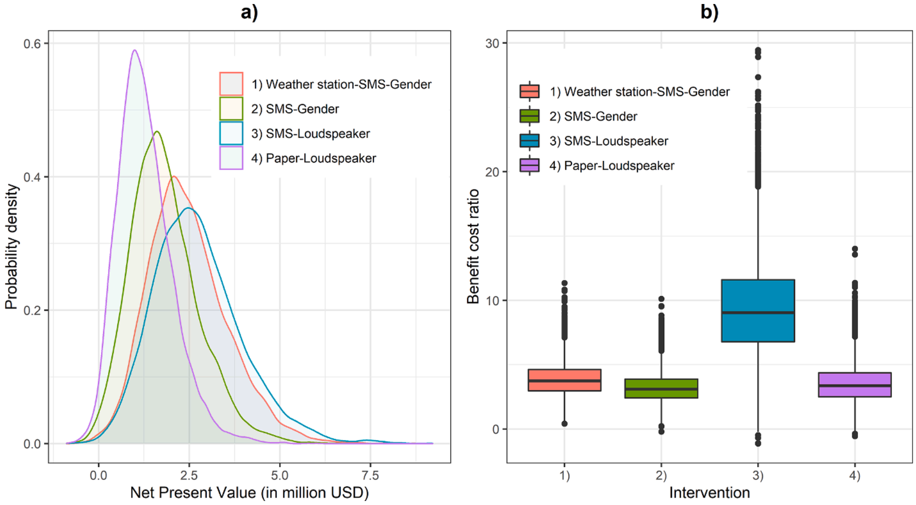


Fig. 5. Net Present Value (a) and benefit-cost ratio (b) of four agro-climate service (ACS) interventions in Dien Bien District, Vietnam. Results were obtained through Monte Carlo simulation with 10,000 runs for each investment scenario.

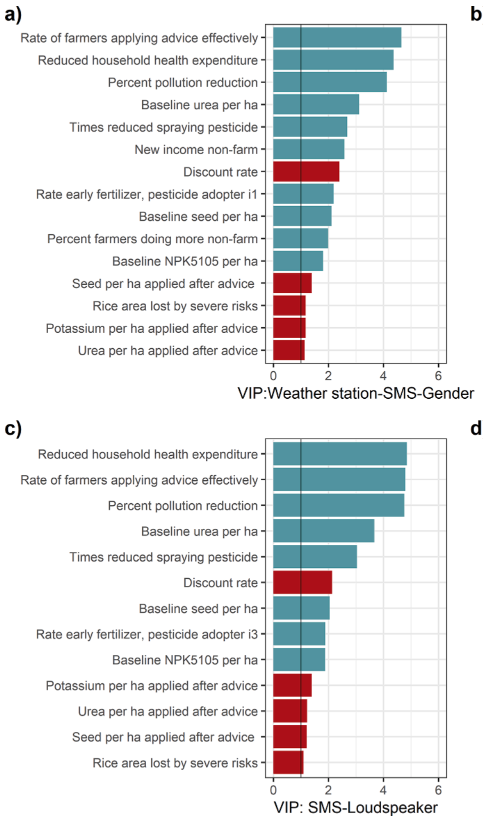


Fig. 6. Variable importance of a Partial Least Squares (PLS) regression model relating uncertain inputs to decision models for four agro-climate service (ACS) interventions in Dien Bien District, Vietnam. The vertical line shows the VIP score threshold at 1, which is used to define if a variable is important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

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.

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).

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

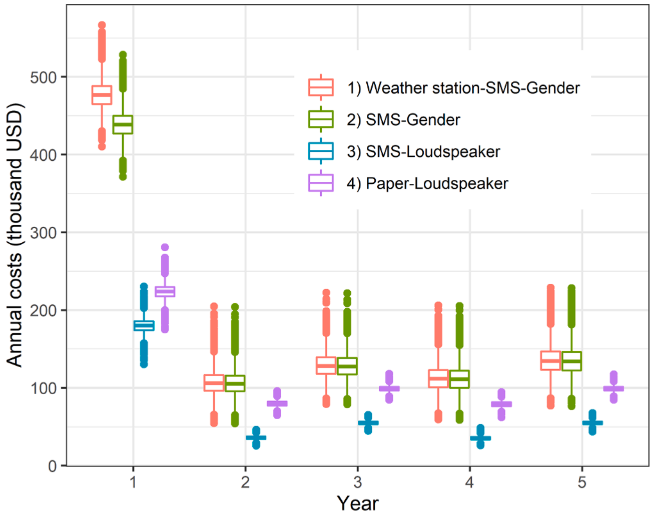


Fig. 7. Simulated annual costs (thousand USD) needed to implement four agro-climate service (ACS) interventions in Dien Bien, Vietnam over five years. Results were obtained through Monte Carlo simulation using 10,000 model runs for each investment scenario.

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 et al. (2013) and Pilli-Sihvola et al. (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 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 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 Competing Interest

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

Acknowledgments

We acknowledge the valuable support from CARE in Vietnam and Centre of Community Development, Dien Bien. We sincerely thank the Schlumberger Foundation for providing a scholarship for the main author through the Faculty for the Future Program. The Schlumberger Foundation also provides open access funding. The views expressed in this research are those of the authors and do not necessarily reflect the views of CARE in Vietnam or the Schlumberger Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2022.100313.

References

Abhijit, B., Duflo, E., 2012. Poor economics. PublicAffairs. https://www.publicaffairsbooks.com/titles/abhijit-v-banerjee/poor-economics/9781610391603/.

Agrifood Consulting International, 2006. Rice Value Chains in Dien Bien Province, Vietnam. http://www.value-chains.org/dyn/bds/docs/554/Agrifood%20Consulting%20Rice%20VC%20Dien%20Bien%20Vietnam%2020.pdf.

Akarachantachote, N., Chadcham, S., Saithanu, K., 2014. Cutoff threshold of variable importance in projection for variable selection. Int. J. Pure Appl. Math. 16. 10.12732/ijpam.v94i3.2.

Ambani, M., Percy, F., 2014. Facing uncertainty: the value of climate information for adaptation, risk reduction and resilience in Africa. https://careclimatechange.org/facing-uncertainty/.

Anderson, C.L., Reynolds, T.W., Biscaye, P., Patwardhan, V., Schmidt, C., 2021. Economic benefits of empowering women in agriculture: assumptions and evidence. J. Dev. Stud. 57, 193–208. https://doi.org/10.1080/00220388.2020.1769071.

Assembly, N., 2015. 83_2015_QH13 Law on State budget [WWW Document]. accessed 1.26.21. https://www.economica.vn/Content/files/LAW%20%26%20REG/83_2015_QH13%20Law%20on%20State%20budget.pdf.

Bass's Basement Research Institute, 2008. The Bass Model Home Page [WWW Document]. accessed 10.28.20. http://www.bassbasement.org/BassModel/Default.aspx.

Bourne, L., Walker, D., 2008. Project relationship management and the Stakeholder CircleTM. Int. J. Manag. Proj. Bus. 1, 125–130. https://doi.org/10.1108/17538370810846450.

CARE, 2018. Practical guide to participatory scenario planning. accessed 2.19.21 CARE Clim. Change. https://careclimatechange.org/practical-guide-to-participatory-scenario-planning-seasonal-climate-information-for-resilient-decision-making/.

CARE in Vietnam, 2013. Climate vulnerability and capacity of ethnic minorities in the northern mountainous region of Vietnam. https://care.org/wp-content/uploads/2020/05/CC-2013-VNM-CARE_ClimChg_Vietnam.pdf.

CARE in Vietnam, 2020. Phat-trien-nong-nghiep-ben-vung.pdf [WWW Document]. URL https://www.care.org.vn/wp-content/uploads/2020/06/Phat-trien-nong-nghiep-ben-vung.pdf (accessed 1.20.21).

CARE International, 2018. Social Analysis and Action - Transforming Gender Norms [WWW Document]. accessed 5.26.21 CARE. https://www.care.org/wp-content/uploads/2020/08/saatoolkit_final_rights_reserved.pdf.

Chong, I.G., Jun, C.H., 2005. Performance of some variable selection methods when multicollinearity is present. Chemom. Intell. Lab. Syst. 78, 103–112. https://doi.org/10.1016/j.chemolab.2004.12.011.

Clements, J., Ray, A., Anderson, G., 2013. The value of climate services across economic and public sectos: A review of relevant literature. https://climate-services.org/wp-content/uploads/2015/09/CCRD-Climate-Services-Value-Report_FINAL.pdf.

Climate Service Partnership, 2019. What are Climate Services? [WWW Document]. accessed 10.27.20. http://www.climate-services.org/about-us/what-are-climate-services/.

Cocchi, M., Biancolillo, A., Marini, F., 2018. Chapter Ten - Chemometric methods for classification and feature selection, in: Jaumot, J., Bedia, C., Tauler, R. (Eds.), Comprehensive Analytical Chemistry, Data Analysis for Omic Sciences: Methods and Applications. Elsevier, pp. 265–299. 10.1016/bs.coac.2018.08.006.

Dien Bien People's Committee, 2009. Giới thiệu về lịch sử hình thành, Vị trí địa lí, Dân số, Khí hậu, Thủy văn huyện Điện Biên [WWW Document]. accessed 4.14.21. http://dienbien.gov.vn/portal/Pages/2009-3-24/Huyen-Dien-Bienxnci89.aspx.

Dien Bien People's Committee, 2015. Thông Tin Giới Thiệu Chung Về Huyện Điện Biên. accessed 10.27.20. http://huyendienbien.gov.vn/Tintuc/One/Gioi-thieu-chung.

Dien Bien People's Committee, 2019. Implementation of information access poverty reduction: National programme on sustainable poverty reduction 2016–2020, in Dien Bien province [WWW Document]. accessed 4.13.21. http://huyendienbien.gov.vn/Vanban/View/Ke-hoach-998-KH-UBND.

Do, H., Whitney, C., Luedeling, E., 2019. Uncertainty analysis in agroforestry planning: A case study in Northwest Vietnam, in: 4th World Congress on Agroforestry. Presented at the 4th World Congress on Agroforestry, INRA, France, Montpellier, France, p. 833.

Do, H., Luedeling, E., Whitney, C., 2020. Decision analysis of agroforestry options reveals adoption risks for resource-poor farmers. Agron. Sustain. Dev. 40, 20. https://doi.org/10.1007/s13593-020-00624-5.

Duong, M.T., Smith, A., Le, T.T., Simelton, E., Coulier, M., 2020. Gender-differences in Agro-Climate Information Services (Findings from ACIS baseline survey in Ha Tinh and Dien Bien provinces, Vietnam) [WWW Document]. URL https://ccafs.cgiar.org/resources/publications/gender-differences-agro-climate-information-services-findings-acis (accessed 1.21.21).

Everett, R., 2003. Diffusion of Innovation. The Free Press.

Fao, 2016. Climate Change, Agriculture and Food Security: The State of Food and Agriculture. FAO, Rome http://www.fao.org/3/i6030e/i6030e.pdf.

FAO, 2015. The impact of disasters on agriculture and food security. http://www.fao.org/3/i5128e/i5128e.pdf.

FAO, 2019. Handbook on climate information for farming communities: what farmers need and what is available. Rome. http://www.fao.org/3/ca4059en/ca4059en.pdf?eloutlink=imf2fao.

Freeman, R.E., 2010. Strategic Management: A Stakeholder Approach. Cambridge University Press, Cambridge. 10.1017/CBO9781139192675.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., Wiltshire, A., 2010. Implications of climate change for agricultural productivity in the early twenty-first century. Philos. Trans. R. Soc. B Biol. Sci. 365, 2973–2989. https://doi.org/10.1098/rstb.2010.0158.

Higgins, G.M., Kassam, A., 1981. The FAO Agro-ecological zone approach to determination of land potential. Pedologie 2, 147–168. https://www.researchgate.net/publication/282283261_The_FAO_Agro-ecological_zone_approach_to_determination_of_land_potential.

Howard, R.A., Abbas, A.E., 2015. Foundations of Decision Analysis. Pearson.

Hubbard, D.W., 2014. How to Measure Anything: Finding the Value of Intangibles in Business, 3rd ed. Wiley.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.

Kahneman, D., 2011. Thinking, fast and slow. Farrar, Straus and Giroux.

Katz, R.W., Lazo, J.K., 2011. Economic value of weather and climate forecasts, in: Clements, M.P., Hendry, D.F. (Eds.): The Oxford Handbook of Economic Forecasting. Oxford Handbooks Online. https://doi.org/10.1093/oxfordhb/9780195398649.013.0021.

Klein, Gary, 2007. Performing a Project Premortem. Harvard Business Review.

Lamers, M., Schreinemachers, P., Ingwersen, J., Sangchan, W., Grovermann, C., Berger, T., 2013. Agricultural pesticide use in mountainous areas of Thailand and Vietnam: Towards reducing exposure and rationalizing use. In: Fröhlich, H.L., Schreinemachers, P., Stahr, K., Clemens, G. (Eds.), Sustainable Land Use and Rural Development in Southeast Asia: Innovations and Policies for Mountainous Areas. Springer Environmental Science and Engineering. Springer, Berlin, Heidelberg, pp. 149–173. https://doi.org/10.1007/978-3-642-33377-4_4.

Lanzanova, D., Whitney, C., Luedeling, E., 2017. Enabling Decision-Making for Agricultural Interventions. World Agroforestry Centre (ICRAF). https://cgspace.cgiar.org/bitstream/handle/10568/83037/WLEmemo_DecisionAnalysis_method%20guide.pdf?sequence=5.

Lanzanova, D., Whitney, C., Shepherd, K., Luedeling, E., 2019. Improving development efficiency through decision analysis: Reservoir protection in Burkina Faso. Environ. Model. Softw. 115, 164–175. https://doi.org/10.1016/j.envsoft.2019.01.016.

Luedeling, E., Goehring, L., Schiffers, K., 2020. DecisionSupport – Quantitative Support of Decision Making under Uncertainty. Contributed Package to the R Programming Language. Version 1.103.2 [WWW Document]. URL https://cran.r-project.org/web/packages/decisionSupport/index.html.

Luedeling, E., Gassner, A., 2012. Partial Least Squares Regression for analyzing walnut phenology in California. Agric. For. Meteorol. 158–159, 43–52. https://doi.org/10.1016/j.agrformet.2011.10.020.

Luedeling, E., Oord, A., Kiteme, B., Ogalleh, S., Malesu, M., Shepherd, K., De Leeuw, J., 2015. Fresh groundwater for Wajir—ex-ante assessment of uncertain benefits for multiple stakeholders in a water supply project in Northern Kenya. Front. Environ. Sci. 3 https://doi.org/10.3389/fenvs.2015.00016.

Luedeling, E., Shepherd, K., 2016. Decision-Focused Agricultural Research. Solutions. 46–54. https://www.thesolutionsjournal.com/article/decision-focused-agricultural-research/.

McKune, S., Poulsen, L., Russo, S., Devereux, T., Faas, S., McOmber, C., Ryley, T., 2018. Reaching the end goal: Do interventions to improve climate information services lead to greater food security? Clim. Risk Manag. 22 https://doi.org/10.1016/j.crm.2018.08.002.

Mendelsohn, R.O., 2006. A Critique of the Stern Report 5. https://resources.environment.yale.edu/files/biblio/YaleFES-00000260.pdf.

Mullins, J., Zivin, J.G., Cattaneo, A., Paolantonio, A., Cavatassi, R., 2018. The adoption of climate smart agriculture: the role of information and insurance under climate change, in: Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S., Branca, G. (Eds.), Climate Smart Agriculture : Building Resilience to Climate Change, Natural Resource Management and Policy. Springer International Publishing, Cham, pp. 353–383. 10.1007/978-3-319-61194-5_16.

Nabati, J., Nezami, A., Neamatollahi, E., Akbari, M., 2020. GIS-based agro-ecological zoning for crop suitability using fuzzy inference system in semi-arid regions. Ecol. Indic. 117, 106646. https://doi.org/10.1016/j.ecolind.2020.106646.

Nascimento, N., West, T.A.P., Biber-Freudenberger, L., de Sousa-Neto, E.R., Ometto, J., Börner, J., 2020. A Bayesian network approach to modelling land-use decisions under environmental policy incentives in the Brazilian Amazon. J. Land Use Sci. 15, 127–141. https://doi.org/10.1080/1747423X.2019.1709223.

Nguyen, P.D., Tong, D., Vu, D., 2018. Valuing health risk due to pesticides use in agricultural production in Tam Binh district, Vinh Long province: A choice experiment approach. Can Tho Univ. J. Sci. 54, 164–171. 10.22144/ctu.jvn.2018.153.

Nguyen, V.V., 2017. Khai thác tài nguyên khí hậu nông nghiệp Việt Nam. Nhà xuất bản Tài nguyên - Môi trường và Bản đồ Việt Nam, Vietnam.

Nicholles, N., Vardakoulias, O., Johnson, V., 2012. Counting on uncertainty: The economic case for community based adaptation in North-East Kenya. CARE. https://www.care.org/counting-uncertainty.

Nordhaus, W.D., 2007. A review of the Stern review on the economics of climate change. J. Econ. Lit. 45, 686–702. https://doi.org/10.1257/jel.45.3.686.

Nurmi, P., Perrels, A., Nurmi, V., 2013. Expected impacts and value of improvements in weather forecasting on the road transport sector. Meteorol. Appl. 20, 217–223. https://doi.org/10.1002/met.1399.

O'Grady, M., Langton, D., Salinari, F., Daly, P., O'Hare, G., 2020. Service design for climate-smart agriculture. Inf. Process. Agric. 10.1016/j.inpa.2020.07.003.

Oxfam in Vietnam, 2017. GALS Manual phase I and phase II [WWW Document]. Oxfam Vietnam. URL https://vietnam.oxfam.org/latest/policy-paper/gals-manual-phase-i-and-phase-ii (accessed 5.26.21).

Perrels, A., 2020. Quantifying the uptake of climate services at micro and macro level. Clim. Serv., Special issue on European Climate Services Markets – Conditions, Challenges, Prospects, and Examples 17, 100152. 10.1016/j.cliser.2020.100152.

Pilli-Sihvola, K., Namgyal, P., Dorji, C., 2014. Socio-Economic Study on Improved Hydro-Meteorological Services in the Kingdom of Bhutan. Finnish Meteorological Institute. https://www.researchgate.net/publication/301286763_Socio-Economic_Study_on_Improved_Hydro-Meteorological_Services_in_the_Kingdom_of_Bhutan.

Polasky, S., Dampha, N.K., 2021. Discounting and global environmental change. Annu. Rev. Environ. Resour. 46, 691–717. https://doi.org/10.1146/annurev-environ-020420-042100.

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989. https://doi.org/10.1038/ncomms6989.

Rogers, E.M., 2003. Diffusion of Innovations. Free Press, New York.

Rojas, G., Fernandez, E., Whitney, C., Luedeling, E., Cuneo, I.F., 2021. Adapting sweet cherry orchards to extreme weather events – Decision Analysis in support of farmers' investments in Central Chile. Agric. Syst. 187, 103031. https://doi.org/10.1016/j.agsy.2020.103031.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111, 3268–3273. https://doi.org/10.1073/pnas.1222463110.

Ruett, M., Whitney, C., Luedeling, E., 2020. Model-based evaluation of management options in ornamental plant nurseries. J. Clean. Prod. 271, 122653. https://doi.org/10.1016/j.jclepro.2020.122653.

Sen, L.T.H., Bond, J., Dung, N.T., Hung, H.G., Mai, N.T.H., Phuong, H.T.A., 2021. Farmers' barriers to the access and use of climate information in the mountainous regions of Thừa Thiên Huế province, Vietnam. Clim. Serv. 24, 100267. https://doi.org/10.1016/j.cliser.2021.100267.

Shepherd, K., Hubbard, D., Fenton, N., Claxton, K., Luedeling, E., de Leeuw, J., 2015. Policy: Development goals should enable decision-making. Nat. News 523, 152. https://doi.org/10.1038/523152a.

Simelton, E., Aus der Beek, R., Duong, M.T., Le, T.T., Le, X.H., Madsen, E.J., Nguyen, T. Y., Noorlander, J., 2019. Participatory agro-climate information services: CGIAR Research Program on Climate Change, Agriculture and Food Security. https://reliefweb.int/sites/reliefweb.int/files/resources/CCAFS%20PB13.pdf.

Springer-Heinze, A., Hartwich, F., Henderson, J.S., Horton, D., Minde, I., 2003. Impact pathway analysis: an approach to strengthening the impact orientation of agricultural research. Agric. Syst., Learning for the future: Innovative approaches to evaluating agricultural research 78, 267–285. 10.1016/S0308-521X(03)00129-X.

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press. https://webarchive.nationalarchives.gov.uk/20100407172811/http://www.hm-treasury.gov.uk/stern_review_report.htm.

Strauch, L., Yann Robiou du Pont, Balanowski, J., 2018. Multi-level climate governance in Vietnam: Bridging national planning and local climate action [WWW Document]. URL https://www.adelphi.de/de/system/files/mediathek/bilder/Multi-level%20climate%20governance%20in%20Vietnam%20-%20adelphi.pdf (accessed 1.26.21).

Strong, M., Oakley, J.E., Brennan, A., 2014. Estimating multiparameter partial expected value of perfect information from a probabilistic sensitivity analysis sample: a nonparametric regression approach. Med. Decis. Mak. Int. J. Soc. Med. Decis. Mak. 34, 311–326. https://doi.org/10.1177/0272989X13505910.

The Socialist Republic of Vietnam, 2020. Updated Nationally Determined Contribution (NDC). https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Viet%20Nam%20First/Viet%20Nam_NDC_2020_Eng.pdf.

Thorn, J., Coast, J., Andronis, L., 2015. Interpretation of the Expected Value of Perfect Information and Research Recommendations: A Systematic Review and Empirical Investigation. Med. Decis. Making 36. https://doi.org/10.1177/0272989X15586552.

Tran T., Nguyen, Thang, Huynh, Huong, Mai, Khiem, Nguyen, Hien, Doan, Phong, 2016. Climate change, sea level rise scenarios for Vietnam. Ministry of Natural Resource and Environment. http://www.imh.ac.vn/files/doc/KichbanBDKH/KBBDKH_2016.pdf, Vietnam.

Tversky, A., Kahneman, D., 1974. Judgment under uncertainty: heuristics and biases. Science 185, 1124–1131. https://doi.org/10.1126/science.185.4157.1124.

Vu, M.T.T., 2008. Comprehensive planning: Does it work? Experiences from Vietnam. J. Adm. Gov. 3, 17–24. http://www.joaag.com/uploads/2_MaiFinal3_2_.pdf.

Weitzman, M.L., 1998. Why the far-distant future should be discounted at its lowest possible rate. J. Environ. Econ. Manag. 36, 201–208. https://doi.org/10.1006/jeem.1998.1052.

Whitney, C., Shepherd, K., Luedeling, E., 2018. Decision analysis methods guide; Agricultural policy for nutrition. World Agroforestry Centre. 10.5716/WP18001.PDF.

Whitney, C.W., Tabuti, J.R.S., Hensel, O., Yeh, C.-H., Gebauer, J., Luedeling, E., 2017. Homegardens and the future of food and nutrition security in southwest Uganda. Agric. Syst. 154, 133–144. https://doi.org/10.1016/j.agsy.2017.03.009.

WMO, 2003. Satellite Remote Sensing and GIS Applications in Agricultural Meteorology. WMO, India https://library.wmo.int/doc_num.php?explnum_id=5030.

WMO, 2013. Localizing Climate Information Services for Agriculture [WWW Document]. World Meteorol, Organ https://public.wmo.int/en/bulletin/localizing-climate-information-services-agriculture (accessed 3.3.21).

WMO, 2019a. Components of GFCS | GFCS [WWW Document]. accessed 11.15.19. https://gfcs.wmo.int/components-of-gfcs.

WMO, 2015. Valuing weather and climate: economic assessment of meteorological and hydrological services. https://library.wmo.int/doc_num.php?explnum_id=3314.

WMO, 2019b. 2019 State of climate services: Agriculture and food security. https://library.wmo.int/doc_num.php?explnum_id=10089.

Wold, S., Sjostrom, M., Eriksson, L., 2001. PLS-regression: A basic tool of chemometrics. Chemom. Intell. Lab. Syst. 58, 109–130. https://doi.org/10.1016/S0169-7439(01)00155-1.

Xu, R., Kuang, R., Pay, E., Dou, H., de Snoo, G.R., 2008. Factors contributing to overuse of pesticides in western China. Environ. Sci. 5, 235–249. https://doi.org/10.1080/15693430802346543.

Yang, J., Shen, G.Q., Bourne, L., Ho, C.-M.-F., Xue, X., 2011. A typology of operational approaches for stakeholder analysis and engagement. Constr. Manag. Econ. 29, 145–162. https://doi.org/10.1080/01446193.2010.521759.