Climate Change Adaptation and Mitigation in Ecosystems - Benefits, Barriers and Decision-Making

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PhD Dissertation
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Title **Climate Change Adaptation and Mitigation in Ecosystems – Benefits, Barriers and Decision-Making**

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Front page: 'Natural regeneration of mangrove forest'. Photo taken by the author in Peam Krasaop, Koh Kong Province, Cambodia, January 2014.

Preface

This PhD thesis is a result of my curiosity as to how synergies between climate change adaptation and mitigation can be achieved in the management of ecosystems, combined with my fascination with getting lost in an ocean of data and making it tangible.

The PhD thesis meets the requirements for the PhD degree at the Technical University of Denmark (DTU). It is the product of the three-year PhD programme at the UNEP DTU Partnership (UDP), Department of Management Engineering, DTU. The project has run from December 2011 to November 2016, interrupted by two maternity leaves from January 2012 to December 2012 and from October 2014 to September 2015. The project has been supervised by Anne Olhoff, Head of Programme at the Climate Resilient Development, UDP, DTU, and Professor Jette Bredahl Jacobsen, Section for Environment and Natural Resources, Department of Food and Resource Economics, University of Copenhagen.

Essential for the project was the collaboration with Henrik Meilby (University of Copenhagen), Santosh Rayamajhi (Tribhuvan University, Nepal), Martin Drews (DTU), Morten A. D. Larsen (DTU), Jens Erik Lyngby (DHI), Tue K. Nielsen and other co-authors.

The thesis includes the following papers:

Paper 1 Bakkegaard, R.K., **Møller, L.R.** & Bakhtiari, F. (2016). Joint Adaptation and Mitigation in Agriculture and Forestry. UDP working paper series. Climate Resilient Development Programme. Working paper 2:2016.

Paper 2 **Møller, L.R.** & Jacobsen, J.B. (submitted 2016). Estimating the Benefits of the Interrelationship between Climate Change Adaptation and Mitigation – A Case Study of Replanting Mangrove Forests in Cambodia. Scandinavian Forest Economics**.**

Paper 3 **Møller, L.R.**, Smith-Hall, C., Larsen, H.O., Meilby, H., Nielsen, Ø.J., Rayamajhi, S., Herslund, L.B. & Byg, A. (manuscript to be submitted). Empirically Based Analysis of Households Coping with Unexpected Shocks in the Central Himalayas Regional Environmental Change.

Paper 4 **Møller, L.R.**, Drews, M. & Larsen, M.A.D. (submitted 2016). Simulation of Optimal Decision-Making under the impacts of Climate Change. Environmental Management.

Acknowledgements

This PhD would not have been possible without the endless support of my husband Anders Jensen and our children Vilfred and Karla, to whom I dedicate this thesis in the hope that their future will be bright and that optimal decisions will be evident to them.

I also owe many thanks to friends and family, especially my mother Lone Møller who has been very supportive and helped with the family logistics, and to our neighbours Susanne Nielsen, Bente Østergaard Madsen and Nils Boesen, who have helped us in many ways and contributed with reflective discussions, offering perspectives on issues of development and constructive feedback.

Next, I want to thank my colleagues at the UNEP DTU Partnership for fruitful discussions and constructive feedback, especially Caroline Schaer, Sara Lærke Meltofte Trærup, Riyong Kim Bakkegaard and Lars Christiansen for invitations to coffee and lunch breaks, addressing the world situation and providing encouraging pep talks when needed. I also want to thank peers and colleagues at the University of Copenhagen for their hospitality during my research stay which made it a great learning experience that resulted in **Paper 3** of this thesis.

Furthermore, I want to thank the people of Peam Krasaop who allowed me to conduct fieldwork in their community, the project team behind the Cambodia Climate Change Alliance Programme, Jens Erik Lyngby from DHI and Tue Kell Nielsen for supportive information. A special thanks to Chea Leng and Sun Try, my interpreter and chauffeur, whose efforts made the fieldwork possible. **Paper 2** would not have been possible had it not been for all of you.

My dyslexia was of great concern to me before I started working on the PhD project, but with great support from Roskilde Municipality, which made it possible for me to hire professional assistance through Marie Lauritzen and Vision Editing, this was one thing that I did not have to worry about. Their support has been an important part in my work on the thesis. Thank you.

That said, there would not have been a thesis to submit if it had not been for my two great supervisors Anne Olhoff and Jette Bredahl Jacobsen, their willingness to answer my endless stream of questions regarding Matlab and STATA coding as well as their comments, clarifying questions and encouragement on rainy days. Thank you so much. It has been fun.

Popular Science Summary of the PhD Thesis, in English

PhD student	Lea Ravnkilde Møller
Title of the PhD thesis	**Climate Change Adaptation and Mitigation in Ecosystems – Benefits, Barriers and Decision-Making**
PhD school/department	UNEP DTU Partnership, DTU Management Engineering

Science Summary

Ecosystems are central to the livelihoods of many people and at the same time highly vulnerable to climate change. This research, which focuses on ecosystems and land use, investigates linkages in joint climate change adaptation and mitigation (JAM) in ecosystems. The research exemplifies how different, empirical and theoretical models for decision-making can be applied under risk and uncertainty, focusing on rural households in developing countries. The thesis consists of four peer-reviewed papers.

The first paper is a review of JAM initiatives in the forestry and agricultural sectors, highlighting current barriers and opportunities and providing insight into areas where the further and future development of JAM activities can be ensured by focused efforts. The paper concludes that the opportunities for achieving JAM are good, especially at landscape-level.

The second paper analyses the economic benefits of replanting mangrove forest – as a JAM initiative, simulated over a 100-year period. The benefit of this adaptation initiative is reflected in the avoided damage costs of storms. The benefits of climate change mitigation are estimated for the replanted area, i.e. a monetary value is projected based on different estimations of the social costs of carbon. The paper concludes that combining adaptation and mitigation can improve the cost-effectiveness of actions and increase their attractiveness to stakeholders and funding agencies.

The third paper considers Nepalese households' dependence on agricultural production and their preferred coping strategies when faced with unexpected climate change shocks. A statistical model is used to describe the households' preferred coping strategies. The main finding is that poor households generally choose coping strategies that give them immediate access to cash as gap filler rather than income and resources from the forests and the environment – contrary to the assumptions of previous research.

In the fourth paper a framework is developed which applies Bayesian updating within decision-making in a forward-looking fashion. The focus is on farmers' choices of agricultural system as adaptation to climate changes compared to their beliefs and the impact of future climate change, simulating the consequences of farmers' choices of adaptation strategies combined with their knowledge of climate change impacts for optimal decision-making.

The overall conclusion of this PhD project is that combining adaptation and mitigation in the agriculture and forestry ecosystems holds significant advantages especially from a landscape perspective. However, the list of barriers is long, and therefore it is important to acknowledge the links between adaptation, mitigation and development.

Abstract

Ecosystems are central to the livelihoods of many people and at the same time highly vulnerable to climate change. This research, which focuses on ecosystems and land use, investigates how households dependent on ecosystems can benefit from climate change adaptation and mitigation.

Adaptation and mitigation are two different approaches to minimising the impact and extent of climate change. The possible synergy between adaptation and mitigation is a topic that is currently attracting increasing attention, but which remains relatively understudied in the academic literature.

The thesis consists of four peer-reviewed papers, each of which considers a subject that contributes with increased knowledge as to how decision-makers prioritise their choices to fight climate change, to maximise welfare and to secure better decisions when facing uncertainty and incomplete information.

Paper 1 Joint Adaptation and Mitigation in Agriculture and Forestry takes a general approach to synergies and trade-offs between adaptation and mitigation of climate change within forestry and agriculture in developing countries and considers previous experiences described in the literature. The paper offers a summary of the described barriers and opportunities for achieving synergy. This is treated in more detail in each of the following papers:

- Empirical welfare economic benefits of climate change adaptation leading to mitigation **(Paper 2. Estimating the Benefits of the Interrelationship Between Climate Change Adaptation and Mitigation – A Case Study of Replanting Mangrove Forests in Cambodia)**

- Choice of coping strategy when rural households dependent on agricultural production experience substantial, unexpected shocks **(Paper 3. Empirically Based Analysis of Households Coping with Unexpected Shocks in the Central Himalayas)**

- Simulation of decision and reaction patterns in relation to the belief in future climate changes and trajectory of decisions when knowledge about future climate is gradually increased **(Paper 4. Simulation of Optimal Decision-Making under the Impacts of Climate Change)**

Overall, the PhD thesis concludes that the opportunities to achieve synergies between adaptation and mitigation of climate change are good, especially from a landscape perspective. **Paper 1** concludes that there is a need for more empirical knowledge on synergy, cost-efficiency, risk and uncertainty as well as the complexity of combining adaptation and mitigation. Joint adaptation and mitigation hold significant advantages especially from a landscape perspective.

Paper 2 considers such empirical knowledge and suggests how incentives to increase adaptation action can be achieved through carbon payments and a carbon credit scheme. Paper 2 highlights the importance of considering the strategies and options for tackling climate change, and how these may change over time. An important aspect hereof is the freedom of action and possible choices by those who feel the impact of climate change. There is great uncertainty about the scale which increases the uncertainty about the actual benefits of adaptation and mitigation of climate change and complicates the process of deciding how to act.

Paper 3 provides a more in-depth empirical analysis of actual decision-making, considering rural Nepalese households dependent on agricultural production. Paper 3 finds that households that experience substantial, unexpected shocks choose coping strategies that give them access to cash to

overcome the shocks. **Paper 4** exemplifies how freedom of action and optimal decisions can change over time, as knowledge increases.

A **policy recommendation** of the PhD thesis is that when striving to achieve synergies between climate change adaptation and mitigation it is necessary to understand that those who are hit the hardest typically are those with the least resources. Thus, these people have limited resources and freedom of action to manage possible crises and do not have resources to consider long-term strategies. This underlines the importance of linking development with the fight against climate change in order to secure increased freedom of action for the world's poorest, thereby increasing their ability to adapt and make optimal decisions for the future. Because climate change is a global issue, mitigation should be included in decisions to maximise global welfare and the PhD thesis exemplifies situation of this.

Summaries of the individual papers are available on page 23.

Danish Summary – dansk resumé

Denne afhandling tager udgangspunkt i muligheden for synergi mellem tilpasning til og reduktion af klimaændringer i økosystemer med fokus på udviklingslande. Økosystemer er oftest yderst sårbare over for klimaændringer, hvilket gør de husstande, der er afhængige af økosystemerne, ekstremt sårbare. Denne afhandling belyser, hvordan sådanne husstande vil kunne drage nytte af en tilpasning til og en reduktion af klimaændringer, samt hvilke synergieffekter der kan opnås herved.

Reduktion af og tilpasning til klimaændringer er to forskellige tilgange til at mindske omfanget og effekterne af klimaændringer. Synergi mellem reduktion og tilpasning er et emne, der tiltrækker sig øget opmærksomhed, men som stadig er relativt underbelyst i litteraturen.

Afhandlingen består af fire artikler, der hver især omhandler et emne, der bidrager til øget viden om, hvordan forskellige beslutningstagere bedst prioriterer indsatsen mod klimaændringer og derved maksimerer velfærden og træffer bedre valg i en situation med usikkerhed og ufuldstændig information.

Artikel 1 Joint Adaptation and Mitigation in Agriculture and Forestry tager en generel tilgang til synergierne mellem tilpasning til og reduktion af klimaændringer inden for skovbrug og landbrug i udviklingslande og ser på, hvilke erfaringer der er beskrevet i litteraturen. Artiklen opsummerer de beskrevne barrierer og muligheder for at skabe synergi. Dette bliver behandlet mere konkret i de tre efterfølgende artikler, der omhandler:

- Empirisk, velfærdsøkonomisk estimering af nytten ved tilpasning til og reduktion af klimaændringer **(Artikel 2. Estimating the Benefits of the Interrelationship Between Climate Change Adaptation and Mitigation – A Case Study of Replanting Mangrove Forests in Cambodia)**

- Beslutningsmuligheder og råderum for bønder i tilfælde af uforudsete klimarelaterede chok **(Artikel 3. Empirically Based Analysis of Households Coping with Unexpected Shocks in the Central Himalayas)**

- Simulering af beslutnings- og reaktionsmønstre i relation til troen på fremtidige klimaændringer og den udvikling, der sker i forbindelse med tilføring af ny viden om klimaets udvikling **(Artikel 4. Simulation of Optimal Decision-Making under the Impacts of Climate Change)**

Overordnet konkluderer denne afhandling, at mulighederne for at opnå synergi mellem reduktion og tilpasning er gode, især på landskabsniveau. **Artikel 1** konkluderer også, at det er nødvendigt med større empirisk viden om synergi, omkostningseffektivitet, usikkerhed og risici samt kompleksiteten ved at kombinere tilpasning til og reduktion af klimaændringer. Der er specielt gode muligheder for at opnå synergi mellem tilpasning og reduktion på landskabsniveau. **Artikel 2** omhandler netop denne empiriske viden. Artiklen viser, hvordan der kan opnås et incitament til øget tilpasning ved udbetaling fra kulstof, svarende til de kreditter, der kan opnås i et kulstofkreditsystem. Derfor er det vigtigt at se på bredden af handlemuligheder og undersøge, hvordan strategierne for handlemuligheder ændres over tid. Netop dette understreges i den anden artikel. Råderummet og handlemulighederne for dem, der er påvirket af klimaændringer, er et vigtigt aspekt, fordi der hersker stor usikkerhed om omfanget (påvirkningsgraden) af klimaændringerne og derved også stor usikkerhed omkring nytten af tilpasning til og reduktion af klimaændringerne. Dette vanskeliggør beslutningsprocessen. Vigtigheden af dette bekræftes i **Artikel 3**, hvor vi ser, hvordan nepalesiske bønders valg i tilfælde af uforudsete kriser er styret af muligheden for at få adgang til penge for at

overvinde krisen. **Artikel 4** eksemplificerer, hvordan optimale valg i forbindelse med aktuelle råderum og handlemuligheder kan ændres, efterhånden som der opnås øget viden.

De politiske anbefalinger i ph.d.-afhandlingen er, at man - for at skabe synergi mellem tilpasning til og reduktion af klimaændringer - er nødt til at forstå, at de, der rammes af klimaændringer, oftest har de færreste ressourcer og derfor rammes ekstra hårdt. Dette betyder også, at de har et begrænset råderum til at klare sig igennem eventuelle kriser og oftest ikke har de ressourcer, der skal til for at tænke i langsigtede strategier. Dette understreger vigtigheden af at sammenkæde udvikling med kampen mod klimaændringer for på denne måde at sikre verdens fattigste et øget råderum. Det vil gavne deres tilpasningsevne over for klimaændringer og sætte dem i stand til at træffe bedre beslutninger for fremtiden. Da der er tale om et globalt problem, bør beslutninger om at maksimere velfærden ved en reduktion af klimaændringer træffes på globalt plan, og afhandlingen konkretiserer situationer, hvor dette vil give mening.

Danish Summary of the Individual Papers - dansk resumé af de enkelte artikler

Artikel 1 (Joint Adaptation and Mitigation in Agriculture and Forestry) tager en overordnet tilgang til tilpasningen til og reduktionen af klimaændringer og ser på, hvilke erfaringer der er beskrevet i litteraturen inden for skovbrug og landbrug i udviklingslande. Vi opsummerer de beskrevne barrierer og muligheder for at opnå synergi. Yderligere konkluderer artiklen, at synergi mellem reduktion og tilpasning ikke bør tilstræbes blot for at gavne begge, men at den mest optimale løsning bør vurderes i hvert enkelt tilfælde - lokalt og globalt. Artiklen understreger desuden vigtigheden af øget samarbejde mellem lovgivende institutioner både lokalt og globalt for at skabe synergi mellem klimatilpasninger og reducerede klimaændringer.

Artikel 2 (Estimating the Benefits of the Interrelationship Between Climate Change Adaptation and Mitigation – A Case Study of Replanting Mangrove Forests in Cambodia) undersøger, hvordan genplantning af mangroveskov kan være et middel til klimatilpasning, der beskytter fattige fiskere bosat i området. Vi beregner tilpasningsgevinsterne ved at betragte de marginale, forventede, men hindrede skadesomkostninger for levevilkårene pr. genplantet hektar mangroveskov og gevinsterne ved at afværge CO_2-binding i skoven. Disse to potentielle gevinster sammenholdes med etableringsomkostningerne for mangroveskov. Artiklen konkluderer, at ud fra et velfærdsøkonomisk perspektiv så er nytten ved tilpasning positiv på tværs af en række klimascenarier og tilplantningsintensiteter. Denne virkning forstærkes, hvis man indregner gevinsten ved at reducere udledningen af drivhusgasser. Sidstnævnte vil føre til en højere grad af optimal tilplantning.

Artikel 3 (Empirically Based Analysis of Households Coping with Unexpected Shocks in the Central Himalayas): På basis af data fra husstandsundersøgelser ser artiklen specifikt på, hvilke beslutninger nepalesiske bønder tager for at komme igennem perioder med uforudsete, klimarelaterede chok (positive eller negative), hvordan de tidligere har håndteret et klimarelateret tab eller en gevinst, og hvad de forventer at gøre, hvis en klimarelateret hændelse finder sted inden for det kommende år. Denne analyse anvendes til at udforske, hvilke handlemuligheder bønderne har, og hvilke de vil vælge, hvis tabene som forventeligt bliver større i fremtiden på grund af klimaforandringer. Specifikt analyserer vi betydningen af deres aktiver (såsom indkomst, antal mænd i familien og husdyr) i forhold til de valg, de træffer, ved hjælp af en 'multinomial logit regression'. Resultaterne af analysen er, at bøndernes foretrukne strategi i forbindelse med tab er at få hjælp fra andre eller optage lån. I forbindelse med en gevinst vælger de hyppigst opsparing. Artiklen konkluderer, at bønderne oftest har et begrænset råderum til at komme igennem en krise, hvilket begrænser deres evne til at tilpasse sig fremtidige klimaændringer samt den nuværende klimavariabilitet.

Artikel 4 (Optimal Decision-Making – Adaptation to Climate Change in the Agricultural Sector) anvender 'Bayesian updating' til at illustrere, hvilke handlemuligheder man har i forhold til tilpasning, og hvilke muligheder der er for at modstå fremtidige klimaændringer. Artiklen demonstrerer, hvordan det optimale valg kan ændre sig over tid, efterhånden som mere information bliver tilgængelig. Vi bruger et eksempel med repræsentative, ghanesiske landmænd. Vi viser, at jo mere viden, der bliver tilgængelig over tid, jo bedre valg kan landmanden træffe. Dette viser værdien af at træffe beslutninger, som er fleksible, og som dermed kan tilpasses den usikkerhed, der ligger i klimaændringer.

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Part 2: Papers

1. Introduction

The main research objective of the PhD thesis is to explore the relationship between climate change mitigation and adaptation in ecosystems, focusing on barriers, opportunities and decision-making at management unit level. Ecosystems are central to the livelihoods of many people, and some are highly vulnerable to climate change. It is generally acknowledged that combining adaptation and mitigation can increase the effect of actions (Chia et al. 2016; Mbow et al. 2014). However, the existing conceptual and empirical knowledge base is too limited to fully assess such potential, and it is also questioned whether combining adaptation and mitigation is suboptimal (Duguma et al. 2014; Watkiss et al. 2015). Following the ratification of the Paris Agreement - the first global agreement on climate change - and the move towards its implementation, there are strong arguments in favour of increased research into this field. Many submissions by countries (Nationally Determined Contributions) specifically emphasise the linkages between mitigation and adaptation and the need to pursue mitigation, adaptation and development jointly. In addition, we are starting to see severe impacts of climate change, and evidence points to a further increased impact in magnitude and scale. More research is required to improve our understanding of ways to link adaptation and mitigation and of the possible benefits and optimal ways of doing so. The PhD thesis focuses on this issue of adaptation and mitigation in ecosystems.

Ecosystems refer to ecological communities which contribute to ecosystem services (Fisher et al. 2009) - defined as the benefits that people and communities obtain from ecosystems (UNISDR 2009). The PhD thesis specifically considers situations where adaptation and mitigation can be considered as ecosystem services arising from ecosystem impulses or ecosystem management to deliver the services in an optimal manner. Ecosystem valuation is a key element in environmental decision-making, making it possible to give ecosystem services a monetary value which can create a foundation for decisions (Fisher et al. 2009). The advantage of an ecosystem approach is that it gives us the freedom to look at interactions between ecosystem complexity and structure on the one hand and at people’s practices, values and regulation of ecosystems on the other (Termansen et al. 2015).

Sometimes it is not enough to know *what* the optimal response to climate change is. We also need to know *whether* it is possible to make the optimal decision, what *conditions* are required for the optimal decision and *who* is taken the decision. Optimal responses will depend on what is found desirable for the future of the individual based upon the existing knowledge level. The notion of capabilities is central to decision-making at farmer and household levels. Individual capabilities are determined by a person's freedoms of action, related to e.g. level of education, literacy and income level (Sen 2003). Low levels of development will often be correlated with low levels of capabilities and can be a barrier to future improved decision-making on how to cope with or adapt to climate change. Capabilities can be increased through sustainable development. Sustainable development is intrinsically linked to adaptation, vulnerability reduction and enhanced climate change resilience and can be supported by local stakeholder involvement, acknowledging local knowledge – and scientific knowledge – in a learning process (Laukkonen et al. 2009). It is therefore important to consider relationships between adaptation and mitigation in the context of decision-making and sustainable development (Locatelli et al. 2015; Matocha et al. 2012; Watkiss et al. 2015).

The following sections provide an overall framing for the research carried out under the PhD project and the approaches and methods employed in the four papers encompassed by the PhD project. Section 1 is an introduction to the main research objective of combining climate change adaptation and mitigation in ecosystems and the link to development. Section 2 discusses the complexity of climate change adaptation and mitigation, their differences and consistencies in goals, impacts and effects.

Section 3 describes the overall and specific research objectives of the PhD thesis and how these have been addressed. This is followed by a delineation of topics covered under the thesis and by an account of the research design of the individual papers, addressing the specific research objectives of the PhD thesis.

Section 4 outlines the analytical framework, presents the empirical context of the individual papers and considers the applied forms of data collection and case study methods. This is followed by a presentation of the theoretical approaches, methods and analyses applied in each paper and a discussion of alternative methods that might have been used to achieve the research objectives.

Section 5 provides an extended abstract of each of the four papers, while section 6 discusses the main findings across the individual papers. Section 7 concludes the PhD thesis, including a discussion of the research contribution, interpretations of the contribution of scientific methods and empirical knowledge and the possibilities of a policy implication that may facilitate international scientific consultancy and options for further research and perspectives.

2. The Complexity of Climate Change Adaptation and Mitigation

The above introduction highlights the need for further research into climate change adaptation and mitigation and the possible disaster consequences if adaptation and mitigation are not achieved in a cost-effective manner. It also highlights the need to gain the required knowledge about the differences and consistencies between adaptation and mitigation, linking it to development and decision-making. Thus, the complexity needs to be understood.

The IPCC defines mitigation as an ‘anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases’ (Klein et al. 2007). Adaptation is defined as an ‘[a]djustment in natural or *human systems* in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities’ (Klein et al. 2007).

Adaptation and mitigation differ at both temporal and spatial scales, which complicate their joint pursuit. Firstly, the benefits of mitigation are typically viewed in a global, long-term perspective, given the time lag between greenhouse gas emission reductions and the achievement of equilibrium of the concentration in the atmosphere. Furthermore, climate change is a global issue with public good characteristics, and therefore, it does not matter *where* emission reductions or sink enhancements take place (Watkiss et al. 2015). On the other hand, climate change adaptation contributes with disaster risk reduction and increased resilience and is therefore generally viewed at a local scale and in a short-term perspective (Landauer et al. 2015; Watkiss et al. 2015).

Secondly, adaptation and mitigation differ in terms of the actors who are involved. Mitigation in ecosystems can be achieved through three main categories (Smith et al. 2014): *reduction/prevention* (conservation of existing carbon pools to avoid emission to the atmosphere), *sequestration* (enhancing the carbon uptake in trees and plants in ecosystems, thus removing carbon from the atmosphere and reducing emissions) and *substitution* (biological products used as substitutes for fossil fuels). This is what is referred to as the supply side of mitigation, dependent on the management behaviour. Mitigation can also be approached from the demand side, considering changes in human lifestyle, behaviour, diet and consumption which are difficult to manage. This falls outside the scope of the PhD thesis. Mitigation can be achieved at many different levels: from governments and national institutions trying to fulfil their national commitments to the Paris Agreement to private and individual stakeholders who recognise the business opportunities of new technologies or carbon payments.

Adaptation can also involve different levels of institutions and actors reacting to climate change, either through planned or unplanned actions. Planned actions can be *proactive,* i.e. occurring before the effects of climate change are experienced, or *reactive*, i.e. occurring after changes have occurred. Unplanned or autonomous adaptation to change (Tschakert &Dietrich 2010; Watkiss et al. 2015) can be an unconscious response to changed conditions, thus improving the situation (Smit et al. 2001). Coping also refers to reactive responses to climate change impacts, i.e. initiatives which are based on the available resources and implemented in situations where shocks are unexpected and short-term, immediate reactions are necessary to overcome the situation (UNISDR 2009). Coping is adaptation to a shock and how to get through a crisis, but does not minimise the long-term effect of climate change as climate change adaptation.

Considering adaptation and coping, there is a risk that short-term actions implemented in order to overcome unexpected shocks increase the vulnerability in the medium to long-term perspective (Olhoff & Schaer 2010). In some situations, actions necessary to cope with unexpected shocks compromise the long-term perspective of adaptation. Such situations can be defined as maladaptation. More precisely, maladaptation is defined by the OECD as 'business-as-usual development which, by overlooking climate change impacts, inadvertently increases exposure and/or vulnerability to climate change. Maladaptation also includes actions undertaken to adapt to climate change impacts that do not succeed in reducing vulnerability but increase it instead' (OECD 2009).

3. Research Objectives and Design

3.1 Research Objectives

The main objective of the PhD thesis is to explore and assess the relationships between climate change adaptation and mitigation in forestry and agriculture in developing countries with a main focus on barriers and decision-making.

The main objective is addressed through the following three research focus areas, including a brief summary of how the focus area in question is addressed in the thesis:

I. Explore options for joint benefits of climate change adaptation and mitigation, and how such benefits can be assessed.

Prior to empirically exploring the options for joint benefits of climate change adaptation and mitigation, ***Paper 1*** *contributes with a literature review and analysis of ways in which mitigation activities can generate adaptation benefits and vice versa. It also considers the integrated and synergetic effects that can be derived.*

Paper 2 *contributes with an assessment of how benefits of JAM can be obtained. It includes a welfare economic analysis of the marginal economic benefits of replanting mangrove forest – as a JAM initiative – simulated over a 100-year period. The benefits of adaptation are reflected in the marginal, avoided damage costs of replanting an extra hectare. The marginal benefits of climate change mitigation are estimated for the replanted area. A monetary value is estimated on the basis of different estimations of carbon values – ranging from a likely price in the market to possible estimates of the social costs of carbon.*

II. Explore how decision-makers make decisions in order to cope with climate change, and how forward-looking adaptation methodologies may improve such decisions.

The PhD thesis takes two approaches to investigating the second research focus. ***Paper 3*** *analyses agricultural production-dependent Nepalese households' preferred choices of coping strategies in the past and in the expected future. It uses a multinomial logit model to describe the households' preferences of coping strategies.*

Paper 4 *takes a forward-looking approach through Bayesian updating. The paper presents a simulation of the consequences of farmers' choices of adaptation strategies combined with their knowledge of climate change impacts for optimal* *decision-making. Both papers discuss the options to improve decisions made by decision-makers. A combination of the contributions of **Papers 3 and 4** provides a perspective as to how the decision-making can be improved at a management unit level.*

III. Explore current barriers to implementation of climate change adaptation and mitigation measures in forestry and agriculture, and how they can be overcome.
*The barriers are derived from the overview and analysis in the four papers, which also discuss options to overcome these, e.g. the complexity of estimating the welfare benefits of local adaptation and global mitigation combined (**Paper 2**), and rural households' dependence on agriculture and their choices for coping with climate change, addressing the capacity barriers in developing countries (**Paper 3**). **Paper 4** contains a simulation of decision and reaction patterns in relation to the belief in future climate changes and a trajectory of decisions when the knowledge about future climate is gradually increased.*

3.2 Delineation of Topics Covered by the Research

A main objective of the PhD thesis is to explore the management of ecosystems within the land use sector, focusing especially on agriculture and forestry and the links between these. Other key sectors for obtaining JAM include waste management, construction, planning and infrastructure (Illman et al. 2012), which, however, fall outside the scope of this thesis. Similarly, governance and political decision-making, bioenergy and migration are not included in the thesis, but play an important role for the choices of analyses in the thesis. Hopefully, the thesis can contribute to increased evidence of the situations where joint adaptation and mitigation should be pursued.

Further discussion of the applied IPCC guidelines (IPCC 2006 and IPCC 2014) regarding calculation of the amount of carbon sequestrated through the replanting of mangrove forest and the possible risks and uncertainties of applying these methods also falls outside the scope of the thesis. The amount of carbon sequestrated and emitted for replanting and destruction of mangrove forest in **Paper 2** is calculated based on IPCC's guidelines.

3.3 Research Design

Table 1 below provides a detailed outline of the research objectives and the methods, theoretical approaches, cases and examples applied in the four papers comprising the PhD thesis.

Table 1 illustrates how research objectives I and II are divided between the four papers and how all four papers contribute to meeting the third research objective (III). The table also illustrates the importance of decision analysis and its relation to climate change adaptation and mitigation.

Table 1 Interlinkages between the research objectives of the PhD thesis and the research questions and relations of the individual papers

Paper	Research objectives of the PhD thesis	Research question(s) of the individual paper	Methods	Cases or examples	Decision-making analysed
1	**I + III**	• How does the literature define joint benefits between climate change adaptation and mitigation? • What are the barriers to obtaining these benefits?	• Literature review of the underlying concepts of JAM. • Applying a snowballing process to identify publications used and cited by others.	• Multiple examples drawn from existing literature regarding practices within agriculture and forestry in developing countries that create benefits for adaptation and mitigation.	N/A
2	**I + III**	• Does approaching adaptation and mitigation as complementary actions allow us to assess whether a combination of climate change adaptation and mitigation at a local case level can contribute to greater welfare compared to initiatives in which adaptation and mitigation are addressed separately in response to climate change?	• Explanatory interviews with households. • Estimation of expected damage costs. • Social cost of carbon.	• Replanting of mangrove forest in Peam Krasaop, Koh Kong Province, Cambodia.	Analysis of the welfare benefits of joint adaptation and mitigation.
3	**II + III**	• Which coping responses have rural households utilised in the past to overcome unexpected shocks, and which coping responses do they expect to use in the future? • How do households differ in their responses and how is this linked to their livelihood strategies and assets?	• Household surveys. • Multinomial logit regression.	• Rural households level information on unexpected shocks, Mustang District, Nepal. • PEN income survey.	Analysis of rural households' dependence on agricultural production choice as coping strategy in case of unexpected shocks (positive and negative).
4	**II + III**	• How fast should we adapt, or more precisely, *when* should farmers shift focus from one agricultural system to another to adapt to climate change?	• Bayesian updating. • Climate realisation based on model combinations from the Coordinated Regional Climate Downscaling Experiment (CORDEX)	• Exemplifying Ghanaian farmers' choice of agricultural production as adaptation to climate change. • The three climate scenarios: one global/regional climate model combination and two future scenarios (RCP4.5 and RCP8.5), representing the GHG reduction policy, moderate and unsustainable.	Analysis of exemplified farmers' choice of adaptation strategy and how it developed as the information of the future climate trajectory is revealed.

4. Analytical Framework

The analytical and conceptual understandings of synergy between adaptation and mitigation and the important links to development, decision-making, agriculture and forestry were outlined in sections 1 and 2. The present section accounts for the empirical data (section 4.1) and the methodologies and theories applied (section 4.2) in the four papers to address the research questions and objectives of the individual papers.

4.1 Empirical Context – Data Collection Methods and Case Studies

The following sections describe the empirical examples, cases and data applied in the individual papers. To a great extent, existing data is applied in the four papers. The countries used as cases and examples are developing countries found north of the equator. **Paper 1** is a literature review and is therefore not considered in this specific section.

Cambodia

Exploratory interviews and observations were conducted by me in Cambodia from January to February 2014. The following cities and rural districts were visited: Phnom Penh, Mondol Seima District, Koh Kong Province and Prey Nob District, Sihanoukville Province, Cambodia. The purpose of the interviews was to get an overall impression and understanding of the living conditions of farmers and fishermen in the rural districts of Cambodia. Focus was on the two projects 'Vulnerability Assessment and Adaptation Programme for Climate Change within the Coastal Zone of Cambodia Considering Livelihoods Improvement and Ecosystems' (VAPP under the Least Developed Countries Fund (LDCF) project) and the 'Coastal Adaptation and Resilience Planning Project' (the CARP project), supporting Cambodia's 'National Adaptation Programmes of Action' (NAPA) strategy. Partnering organisations and staff at ministries associated with the projects were interviewed to obtain key information and interviews of fishermen and farmers implementing integrated farming. Project documents and reports have been used to gain in-depth knowledge about the CARP project and the cost and income options of fishermen in Peam Krasaop (CCCA 2012). The CARP project is being implemented alongside the longer running LDCF project.

The Peam Krasaop community is located inside the Peam Krasaop Wildlife Sanctuary on the coast of Cambodia in the Koh Kong Province and is part of the CARP project. In October 2013, 15 hectares of mangrove forest were replanted just outside the community border of Peam Krasaop - as a climate change adaptation initiative.

For simulation of wind damage caused by climate change and the ability of the mangroves to protect the community from storm damage, historical data is applied. It is the experience that damage occurs when the wind speed reaches 12 m/sec (CCCA 2012). Therefore, this has been referred to as a storm, even if it is not defined as such in technical terms. From 1979 to 2012, wind speeds over 12 m/sec were measured at two points outside Cambodia's coast. These historical data have provided us with an opportunity to calculate the daily probability of storms for each month of the year (Nielsen 2013) and assess the community's vulnerability to climate changes and cost of damages caused by wind in 2011 (CCCA 2012). The data is used to simulate day-specific risk of wind speeds higher than 12 m/sec for a 100-year period. Data from that CARP project and historical wind data are used as an empirical case in **Paper 2.**

Nepal

The data applied in **Paper 3** are from Nepal, focusing on the Lete and Kunjo Village Development Committees (VDCs – the smallest, local administrative unit in Nepal) in the lower part of the Mustang District in the Western Development Region of Nepal. Data originate from two different surveys, both of which were conducted from December 2008 to November 2009. The first stream of data consists of a time series of all environmental, farm and non-farm income and asset data surveys originating from CIFOR's Poverty Environment Network[1] (PEN), following the PEN protocol (Angelsen et al. 2011; Larsen et al. 2014) (n=186). The second survey is a not previously published elaboration of the PEN survey, where household level information on unexpected shocks (negative or positive) is investigated. Data are obtained by asking the rural households about their behaviour in the past and their expected behaviour in the future, elaborating on affected crop types in the agricultural production, the value of losses or gains and the expected standard value of the crop production that year, thus making it possible to calculate the lost or gained percentage and to specify whether the shock in question was moderate (< 50 per cent) or substantial (> 50 per cent). The cause of the losses or gains was also registered as closed-ended questions. A sequence of up to three chosen coping strategies applied by the households in case of unexpected shocks was specified. The households were also asked to specify how much a given coping strategy contributed to covering the unexpected loss or gain in production – within the range of 0-20 per cent, 20-80 per cent or 80-100 per cent. In addition, they were asked to assume that they would experience a substantial

[1] http://www.cifor.org/pen

unexpected increase or loss in total agricultural production in the coming year (moderate or substantial).

A number of households were excluded as they did not complete all the income surveys or could not be located at the time of interview (n= 112). The survey is a subset sample of the PEN dataset. The two surveys were composed by Øystein Juul Nielsen and Santosh Rayamajhi, respectively. **Paper 3** contributes with a detailed description and the characteristics of the study area.

Ghana

Paper 4 uses Ghanaian farmers' choices of agricultural systems as adaptation to climate change as an example of the behaviour of farmers. The basis is a representative farmer. The functions used to estimate the net revenue of Ghanaian farmers' income from the three agricultural systems are: dryland crops, irrigation crops and livestock. These net revenue functions originate from Kurukulasuriya et al. (2006). The functions contributing with the marginal climate impacts on net farm revenues per farm (in USD) which are determined through a Ricardian model and ordinary least squares regression. The results of Kurukulasuriya et al. (2006) are based on more than 9,000 surveys conducted in 11 different countries. The coefficients applied for the net revenue functions are found to be biased towards irrigated farming, which Kurukulasuriya et al. (2006) explain as an overrepresentation of data on irrigated farming from Egypt, whereas the crop in Ghana is mostly rainfed. Therefore, we are not just considering the mean coefficients, but also their minimum and maximum values for the net revenue functions.

The main advantage of the data from Kurukulasuriya et al. (2006) is that the net revenues revealed by their analyses reflect the benefits and costs of autonomous adaptation and coping strategies, such as the preference for more heat-tolerant goats over cattle. Autonomous adaptation includes a variety of contributions and the introduction of substitute actions, which farmers have incorporated in order to adapt to the current climate variabilities (Kurukulasuriya et al. 2006).

The focus of **Paper 4** is to show how the farmers' belief in climate change can influence the management decision. The exact results in quantitative terms are of less importance.

The second data part of **Paper 4** is a detailed analysis of state-of-the-art regional climate model projections for Ghana, analysing the changes in inter-annual variations of temperature and precipitation in chosen climate scenarios and trajectories of climate realisations. **Paper 4** applies three climate scenarios to represent different, possible climate realisations, using precipitation and (near surface air) temperature output from model combinations in the COordinated Regional climate Downscaling EXperiment (CORDEX) database (Nikulin et al. 2012).

The climate data is based on seven model combinations of output from where three global/regional climate model combinations and two future scenarios (RCP4.5 and RCP8.5), representing moderate and unsubstantial GHG reduction policies, respectively, were selected. The first scenario is the RCA model, downscaling the RCP4.5 scenario (hereafter titled C1) to constitute a 'baseline' climate of minimal change. The second scenario (HIRHAM, RCP8.5 – titled C2) was chosen as it was wetter than most, representing a temperature increase in the lower range of the included models and exhibiting a positive temperature and precipitation. Conversely, the third scenario (MPI-CCLM, RCP8.5 – titled C3) was selected for being the driest, having the highest temperature increase by the end of the century and a strong, negative temperature and precipitation correlation.

4.2 Theoretical Approaches, Methods and Analyses

The following provides an overview of the methods and analyses applied in the different papers. It includes a discussion of why these methods are applied and what alternative methods could have been selected.

Paper 1: Literature Review of JAM

In order to fulfil the research objective, it is necessary first to provide an overview of the existing literature on JAM, and how this subject has previously been treated within the ecosystem management literature, focusing on land use sectors – forestry and agriculture especially – with a large potential for JAM.

Method and Analysis

The complex connections between climate change adaptation and mitigation were captured in a literature review, which applied a snowballing process to identify publications used and cited by others. This approach was specifically chosen as a result of the lack of consistently used keywords within JAM and the very fragmented literature. The literature search was conducted during the period December 2015 to March 2016. The starting point for the literature search was peer-reviewed papers, however, due to the fragmentation of the literature also grey literature was included.

Paper 1 thus contributes with a necessary overview of JAM. With this information in hand, it was possible to identify the research gaps and to use this knowledge to further develop the study area.

This study does not claim to be a complete review of all existing literature on the topic, as its focus has been on forestry and agriculture. However, we believe that the study covers the topic adequately to provide an analysis of where JAM can be found within agriculture and forestry, and also where the barriers to obtaining joint benefits are currently found. These findings shed light on new research directions that can contribute with new knowledge and fill in the research gaps in the fight against climate change.

Discussion of Alternative Approaches

Meta-analysis might have been an alternative approach to conducting the literature review of JAM in the land use sectors. A meta-analysis enables the researcher to identify and gather research findings across studies that examine clearly defined subjects through identification of common effects. Typically, it adopts a statistical (meta-regression model) approach to interpreting and explaining the results (Hunter & Schmidt 2004). However, it was not possible to conduct a meta-analysis in **Paper 1** as the literature on JAM is fragmented, the complexity of the subject high and the approach to the subject exploratory. Existing studies do not have adequate information and characteristics, and the current and general lack of empirical examples of JAM makes it impossible to treat the gathered information in a regression or similar, statistical analysis.

Paper 2: Estimating the Joint Benefits of Adaptation and Mitigation

The main research question we wish to answer in **Paper 2** is whether a combination of adaptation and mitigation can lead to higher welfare. The focus of the paper is a marginal valuation of avoided, expected damage cost (EDC) and the possible benefits of carbon sequestration from mangrove forest. The following describes how EDC may be used to estimate the value of the potential contribution of ecosystems to joint adaptation and mitigation.

Method and Analysis

The approach takes the perspective of a social planner. It assumes a utility function $U_i(A,M,H,Z)$ of the services from an ecosystem under the impact of climate change in scenario *i*. *U* is a function of *A*, *M* and *H*, where *A* represents the benefits of climate change adaptation, *M* represents the benefits of climate change mitigation, and *H* represents the possible co-benefits of combining adaptation and mitigation. Finally, *Z* is the cost of enabling, establishing or increasing the area of the ecosystem to contribute with mitigation and adaptation. If we allow *U* and the parameters within it to depend on time *t*, then the utility of the ecosystem services can be written as:

$$\boldsymbol{U_i(A,M,H) = \int_{t=0_0}^{T} U_{ti}(A_t, M_t, H_t)\, e^{-rt} dt} \qquad (1)$$

where r is the discount rate, and subscript t denotes the time.

Assuming that the utility is linear in input, we can write equation 1 as follows:

$$\boldsymbol{U_i(A,M,H) = \int_{t=0_0}^{T} (A_t + M_t + H_t - Zs_t)\, e^{-rt} dt} \qquad (2)$$

We assume that A_t, M_t and H_t are functions of the area of the entire ecosystem (S_t). This can e.g. be the case where the ecosystem has erosion-protective or carbon sequestration effects, increasing with area size. We also assume that Z solely depends on the change of the size of the ecosystem (s_t) at time t. Thus, we assume that the cost of changing the size of the ecosystem is independent of whether we look at climate change mitigation or adaptation initiatives. Thus, if the cost has been accounted for when estimating the benefits of adaptation, it is not necessary to account for the cost again when estimating the benefits of mitigation.

The decision to be made is *how much of an ecosystem* should be re-established (s_t). In **Paper 2** we assume that the re-established and the existing ecosystems have the same value, which is a reasonable assumption by the margin. This could be modelled differently if the health of the ecosystems, i.e. their ability to regenerate (Pramova & Locatelli 2013), was included explicitly in the valuation.

We now look at how A and M can be estimated. The benefits achieved in addition to the benefits of adaptation and mitigation are referred to as co-benefits (H) of replanting mangrove forest (see Equation 1). H is assumed to be zero ($H_t = 0$) in the applied case of **Paper 2**.

The Use of the Expected Damage Cost Approach to Estimating the Benefits of Adaptation (A)

We estimate the increased welfare benefits of adaptation as the area increase (s_t) in relation to the ability of the overall area (S_t) to contribute with adaptation of climate change. This may e.g. be coastal protection as in **Paper 2**. For this estimate, we need to look at the expected damage occurring for a given size of ecosystem. We do so by using the framework of an Expected Damage Function (EDF) based on Barbier (2007) and Hanley & Barbier (2009).

The EDF has been used regularly in risk assessments and health economics looking at how changes in assets affect the probability of the occurrence of a damaging event. The method requires use of the ecosystem as input, developing a 'production function' (Dupont 1991) for the ability of ecosystems to adjust and increase the resistance of the community against impacts from climate change. The EDC is generally considered to be a valid approach to estimating the lower boundary of the value of avoided damage costs by mitigation of damages (Boutwell & Westra 2015), as it captures the full value of an ecosystem providing a service. The strength of applying the EDC is that it allows for careful evaluation of the assumptions behind it and thereby points out knowledge gaps. Boutwell & Westra (2015) highlight that errors may appear if the case is not well-defined or the quality of the data is poor (Boutwell & Westra 2015). In **Paper 2**, the case is a well-defined and very narrow – the case of Peam Krasaop in Cambodia. However, it is also a developing country context, where data is often limited, as is the case here. Nevertheless, decisions are still made – more or less informed. Consequently, judging the reliability of the assumptions is crucial, and possible caveats are discussed in **Paper 2.** Here the emphasis is on the setup.

The expected cost of the damage is a measure of the welfare loss caused by changes in the minimum number of acquired goods in their expenditure function, which again is a result of the expected damage to the households due to climate change. This can be estimated as the minimum income for a household in order to maintain the utility level from a no-change scenario in a given climate scenario. This difference is called the compensating surplus. This difference in utility can be expressed as a marginal willingness to pay (USD/ha) (the expected gain from changing a wetland/mangrove area by one unit) and is analogous to the Hicksian compensated demand function for market goods (Freeman III et al. 2014).

Discounting and aggregating the value of the compensating surplus for the establishment of an ecosystem area can be calculated as the integral of the reduced damage at all points in time. This makes it possible to estimate the marginal value (in present value terms) of the last replanted hectare of mangrove forest in the context of climate change adaptation. It can be expressed as the marginal, avoided EDC.

Estimating the Benefits of Mitigation (M)

The underlying assumption of the ability of ecosystems to mitigate climate change is their ability to sequestrate CO_2 from the air through plant growth and to capture it in organic material, e.g. wood, roots, dead organic matter. The benefits of mitigation may be calculated as the monetary value of the carbon sequestration in the ecosystem at time *t. A*s we have a social planner perspective, the monetary value can be seen as the social cost of carbon.

The benefits of mitigation at time M_t can be expressed as a function of $\dot{S}_t$ over the time period we are considering:

$$\boldsymbol{M_t = L(\dot{S}_t)} \qquad (3)$$

Here L is the function for captured CO_2 in the ecosystem.

Aggregating and discounting over time, we have the contribution to Equation 1, and the marginal value of mitigation can be obtained in a manner which for the last established hectare is similar to the marginal value of the avoided EDC.

In **Paper 2** the focus is on replanting mangrove. Another example where the same approach could be used is the possible benefit of adaptation and mitigation found through avoided deforestation. Deforestation (or clear cutting) can create an actual threat to a community due to an increased risk of land slides and flooding combined with increased precipitation levels from climate change (Matocha et al. 2012). In that case *A*, *M* and *Z* from equation 2 could be defined as followed: *A* could be the benefit of adaptation, i.e. the economic value of the avoided damage to the community from landslides. *M* could be the benefits of mitigation, i.e. the amount of carbon stored above and below ground which is at risk of being emitted to the atmosphere in case of forest clearance. *Z* would be the cost per hectare of avoided deforestation, i.e. the opportunity cost, and will depend on the driver of the deforestation (e.g. deforestation caused by cattle farming or small scale slash-and-burn agriculture).

Discussion of Alternative Approaches

Considering alternative approaches to fulfilling the research objective of **Paper 2**, one must remember the complexity of modelling the joint benefits of adaptation and mitigation.

An alternative to the EDC approach is to consider the provision of *A* and *M* as a joint production[2]. In that case, the approach of Vincent and Binkley (1993) can be used, i.e. considering the production of two goods or products in two stands. The Production Possibility Frontier (PPF) summarises the information regarding the benefits of the two products when sharing the management effort of the stands. Based on the classical theories of microeconomics with diminishing marginal return (Gravelle & Rees 2004), it is assumed that the PPF will be concave. However, it may take other forms. The products that Vincent and Binkley (1993) consider are timber (*T*) and non-timber forest products

[2] A similar distinction is the concept of land sparing and land sharing. Here I choose to refer to joint production as it emphasises the value, as does the EDC approach.

(*NT*), two independent products. The production of *T* and *NT* is considered for two stands and jointly produced in each stand, sharing the management effort per hectare. They show how the leading product can be superior to joint production by allocating the management effort to the product that does best under the specific conditions of the stand. They highlight how products can contribute with a higher (economic or ecological) value.

Joint production was not applied, as the production of adaptation and mitigation in the specific case of mangrove replanting is not a trade-off between the two objectives. Carbon sequestration is inevitable when mangrove is replanted for climate change adaptation. The marginal curve for the welfare benefits of adaptation and mitigation was estimated. This makes it possible to identify the optimal level for replanting mangrove forest in three climate scenarios and two replanting strategies. These scenarios and strategies reflect a broad range of results and visualise the uncertainty which must be considered in future decision-making.

Vo et al. (2012) and De Groot et al. (2002) review different valuation methods for mangrove ecosystems, and both suggest applying avoided cost in the form of indirect market pricing as a disturbance regulator where the ecosystems provide protection from environmental disturbances. However, avoided cost approaches are normally static. When we add the level of replanting scenarios and different damage regimes from climate change scenarios, the evaluation becomes dynamic. Therefore, we further elaborate on it by applying the theory of the EDC (Hanley & Barbier 2009).

However, it is possible to apply joint production in other cases where adaptation is included as a trade-off for mitigation initiatives or vice versa. An example is a forest that contributes with timber production and protection from soil erosion. If the harvest regime is increased, the erosion of the soil will increase and vice versa. Therefore, it is necessary to determine what has the highest priority. It is also possible to make the principle of joint production dynamic by discounting the different net revenues over time. In the case of this PhD thesis it reflects how adaptation and mitigation benefits are most suitable across the landscape as a multi-functional space (Scherr et al. 2012).

If we had broadened the evaluation to also include the co-benefits of replanting mangrove forest as mentioned above, this could have been included by the preference-based methods to capture e.g. non-use values. However, as the case considered focuses on poor households, we consider it of less relevance to measure non-use values.

The valuation of the mitigation benefits is expressed as an indirect use value that benefits society on a global scale. It originates from the fact that forests sequester carbon. As mentioned, the paper does not go into details with the accounting rules, however, it is highly relevant to discuss which carbon prices should be applied. The results of **Paper 2** clearly show that an increase in carbon prices changes the optimal level for replanting mangrove forest, increasing the benefits of adaptation. The paper applies carbon prices in the range of USD 0.54 per tCO_2e to USD 13.18 per tCO_2e. Critical voices are likely to argue that we should apply a social cost of carbon (SCC) of about USD 200 per tCO_2e. The SCC is the net present value of one more or one less tonne of CO_2e emitted (van den Bergh & Botzen 2015). SCC is obtained from integrated assessment models (IAM), but it is outside the scope of this PhD thesis to discuss the details hereof (see van den Bijgaart 2016, Tol 2008 and Nordhaus 2014, for a discussion of the topic).

The argument for applying the low carbon prices was that they should reflect prices that could likely be obtained in a market for quotas and thus rely on the political will to reach agreements that maximise global welfare. An optimal, global policy would lead to a traded carbon price corresponding to the SSC. **Paper 2**, Appendix C, Figures C1 and C2, shows similar results as Figures 4 and 5 in **Paper 2**, but with substantially higher carbon prices (CP1 = USD 50 per tCO_2e, CP2 = USD 100 per tCO_2e, CP3 = USD 200 per tCO_2e) with a discount rate of four and 12 per cent, respectively. What both figures show is that regardless of the damage regime of the different climate scenarios, it is beneficial to replant mangrove forest in the case studied, and a higher carbon price makes it even more beneficial. This supports the original conclusion in **Paper 2** that from a social planner perspective, there are benefits by replanting mangroves even when you only consider adaptation. The benefits are even higher when mitigation is included.

The caveats stated in the paper are fully acknowledged. However, the above section argues in favour of the theoretical approach applied in **Paper 2**, which I believe to be well selected for the objective of the paper.

Paper 3: Multinomial Logit Regression for Analyses of Household Resources

The objective of the third paper is to increase existing knowledge about rural households dependent on agricultural production and their choices of coping strategies when faced with unexpected shocks, positive and negative, in the past as well as in the future.

Method and Analysis

In **Paper 3**, a multinomial logit (MNL) regression is applied to analyse household resources, their choices of coping strategies in the past and their expected future behaviour. When there are more than two choices, it is - following the argumentation in Gebrehiwot & van der Veen (2013) - correct to apply the multinomial regression model. For the specific study in **Paper 3** of households' choices of coping options, we estimated the likelihood of a certain choice characterised by a set of response variables. Thus we assume that households' responses are rational and that they will choose the coping response that maximises their utility (McFadden 1973). The most preferred coping responses are used as the base category, as they are assumed to be available to all household types regardless of characteristics. The households' resources are applied as explanatory variables.

In this way it is possible to analyse the probabilities of the households' choices of coping responses over the reference category compared to the households' resources.

Discussion of Alternative Approaches

Alternative approaches to the data analysis method of **Paper 3** include a hierarchical MNL regression, able to handle the prioritisation of coping strategies which the households were asked to make as well as the degree to which the coping strategy was able to cover the loss or gain experienced by the household. It would presumably have required a larger dataset to maintain a fair degree of freedom.

However, it might have been very interesting to apply the hierarchical MNL regression as this would allow an analysis in case of differences between the 'most common' and 'first choice' coping responses. It could potentially show differentiation between coping response appearances, e.g. where households would make a 'first choice' to cushion the impact of a shock and then later realise the impact and apply another coping response. However, in the MNL model there were no significant difference between moderate (< 50 % loss or gain) and substantial (> 50 %) shocks, so it is unlikely that there would be significant differences between 'most common' and 'first choice' coping responses in a hierarchical MNL regression.

Another issue that might have been interesting to capture is the degree to which households diversify their income. In the survey this could have been investigated by looking at the number of crops species that the individual household was growing, as this could increase the resistance and ability to overcome shocks (cf. Branca et al. 2013; Jacobi et al. 2015; Linger 2014). This might also be considered as increased capabilities of the household and might have been investigated by means of questions regarding adaptation (e.g. intercropping, wind breaks, agroforestry or having an orchard) and autonomous adaptation (e.g. change in crop species, increased irrigation, change in planting and sowing dates). However, these questions were not asked in the survey. An indication that it might have been relevant is the fact that the MNL regression actually showed that households which spend money on irrigation choose to reduce consumption rather than selling livestock or land or getting loans or assistance for coping with shocks (Table 6, **Paper 3**).

Exploratory interviews might have been of huge interest in order to see how the households would reply if they were asked specifically how they would react to a devastating natural disaster like earthquake or landslides and they plan to spend the money saved from positive shock. Exploring if the households' reaction pattern and coping strategy would be different depending on the shock type they are hit by. The fear - as in Wunder et al. (2014) – might be that the questionnaire does not capture shocks sufficiently severe to capture the coping strategies that really matter, the deep-uncertainty, high-consequence, low-probability events that can be devastating for a household.

A conclusive question that needs to be asked in relation to this analysis is regarding people's ability to recall what they did five years back. Rayamajhi et al. (2012) highlight that the ability of recall is one of the limitations of quantitative forest income studies, as one-year recall periods suffer from a serious underestimate of forest income (Lund et al. 2008). The income survey applied in **Paper 3** includes annual surveys (at survey start and end) and four quarterly income surveys in order to accommodate this limitation. The second part of the data set applied in **Paper 3** considers substantial and unexpected shocks which the households have experienced and which they must be expected to be able to recall - otherwise they would not be substantial. There is a small difference between the households' past and future behaviour. A critical voice might interpret this as if they choose to remember what they were expected to do. An alternative interpretation is that households are capable of critically judging how they got through past shocks and consequently judging how they expect to handle future shocks. This would indicate that the questionnaire exploring the households' choices of coping is well defined for the past and the future.

Based on this evaluation of methods and approaches for the analysis in **Paper 3**, it is found well selected for **Paper 3**.

Paper 4: Bayesian Updating – An Adaptive Approach to Management Decisions

Paper 4 deals with the way in which we make decisions and how we update the decisions as we acquire new information. In fact, we make subjective decisions about the future every single day.

When we plant trees in the forest, we assume that they will be able to survive despite climate change – if we consider climate change at all. If we buy a house by the coast, we evaluate whether the house will be affected by rising sea levels during the time that we will be living there. These decisions are irreversible in the short term due to the high costs associated with changing them, but they may be reversible in the long term as we gain more knowledge about the development of climate change. If we change our beliefs concerning climate change, we will likely plant different species. If new information emerges, e.g. new flood risk maps, we will make different decisions regarding housing. In Paper 4 we simulate this pattern of decision-making based on our beliefs, and how the decisions may change as we gain more knowledge. Consequently, using Bayesian updating can simply be seen as a way of formalising decision-making processes. It enables us to systematically analyse decisions and make recommendations that reach further than decisions based on current beliefs.

Method and Analysis

We apply Bayesian updating of beliefs concerning climate change. Basically, a set of subjective beliefs about the likelihood of various climate scenarios is identified. These may be based on past experience, on current observations, on rumours in society or on scientific evidence. Consequently, they may be considered to be subjective (Jacobsen et al. 2010). As time passes, a proactive decision-maker will observe the development of the climate (temperature and precipitation) and increase his knowledge of the realised climate scenario, changing the likelihood of the various climate scenarios, enabling him to gradually adapt his choices in order to make an optimal decision. Assuming the decision-maker makes rational decisions, he updates the beliefs of the probability of outcomes – conditional on the initial belief. Bayesian updating uses Bayes' theorem (Bayes and Price 1763), which is given by (Equation 4):

$$P(\mathrm{A}|B) = \frac{P(B|\mathrm{A})P(A)}{P(B)} \qquad (4)$$

The equation states that the probability of outcome *A* given another outcome *B* can be estimated based on the probability of *B* given *A* and the unconditional probabilities for each. In our setting, *A* is the probability of a given climate scenario and *B* the current beliefs of probabilities. This makes it possible to express a change in the probability as new data is observed (Skovgaard et al. 1999).

Discussion of Alternative Approaches

The ecosystem services management literature on estimation of future optimal decisions adopts either a static approach (as the theory of joint production previously described) or a dynamic approach. Bayesian updating belongs to the dynamic approach which takes into account that conditions may change over time.

Traditional approaches to characterising such uncertainty are based on past experiences. This includes e.g. the real option literature, where you estimate the value gained from additional information before making an irreversible investment (Arrow & Fischer 1974; Simal & Ortega 2011). Such approaches are not suitable in this context though, because they are based on known probability distributions which are not present when dealing with climate change (Yousefpour et al. 2014). Using Bayesian optimisation makes it possible to establish if the optimal choice will differ in accordance with the different beliefs in climate change and realised climate change. However, it is not possible to identify the initially optimal decision.

Applying the results in Paper 4 to the applied Bayesian updating we see an example of how the simulations reveal that the optimal choice actually does not change when using the mean coefficient from Kurukulasuriya et al. (2006) (Table 5, **Paper 4**), even when influenced by huge variabilities from the applied climate scenarios. The simulations show how the expected net revenue changes based on the decision-maker's beliefs in the future climate scenario, but the optimal agricultural system does not change. So even though the decision-maker will not get the net revenue he expected based on his belief, the truth will prevail in this specific simulation.

When applying the Bayesian updating, it is also interesting to reflect on the apparent 'nervousness' connected with the choice of optimal agricultural systems, applying the minimum coefficient from Kurukulasuriya et al. (2006) (Table 5, **Paper 4**). Such vagueness is likely because of the variabilities in the climate scenarios, making it difficult for the decision-maker to identify what climate scenario is the realised one. Here, this approach gets interesting as it means that it would be possible to simulate the ambiguity of people's beliefs in climate change and the consequences hereof and at the same time simulate how the decision-maker's information of the realised climate increases, thus enabling the decision-maker to make the optimal choice - something which is not possible applying in the real option theory.

In the current approach we have assumed a risk neutral decision-maker. It would actually be possible to include risk aversion in the optimisation process within the Bayesian updating framework, but we will leave this for future research.

5. Extended Abstracts of the Papers

5.1 Paper 1

Joint Adaptation and Mitigation in Agriculture and Forestry

Authors: Riyong Kim Bakkegaard, Lea Ravnkilde Møller and Fatemeh Bakhtiari.

UNEP DTU Partnership Working Paper series, Climate Resilient Development Programme, Working Paper 2: 2016.

Keywords: Climate Change, Adaptation, Mitigation, Agriculture, Forestry.

Introduction and Objective

This working paper starts with an overview of the underlying concepts of joint adaptation and mitigation (JAM). It captures how literature has defined the concept as benefits, synergies, integration, interlinkages and interrelationships and analyses of how mitigation activities can generate adaptation benefits and vice versa, and which synergetic effects might be derived from the pursuit of joint activities in the forestry and agricultural sectors. This is illustrated by practices and actions in agriculture and forestry in developing countries which are creating benefits for adaptation and mitigation.

Main Findings and Contributions

The paper outlines current barriers and opportunities for the pursuit of JAM within agriculture and forestry, offering guidance on *where* efforts should be focused to ensure the future development of JAM activities. These can among others include institutional and capacity barriers and opportunities, knowledge barriers and, importantly, funding barriers and opportunities.

For example, the historical and traditional way of separating adaptation and mitigation creates barriers at institutional and governance levels. The lack of adequate metrics for measuring adaptation is also a major barrier to the success of joint activities and to the further development of JAM activities. Likewise, the lack of funding is a barrier to both adaptation and mitigation. The prospect identified in JAM at landscape level is the opportunity to increase biodiversity and sustainable solutions. Furthermore, by including carbon income from mitigation it is possible to create incentives for adaptation and opportunities to overcome the underfunding of adaptation, making projects cost-efficient. The synergetic and individual effects of adaptation and mitigation are often felt at different times and places.

In conclusion, the most optimal results from JAM are achieved through a holistic landscape approach, seeing the landscape as a multi-functional space supporting food production, ecosystem conservation and rural livelihood. However, steering specifically after win-win situations of adaptation and mitigation, may be at risk of trade-offs for the sake of doing so and may jeopardise important solely adaptation or mitigation benefits.

5.2 Paper 2

Estimating the Benefits of the Interrelationship between Climate Change Adaptation and Mitigation – A Case Study of Replanting Mangrove Forests in Cambodia

Authors: Lea Ravnkilde Møller and Jette Bredahl Jacobsen (IFRO, KU).

Submitted October 2016 to Scandinavian Forest Economics.

Keywords: Synergies, Adaptation, Mitigation, Expected Damage Costs, Climate Change.

Introduction and Objective

The paper demonstrates the welfare benefits of climate change adaptation leading to mitigation in a case study of mangrove forest replanting in a part of the coastal wetland of the Peam Krasaop Wildlife Sanctuary in Cambodia. The community is suffering from storm damage which is expected to increase with climate change. Replanting of mangrove forests is a means of adapting to climate change by protecting the local community from storm damage. Based on information on income, climate change and expected changes in the mangrove area, we simulate the development of the mangrove forest area and the associated welfare economic consequences in terms of income loss and mitigation benefits. We estimate the adaptation benefits based on an expected damage cost approach and the mitigation benefits based on the amount of carbon sequestrated in the replanted area as well as the carbon price.

Main Findings and Contributions

For a wide range of scenarios and assumptions the paper concludes that the welfare benefits of replanting are positive if one looks at adaptation alone, and even more so if mitigation is included. Consequently, considering adaptation and mitigation benefits jointly leads to higher replanting intensities than considering adaptation alone. Payment for mitigation needs to be implemented if it is to attract private decision-makers. The paper contributes with empirical knowledge of the benefits of JAM when replanting mangrove forest.

5.3 Paper 3

Empirically Based Analysis of Households Coping with Unexpected Shocks in the Central Himalayas

Authors: *Lea Ravnkilde Møller[1], Carsten Smith-Hall[2], Henrik Meilby[2], Santosh Rayamajhi[3], Lise Byskov Herslund[4], Helle Overgaard Larsen[2], Øystein Juul Nielsen[5], Anja Byg[6].*

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Manuscript to be submitted to Regional Environmental Change.

Keywords: Coping, livelihoods, Vulnerability, Nepal.

Introduction and Objective

The focus of the paper is rural households' decisions in relation to income loss or gain in agricultural production due to substantial, unexpected shocks caused by climate change. Empirical data on household resources is derived from randomly selected households in the high mountains of central Nepal (n=112).

The paper applies a MNL regression to analyse households' coping responses. The households' choices of coping responses are used as response variables and the explanatory variables are based on an elaboration of the PEN survey, thus including household resources: demographics, debt, assets (agricultural land, livestock), value of other assets (such as furniture, bicycles and agricultural implements), and income sources (wage income, forest and environmental resources, remittances).

Main Findings and Contributions

With respect to both past and expected future behaviour respondents are significantly more likely to choose the coping capability of obtaining a loan or getting monetary assistance than they are to reduce household consumption. Comparing the results, 'save cash' is the dominant choice of coping capability in the case of both past and future income gains.

More specifically, we find that poor households generally choose coping strategies that give them access to cash as a gap-filler rather than income and resources from the forests and environment.

5.4 Paper 4

Optimal Decision-Making – Adaptation to Climate Change in the Agricultural Sector

Authors: Lea Ravnkilde Møller, Martin Drews (DTU) and Morten Andreas Dahl Larsen (DTU).

Submitted November 2016 to Environmental Management.

Key words: Bayesian Updating, Monte Carlo Simulation, Climate Change, Adaptation, Agriculture, Uncertainty.

Introduction and Objective

This paper presents a novel approach to the handling of decision-making under uncertainty and simulates actual decision-making. We develop a framework for the application of Bayesian updating to study decision-making, reaction patterns and updating and changing of beliefs among farmers in a developing country, when they are faced with the complexity of adapting agricultural systems to climate change.

This is exemplified by a Ghanaian farmer who has to choose between three agricultural systems: livestock, irrigated crop and dryland crop. The farmer makes rational decisions based on the climate-depending, expected net revenue from the agricultural system, determined by his belief in climate change. We simulate how the farmer updates his belief in climate change as he experiences changes in temperature and precipitation. Then we simulate how the farmer's choice of agricultural system changes over time, as his knowledge about realised climate scenario and the optimal choice of agricultural system increases.

The paper applies three climate scenarios based on global/regional climate model combinations and two future scenarios (RCP4.5 and RCP8.5) representing the GHG reduction policy, moderate and unsustainable, respectively.

Main Findings and Contributions

The paper is a first attempt to bridge the gap between modelling of management decisions and climate change. It does so by simulating the consequence of decision-making under uncertainty.

The results show that when the beliefs of the farmer (the decision-maker) are contrary to the direction of the realised climate development, Bayesian updating of beliefs allows for an adjustment of such beliefs, as more information becomes available to the farmer, helping him make the optimal choice between agricultural systems as he is considering the influence of climate change.

6. Discussion

6.1 Main Findings

The main findings and contributions of each of the four papers are as follows: **Paper 1** contributes with an overall focus on possible JAM initiatives in agriculture and forestry, specifically barriers and opportunities for future JAM initiatives. **Paper 2** finds that joint adaptation and mitigation can improve the cost-effectiveness of actions and increase their attractiveness to stakeholders and investors. **Paper 3** finds that access to cash is an important element, and that for rural households it is more important than income from forestry and the environment when it comes to coping with unexpected shocks due to climate change. Finally, **Paper 4** shows how farmers may benefit from having the option to update their decisions as they learn more about climate change.

The PhD thesis concludes that the opportunities for JAM in ecosystems are good. **Paper 3** finds that cash plays a significant role for households to overcome unexpected shocks, and in **Paper 2** it is shown that payments from carbon can increase the level of adaptation in the area replanted with mangrove forest. Combined, these present a strong argument for the potential benefits of introducing carbon payments in JAM initiatives.

A finding across **Papers 3 and 4** is that the knowledge level on which farmers make decisions may have a significant impact on their net income (**Paper 4**), drawing lines to the findings concerning household behaviour in **Paper 3 -** which does not seem to change over time, indicating that more knowledge is needed about future consequences in order to ensure better adaptation at farm and household level.

A cross-cutting finding for the PhD is that while it is important to recognise knowledge about development, adaptation and mitigation - and how they support each other – it is equally important to be able to address barriers, benefits and decision-making in respect of climate change. The following discussion is based on such cross-cutting findings. Section 6.2 discusses adaptation and mitigation in an ecosystem perspective and the option of valuing adaptation and mitigation as an ecosystem service, estimating a possible benefit. Section 6.3 discusses adaptation, mitigation and development and how development can contribute with knowledge about overcoming barriers, contributing to better decisions for the future. Finally follows a discussion of how the perspective on decision-making can be a barrier (section 6.4).

6.2 Adaptation and Mitigation in an Ecosystem Services Perspective

In this thesis I have treated adaptation and mitigation as ecosystem services. Hereby it becomes possible to consider the complexity of ecosystems on the one hand and people's practices, values and regulation of ecosystems on the other (Termansen et al. 2015). It is not unproblematic though. Due to the complexity of ecosystems and the services they provide, there may be price changes for the services which do not reflect the importance or scale of the service provided. For example, the payment for irrigation may not reflect the quantities of water needed for the delivery of the service, or the service of groundwater may be scarce (Fisher et al. 2009). Furthermore, an assessment of the value relies on environmental valuation methods, and often stated preferences are criticised and may be inconsistent and biased (Fisher et al. 2009) or - more importantly - may only capture certain aspects of the value. Thus, the EDC approach is likely not to capture the full value of an ecosystem (Boutwell & Westra 2015). Understanding the valuation used in an ecosystem services framework may help highlight which services are not included – and also where potential double counting may take place.

Chia et al. (2016) highlight some challenges of JAM, similarly to the barriers listed in **Paper 1:** a lack of metrics or quantification of adaptation for comparison with mitigation or other adaptation initiatives. This may be eased by considering adaptation from an ecosystem services perspective, using its systematic approach of breaking down the services into marginal changes which can be valued based on a business-as-usual scenario and thus make it possible to quantify adaptation and mitigation in relation to not doing anything.

6.3 Linking Adaptation, Mitigation and Development

It is recognised that a comprehensive response to climate change requires both mitigation and adaptation actions (Magnan et al. 2016; Watkiss et al. 2015), but also sustainable development in order to enable individuals, communities and countries to address climate change (Laukkonen et al. 2009). However, there are currently barriers at policy, institutional and investment levels which must be overcome if JAM initiatives are to be successful. Consider some of the findings from the literature review in **Paper 1**, such as the problematic issue of not being able to compare adaptation and mitigation benefits, also formulated as a lack of a metrics for adaptation, to be able to compare adaptation with mitigation (Watkiss et al. 2015). The barrier for implementing JAM initiatives at farm and household level is formed by lack of knowledge, tradition and social acceptance that hinder transition and implementation (Smith and Olesen 2010) and the general separation of adaptation and mitigation at institutional and policy level (Mbow et al. 2014). The need for up-front payment for initiatives, have created a barrier and the traditional separation of adaptation and mitigation that have created silos in the implementation of projects (Schaletek et al. 2012), reinforce the funding barrier.

The need for development to increase the knowledge for better decision-making is supported by **Paper 3.** **Paper 3** emphasises the need for development in order to improve the capabilities for better decision-making for the future and also improve awareness of adaptation in a long-term perspective. Duguma et al. (2014) find that there is a need both for a more holistic approach to JAM and for a shift in focus from individual projects to the synergies found across ecosystems and at landscape level. This PhD supports this finding, but emphasises that in order to fight climate change and the challenges that it will bring, it is equally important to recognise the knowledge about development, adaptation and mitigation and the way in which they support each other.

If we are to meet the agreement made in Paris in 2015 of staying below a two degrees Celsius warming, we need to think of development as an integrated part of adaptation and mitigation (Magnan 2016). Therefore, it is crucial that the adaptation measures and initiatives in agriculture are not just a cover-up for development aid, but that the development motivates people to make better decisions for the future, including adaptation and mitigation of climate change. This is supported by scholars who are highlighting that common metrics are lacking to monitor if agriculture is environmentally sustainable, as it is currently being evaluated at different levels (Sachs et al. 2010; Steenwerth et al. 2014). Yields of a field are not enough, in a long term perspective, as it does not say anything about the sustainability of the crop or address environmental sustainability, food security, human health, economic and social well-being, factors which sustainable agriculture should grasp (Sachs et al. 2010). The factors limiting the creation of sustainable agriculture are similar to the ones in favour of promoting JAM at landscape level (Harvey et al. 2014), e.g. poverty, clear tenure rights, institution capacity, market access, education and cultural factors. Referring to the findings of this PhD thesis, a development contributing with increased knowledge and awareness could overcome these limiting factors. Development will strengthen the capabilities as defined by Sen (2003) and enable the decision-maker to make better decisions for the future, including coping and adaptation strategies.

6.4 Barriers to Decision-Making

Linking adaptation and sustainable development could be of significance if donors of development aid want to help people in developing countries make optimal decisions when faced with the threats of climate change in the near and far future.

However, recognising the complexity of adaptation and mitigation described in section 2, things may not be as simple as they seem. The decision to implement climate change adaptation, mitigation or JAM has to be discussed and considered from the perspective of the person making the decision (public or private decision-maker). Adaptation can be both a private, club, common and public good. Mitigation is a public (global) good which only considers the benefit of reducing climate change, however, there may be significant private and social co-benefits. Furthermore, if the co-benefits of carbon emission are institutionalised, e.g. through carbon payments, there may be private benefits - depending on who is entitled to the payments. Therefore, the optimal decision as to how to address climate change is not evident, as in many situations it is unclear who is entitled to the carbon payments. Thus, it creates a barrier to the decision of creating a JAM initiative. One way to visualise this differences in perspective is the way a discount rate is applied - when the benefits of adaptation, mitigation and JAM are given a monetary value, as illustrated in **Paper 2**. The application of discount rates reflects the choice that the decision-makers have to make and their priorities (Arrow et al. 1996), while also reflecting the time frame of the decision-maker. A public decision-maker is likely to have a long-term horizon, whereas private decision-makers will typically have a shorter horizon to ensure that they receive a return on the investment made. Public decision-makers' decisions should also reflect the possible damage cost and the increase in damage cost if nothing is done to stop the impact of climate change. Thus, in theory the willingness to invest in adaptation and mitigation should be at least equal to the expected damage cost (Halsnæs et al. 2016), however, a situation where there is no money to invest in adaptation or mitigation is very likely. Still, keeping the pending damage cost for the public decision-maker in mind if no action is taken, it may be an attractive solution to motivate the private decision-maker through various benefits of adaptation and co-benefits of mitigation (carbon payment) if we want to see adaptation and mitigation in action to minimise damage cost. The costs of an initiative will in most situations occur in the early stage of the project. Thus, the willingness to pay for these costs is determined by the future perspective and possible income options and costs from the impact of climate change. The costs may therefore seem much higher in relation to the possible return for a private decision-maker than a public. This explains how the decision-making can be a barrier, when the perspective on the initiative is viewed from different angles. **Paper 2** demonstrates how combining adaptation and mitigation can help overcome this barrier by including carbon payment, making the initiative more cost-efficient, motivating both private and public decision-makers. Increased awareness and knowledge are needed to achieve this target while not ignoring the need for a carbon market.

7. Conclusion

It is the overall conclusion of this PhD project that combining adaptation and mitigation in agriculture and forestry ecosystems holds significant advantages, especially from a landscape perspective. However, the list of barriers is long. In order to understand the complexity behind benefits, barriers, decision-making and their influence on the fight against climate change, it is important to acknowledge the links between the included adaptation, mitigation and development. For a more nuanced picture of the research contributions, the following has been divided into three parts: *Contributions to Scientific Methods, Empirical Knowledge and Policy Implication*, concluding with section 7.1: Further Research.

Contribution to Scientific Methods

Paper 1 creates an overview of the complexity of the joint pursuit of mitigation and adaptation and an indication of effective ways to approach JAM in agriculture and forestry.

Paper 2 contributes to the scientific research methods by applying a marginal valuation approach to estimating the possible benefit of JAM.

Paper 3 contributes with an analysis of past and future choices for coping with unexpected shocks. Previously, this has been only sporadically described in livelihood literature.

Paper 4 contributes with a novel approach for simulation of management decision-making under the uncertainty of climate change, and how this topic might be addressed in the future.

Empirical Knowledge

Paper 1 creates an overview of management practices and actions which include adaptation and mitigation benefits in agriculture and forestry and a method to maximise these benefits in a holistic landscape approach, seeing the landscape as a multifunctional space.

Paper 2 shows how incentives to increase adaptation can be achieved through carbon payments for mitigation. This may advance both development and adaptation, demonstrating the benefits of JAM. Taking a dynamic approach, **Paper 2** demonstrates how things can change over time, which few case studies in the categories of adaptation and mitigation take into consideration.

Paper 3 confirms how important the issue of decision-making is, considering rural Nepalese households dependent on agricultural production. The paper finds that households which experience substantial, unexpected shocks choose coping options that give them access to cash to overcome the shocks. Furthermore, it is shown that forest and environmental resources do not have any significant influence on the coping response – which has previously been assumed.

Paper 4 exemplifies how decision-making and the optimal choice can change over time as knowledge increases. It shows the importance of considering such adaptation options when the future climate is unknown.

Policy Implications

The link between adaptation and development must be acknowledged if it is the intention to help those who need it the most in the face of climate change impacts. As often said, it is the poorest and weakest who are hit the hardest, and their resilience needs to be strengthened. The policy implications should therefore to steer towards increasing the capabilities of those who have to make decisions under the uncertainties of climate changes, to increase the freedom of actions for the world's poorest people and to acknowledge the findings in this PhD thesis about barriers, benefits and decision-making.

A further development of JAM would be especially beneficial from a social planner or public perspective. It is also found to be most beneficial from a landscape perspective. However, there is still a need for an overview, quantifying the benefits of the available practices and actions for the individual, and enabling the individual decision-maker to make better decisions for the future. This would lead to the empowerment of the prospect of sustainable development in the long term and would probably enable farmers to increase their production based on better decisions. I argue that to intensify the current objectives of JAM it is important to link adaptation and development. Everything is connected, and this needs to be respected if impacts from climate change are to be hindered.

7.1 Further Research

An obvious choice for further research from the narrow perspective of this PhD thesis would be an extended analysis of the results of **Paper 3,** applying the theory of Bayesian updating used in **Paper 4**. Furthermore, it would be interesting to return to Mustang to collect a new set of recall data with existing households going back to 2009, to determining whether their strategies for coping with unexpected shocks, positive or negative, have changed or are changing. Including, further investigation of Meilby et al. (2014) documentation of that forests in the study area are under-utilized and that household incomes from timber trade could be increased three-fold within sustainable harvesting limits.

In a broader perspective, a major limitation I have encountered during my work is the lack of data. More empirical knowledge is needed. **Paper 2** reflects what was currently possible, but further analysis and more accurate data are required. This goes for case studies as applied in this thesis - where it is often difficult to find a combination of data from different disciplines – and also for obtaining data on a larger scale in order to evaluate the degree of generalisation of the case studies. Specifically, the landscape approach for JAM should be further researched, and it might be interesting to investigate the potential of JAM for use in cities and urban settings as these are likely to contain some of the same dynamics that we recognise in the landscape. If the above-mentioned policy implications should be achieved, the benefits of JAM need to be quantified for verification of the benefits of the landscape as multi-functional space, enabling poor people with a low level of capabilities to make better decisions and increase their capabilities through development.

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Paper 1

Joint Adaptation and Mitigation in Agriculture and Forestry

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Keywords: Climate change, Adaptation, Mitigation, Agriculture, Forestry.

Abstract
This working paper aims to provide an overview of joint adaptation and mitigation (JAM) concepts and practices in the forest and agriculture sectors of developing countries in tropical and temperate regions. The approach used for this study was a literature review, analysing in what ways mitigation activities can derive adaptation benefits and vice versa. It also considered the integrated and synergetic effects that could be derived from pursuing joint activities in the forest and agricultural sectors.

The paper outlines current barriers and opportunities for pursuing JAM within agriculture and forestry, which provides guidance on where efforts should be focused to ensure future development of JAM activities. These can include institutional and capacity barriers and opportunities, knowledge barriers, and importantly funding barriers and opportunities, among others.

The synergetic and individual effects of adaptation and mitigation can often be felt at different times and places. In conclusion, a holistic landscape approach is necessary and an urgent need to understand the enabling condition that can pursuit join activities, but JAM activities should not be pursued for the sake of doing so.

LIST OF ABBREVIATIONS

CDM	Clean Development Mechanism
CO_2	Carbon dioxide
GHG	Greenhouse gas
INDC	Intended Nationally Determined Contribution
JAM	Joint Adaptation and Mitigation
NAMA	Nationally Appropriate Mitigation Actions
NAPA	National Adaptation Plans of Action
PES	Payment for Environmental Services
REDD+	Reducing Emissions from Deforestation and forest Degradation, including the role of sustainable forest management and enhancement of carbon stocks
SDG	Sustainable Development Goal
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

Adaptation and mitigation are both processes aimed at reducing the risks and impacts of climate change, although this can happen across different temporal and spatial scales (Felgenhauer and Webster, 2014; Locatelli et al., 2015; Watkiss et al., 2015). Put simply, mitigation reduces the risk of climate change from a mostly global and long-term perspective (Watkiss et al., 2015), whereas climate change adaptation contributes by reducing vulnerability and increasing resilience, often at the local scale and in a near-term perspective (Landauer et al., 2015; Tol, 2005; Watkiss et al., 2015) (see Table 1). A broad overview of the general differences between climate change adaptation and mitigation is given in Table 1, but these broad differences are increasingly being challenged, as adaptation can occur at the broader level for relatively longer term perspectives and vice versa. Furthermore, the co-occurrence of adaptation and mitigation is evident in sectors that would traditionally involve one or the other but not both. For example, adaptation in transport is increasing, with new design standards being developed to minimise the risk of flooding to metro stations in Copenhagen, Denmark (EEA, 2014).

TABLE 4 GENERAL DIFFERENCES BETWEEN ADAPTATION AND MITIGATION (ADAPTED FROM LOCATELLI, 2011).

	Mitigation	**Adaptation**
Spatial scale	Primarily global	Primarily local
Time scale	Long term	Short term
Metric	GHG emissions (CO_2 equivalent)	Various, according to intervention
Main sectoral focus	Energy supply, transport, industry, waste and wastewater management	Water, health, coastal zones
	Forestry and agriculture	Forestry and agriculture

Several characteristics of mitigation and adaptation create opportunities and challenges for implementing both processes simultaneously and with displaced benefits both temporally and spatially. First, in many sectors mitigation and adaptation are inextricably linked, as the amount of adaptation needed depends on the success of international mitigation efforts and vice versa to some extent (Watkiss et al., 2015). Second, mitigation has had little impact in the short term, whereas adaptation could play a greater role. Third, the scale of implementation often differs, which has a bearing on how the costs and benefits of adaptation and mitigation are distributed. Mitigation is a public good, and its benefits are enjoyed at the global level. For adaptation, the costs and benefits are local, with potential contributions to improvements globally (Harvey et al., 2014; Moser, 2012; Watkiss et al., 2015). This simple spatial division is not without exceptions, however, since adaptation might have global consequences (e.g. more resistant crops are grown globally), and mitigation actions might have local consequences (e.g. less air pollution locally by closing coal-fired power plants, or the effect of biofuels on local food security; Swart and Raes, 2007, Moser, 2012). Fourth, income generation from mitigation initiatives can be used to achieve adaptation benefits, a field that is largely underfunded (Matocha et al., 2012).

Even though adaptation and mitigation share the ultimate goal of reducing the unwanted effects of climate change, they have been addressed differently by scholars, institutions and politicians (Ayers and Huq, 2009). Mitigation has been promoted as especially relevant to developed countries, adaptation as imperative to developing countries (Ayers and Huq, 2009; Somorin et al., 2012). JAM is currently receiving increased interest from scientific scholars (Duguma et al., 2014; Landauer et al., 2015; Watkiss et al., 2015), who are producing examples of the complementary and synergetic effects of adaptation and mitigation globally, nationally and locally and their integration at the landscape level.

In 2015 several international milestones were achieved, each with a bearing on climate change action, and highlighting the need to link climate change adaptation and mitigation action: countries have formulated their Intended Nationally Determined Contributions (INDC) towards climate action; the global goal for adaptation in the Paris Agreement, adopted in November 2015, directly links to the target for mitigation to staying below two degrees Celsius (Magnan, 2016); and the new UN Sustainable Development Goals were also adopted (UN, 2016). Indeed, adaptation and mitigation share several common elements that advance the sustainable development agenda, including poverty reduction and ecosystem resilience locally (Somorin et al., 2012).

To this end, some are arguing that there is a window of opportunity for the development of policies to promote both mitigation and adaptation as complementary rather than direct substitutes. – where adaptation is cost effective, and mitigation contributes to avoiding threatening climate change (Watkiss et al., 2015) – and that mitigation and adaptation should be pursued equally (Felgenhauer and Webster, 2013; Laukkonen et al., 2009; Warren et al., 2012).

1.1 Scope and Objective

Land use is one of the key sectors with great potential for creating synergies between mitigation and adaptation actions, potentially achieving both objectives at little or no extra cost. Other key sectors include waste management, construction, planning and infrastructure (Illman et al., 2012). In this working paper, we focus on land use and discuss agroforestry, climate-smart agriculture, ecosystem-based adaptation and reduced emissions from deforestation and forest degradation (REDD+) as some of the important approaches to capturing both climate change adaptation and mitigation. These approaches are often aligned with sustainable development objectives, with significant co-benefits for local communities (Locatelli et al., 2015; Matocha et al., 2012; Watkiss et al., 2015).

While JAM shows potential in terms of cost-effectiveness, the existing evidence and knowledge of the measurement, operationalisation and implementation of JAM need to be enhanced in order to provide input to improving the design of synergetic projects (Locatelli et al., 2015). The aim of this working paper is therefore to gather knowledge of and insights into the current use of JAM both as a concept and in practice. The paper is based on a literature review, using a snowballing process to identify publications used and cited by others. This approach was chosen especially as a result of the lack of keywords that can capture the complex connections between climate change adaptation and mitigation. The literature search was conducted between December 2015 and March 2016.

This working paper starts by providing an overview of the underlying concepts of joint adaptation and mitigation (JAM) and captures how the literature has defined the concept as benefits, synergies, integration, interlinkages, interrelationships and linkages between climate change adaptation and mitigation. This is illustrated by current examples and practices in agriculture and forestry in developing countries that are creating benefits for adaptation and mitigation. Specifically, the paper highlights current barriers within agriculture and forestry to pursuing JAM by providing insights as to where efforts can be focused to ensure the further development of JAM activities. The remainder of this working paper is organised under the following headings: overview and importance of JAM in climate action, outline of basic JAM concepts, sectoral overviews linking mitigation to deriving adaptation and adaptation to deriving mitigation, as well as integrated and synergetic practices and activities in the sectors of agriculture and forestry, barriers and solutions to joint activities in the two sectors, and the conclusion to the working paper.

1.2 Review of JAM Concepts

One way of categorising JAM was suggested by Locatelli et al. (2015), who used a deductive approach involving 274 cases. JAM activities were put into three broad groups (see Figure 1). First, joint outcome activities are activities with non-climatic primary objectives (e.g. development or recreation) that deliver joint outcomes for adaptation or mitigation. Secondly, activities with unintended side effects are characterised as activities that are aimed at only one climate objective – either adaptation or mitigation – but also affect the other objective. Finally, activities with joint objectives are activities with combined adaptation and mitigation objectives that in turn may lead to interactions strengthening or weakening outcomes, that is, synergies or trade-offs. It is this final group of activities that we define as JAM in this working paper (see Landauer et al., 2015 for a further review of the concepts used in the literature).

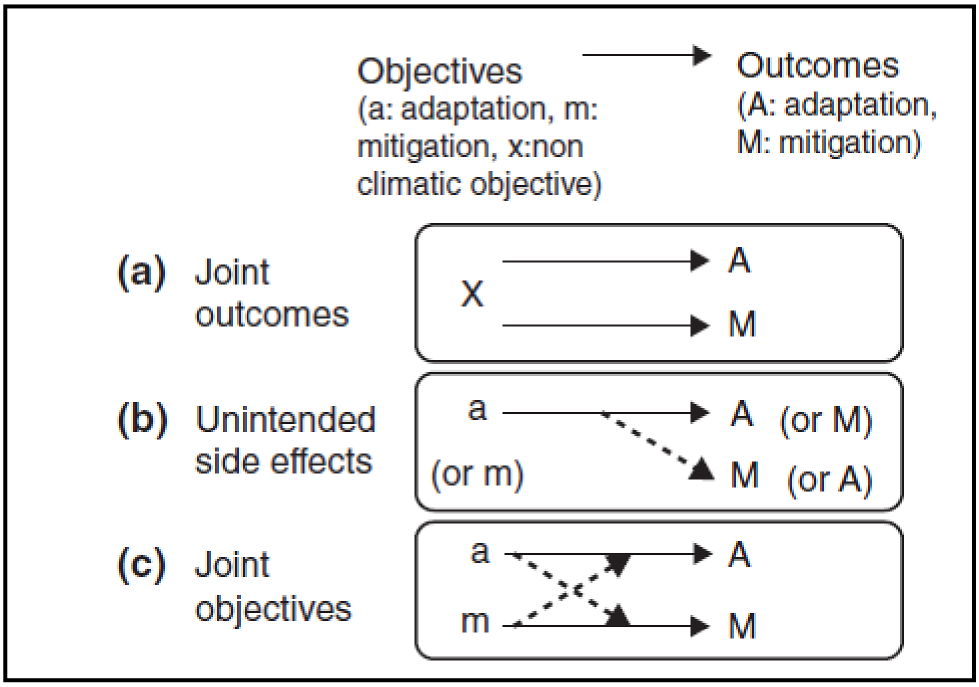

FIGURE 1 RELATIONSHIPS BETWEEN ADAPTATION AND MITIGATION CONCEPTUALISED IN THREE MAIN CATEGORIES (LOCATELLI ET AL., 2015).

This followed on from earlier classifications by the IPCC Fourth Assessment Report, which included a specific chapter on interactions involving adaptation and mitigation and the potential value-added that joint actions could offer. Klein et al. (2007a) identified four types of JAM, which were further elaborated on by Watkiss et al. (2015). These are described below with some examples.

a. Adaptation actions that have consequences for mitigation**:** (i) positive mitigation consequences, for example, when crop residue is returned to the field to improve its water-holding capacity, which also sequesters carbon; or (ii) negative mitigation consequences, for example, increased use of nitrogen fertiliser to prevent falling yields can lead to increased nitrous oxide emissions.

b. Mitigation actions that have consequences for adaptation**:** (i) positive adaptation consequences, for example, carbon sequestration projects can lead to greater access to forest products; or (ii) negative adaptation consequences, for example, when land is taken over for carbon sequestration, thus negatively affecting livelihoods and food security.

c. Decisions that include trade-offs or synergies between adaptation and mitigation**: Trade-offs** between adaptation and mitigation, as defined by Klein et al. (2007), represent a way of prioritising or balancing between adaptation and mitigation. However, there are many examples of negative or conflicting trade-offs that need to be avoided, for example, when adaptation leads to increased carbon emissions. Specifically, the pursuit of one objective negatively affects the outcome of the other (Moser, 2012; Landauer et al., 2015). **Synergies** between adaptation and mitigation are defined in the IPCC Fourth Assessment Report (Klein et al., 2007a, p. 749) as the 'interaction of adaptation and mitigation so that their combined effect is greater than the sum of their effects if implemented separately' (see Box 1). Indeed, the main motives for applying a synergetic approach are to increase effectiveness, minimise costs and ensure continuity of production and/or service provision through adaptation, mitigation or mitigation combination of the two, thereby minimising the risk of failure in fighting climate change (Duguma et al., 2014). This suggests that the benefits of an integrated approach are greater than those of two independent, parallel strategies. Importantly, striving for both adaptation and mitigation may also optimise investments – for example, reducing climate change by reducing the transaction costs of implementing projects separately (Matocha et al., 2012).

d. Processes that have consequences for both adaptation and mitigation**,** or that contribute with both adaptation and mitigation, for example, trees in an urban setting that provide shade during heat waves and simultaneously contribute with carbon sequestration.

The concepts of substitutability and complementarity are also increasingly being discussed in relation to climate policy development and economic theory from a global perspective[1] (Ingham et

[1] The two concepts are discussed especially in relation to Integrated Assessment Models (IAM), estimates of the Social Costs of Carbon (SCC) and the application of these results. IAM offers an 'end to end' modelling of climate change, summarising its positive and negative causes and effects (Nordhaus, 2013). SCC represents the

al., 2013; Kane and Shogren, 2000; Lecocq and Shalizi, 2007). **Substitutability** is the extent to which an agent can replace adaptation by mitigation or vice versa to produce an outcome of equal value. In general, adaptation and mitigation are often substitutes, particularly in the policy field at the global level, where large, long-term investments in mitigation can lead to fewer investments in adaptation and, in theory, reduce the need for adaptation (Ingham et al., 2013; Kane and Shogren, 2000).

Complementarity occurs when the outcome of one supplements the outcome of the other (Klein et al. 2007a, Watkiss et al. 2015). However, complementarity can also occur when the costs of adaptation may depend on the amount of mitigation (Watkiss et al., 2015). Thus, a mix of adaptation and mitigation is considered the optimal approach, depending on local conditions, values, preferences and uncertainties, and evidence of climate change supports the simultaneous pursuit of such a joint approach (Felgenhauer and Webster, 2013; Warren et al., 2012).

While we may be able to justify the principles of JAM theoretically, the evidence is limited when it comes to concrete estimates of its costs and benefits and to how such joint objective projects can be operationalised; thus, a critical gap has been identified (Duguma et al., 2014; Locatelli et al., 2015; Steenwerth et al., 2014; Watkiss et al., 2015). Moreover, although there are many ways of pursuing JAM, purposefully seeking such synergies may lead to unnecessarily complex projects that are neither cost-effective nor efficient in producing the adaptation and mitigation benefits they seek to harness (Klein et al., 2005). The risks and uncertainties on the level of adaptation and the spatial and temporal scale on which adaptation operates compared to mitigation pose challenges to the design and implementation of synergetic adaptation and mitigation projects. Conceptualising and operationalising JAM is evidently highly complex for these reasons, and there is a critical need for a clear methodology and guidance in the implementation of JAM projects in order to secure the best outcome of any one investment and to avoid pitfalls and barriers (Laukkonen et al., 2009).

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present net value of the impact of an increase or decrease, aggregated over the period until 2200, caused by emitting one more or one less ton of CO_2 (Stern, 2007).

Box 2. Basic concepts in JAM

Interrelationship, interaction, interlinkage: adaptation that has consequences for mitigation or vice versa, or processes that have consequences for both (Landauer et al., 2015).

Synergy: interaction between adaptation and mitigation, so that their combined effect is greater than the sum of the effects derived from implementing them separately (Klein et al., 2007).

Trade-off: balancing adaptation and mitigation when it is not possible to carry out both activities fully at the same time (Klein et al., 2007), or 'inadequate conditions, competition among means for implementation and negative consequences of pursuing both simultaneously' (Moser, 2012).

Substitutability: the extent to which an agent can replace adaptation by mitigation or vice versa to produce an outcome of equal value (Klein et al., 2007).

Complementary: the interrelationship between adaptation and mitigation, whereby the outcome of one supplements or depends on the outcome of the other (Klein et al., 2007).

2 JAM Agriculture

Farmlands or lands used for agricultural production, consisting of cropland, managed grassland and permanent crops (including agroforestry and bioenergy crops), occupy about 40-50 per cent of the earth's land surface. The IPCC estimates that in 2010 about 24 per cent of the anthropogenic emissions of GHGs came from agriculture, more specifically from fuels, deforestation, shifting cultivation, land-use changes, synthetic fertilizers and animal waste (Smith et al., 2014). 13.7 per cent of global GHGs come directly from agriculture, and 96 per cent of the latter from Africa, the Americas and Asia (Tubiello et al., 2013).

Mitigation in agriculture can be divided into three types of initiative (Harvey et al., 2014; Jarvis et al., 2011): initiatives that increase the carbon stock and sequestration above and below ground, e.g. revegetation of degraded land and agroforestry initiatives (Smith et al., 2014); initiatives that reduce the direct emissions from agriculture, e.g. improved feed and dietary additives for livestock and improved use of fire for sustainable grassland management (Smith et al., 2014); and initiatives that work against the creation of a new type of farmland by causing deforestation and degrading ecosystems. Most countries include agriculture and other land-use sectors in their INDCs to reach the goal of the UNFCCC (UNEP, 2015), and agriculture predominates in the adaptation actions taken in Asia and Africa (Ford et al., 2014). Emission reductions and mitigation in the agricultural sector can thus be a meaningful way for countries to contribute to minimising climate impacts.

Agriculture is the human activity that is most vulnerable to climate change (Verchot et al., 2007), meaning that the greatest percentage of livelihoods depend on agriculture and will inevitably be affected by climate change (Steenwerth et al., 2014). The main climate vulnerabilities in the agricultural sector are related to seasonal weather changes, increased precipitation and temperatures, and extreme weather events, leading to decreases in crop yields (Gustafson et al., 2014) and disease and death among livestock (Steenwerth et al., 2014), which indirectly can have an impact on market prices and farmers' incomes. Farmers are especially vulnerable to recurrent droughts, floods, soil degradation, water shortages, limited availability of inputs and improved seeds, limited technology options, and limited infrastructure and access to markets. A lack of knowledge of the threats of climate change can further increase their vulnerability (Li et al., 2015; Mutabazi et al., 2015; UNEP, 2015).

Box 2. Climate-smart agriculture

Climate-smart agriculture (CSA), or climate-related agriculture, is a term used widely in the academic literature and by multilateral agencies and practitioners who are trying to adapt to the climate-related challenges facing agriculture. This is done by increasing farmers' resilience to climate change and decreasing GHG emissions from agriculture, while at the same time supporting sustainable development of the entire sector from small-scale farmers to large agribusinesses (Steenwerth et al., 2014).

The aim of CSA is to enhance the capacity of agricultural systems to meet the need for food security and poverty alleviation under conditions of a changing climate through science-based actions. It incorporates the need for adaptation and the potential for mitigation into sustainable agricultural development strategies without jeopardising the sustainability of the production process (Harvey et al., 2014; Smith and Olesen, 2010; Steenwerth et al., 2014).

Climate change adaptation in agriculture can potentially increase the resilience and adaptive capacity of farmers. Adaptation activities in the agricultural sector can include crop diversification, intercropping, use of irrigation, water conservation activities, rainwater harvesting, reduced tillage, shifting cultivation, changes in livestock composition and diversification of incomes from kitchen and home gardens. These activities can also occur autonomously – introduced by the farmers themselves – and can include activities such as changes in sowing, planting and harvesting dates, and often several adaptation activities can be tried at the same time (Abid et al., 2015; Li et al., 2015; Rogé et al., 2014; Simelton et al., 2015). Moreover, agricultural extension services and other external supporting initiatives such as crop and index insurance can be important in supporting farmers' resilience to climate change, but these services are not always available (Abid et al., 2015; C. A. Harvey et al., 2014; Nguyen et al., 2013; Steenwerth et al., 2014).

The agricultural sector can combine mitigation and adaptation activities to contribute with synergies, as is evident in the approaches and effects of sustainable agriculture or climate-smart agriculture (see Box 2) (Harvey et al., 2014). Likewise, agroforestry has the opportunity to provide food security and income diversification to increase households' adaptive capacities in cases of climate shocks or impacts, as well as achieve significant potential GHG reductions through the planting of trees (see Box 3; Pandey et al., 2016; Rahn et al., 2014).

Box 3. Agroforestry

Agroforestry has been defined as a 'land use system that seeks to deliver sustainable improvements to food security, through integrating trees with other components of agriculture in multifunctional landscapes' (Mbow et al., 2014). Large areas of agroforestry are found in South America (3.2 million km^2), Sub-Saharan Africa (1.9 million km^2) and Southeast Asia (1.3 million km^2). Europe and North America also have large areas of agroforestry, despite having large commercial agricultural sectors (Zomer et al., 2009). Agroforestry systems in tropical and temporal regions tend to be tree-based production systems, such as the jungle rubber system in Sumatra, Indonesia, the mixed cocoa and fruit tree plantations in Cameroon, the peach palm systems in Peru, the pine-banana-coffee system in Java, Indonesia (Verchot et al., 2007), the shade coffee systems in Nicaragua (Rahn et al., 2014) and the Grevillea agroforestry system in Kenya (Lott et al., 2009). However, agroforestry is also found on a smaller scale as tree-based home gardens, contributing to household food security and income diversification (Linger, 2014; Nguyen et al., 2013). Agroforestry as an adaptive practice provides certain benefits. In general, farm profitability can be increased through improvement and diversification of the output per unit area of tree/crop/livestock. This is done through protection against the damaging effects of wind or water flow and by introducing new products, adding to the diversity and flexibility of the farming enterprise (Mbow et al., 2014). Agroforestry also provides households with fuel wood, livestock feed and hydrological services, thus increasing farmers' and households' resilience to climate variables (Branca et al., 2013). It can also substantially contribute to climate change mitigation (Smith, 2009; Thorlakson and Neufeldt, 2012; Verchot et al., 2007), as it increases the storage of carbon and carbon sequestration above ground. The positive and negative effects of mitigation and adaptation in agroforestry are shown in the table below (taken from Mbow et al., 2014).

<table>
<tr><td rowspan="4">Adaptation</td><td colspan="3">Mitigation</td></tr>
<tr><td></td><td>Positive</td><td>Negative</td></tr>
<tr><td>Positive</td><td>• Soil carbon sequestration
• Improving water-holding capacity
• Use of animal manure and compost
• Mixed agroforestry for commercial products
• Income diversification with trees
• Fire management</td><td>• Dependence on biomass energy
• Overuse of ecosystem services
• Increased use of mineral fertilisers
• Poor management of nitrogen and manure</td></tr>
<tr><td>Negative</td><td>• Limited (use) rights to agroforestry trees
• Forest plantation, excluding harvest</td><td>• Use of forest fires for pastoral and land management
• Tree exclusion on farmland</td></tr>
</table>

2.1 Agricultural Mitigation Activities that Lead to Adaptation Benefits

Mitigation in agriculture can include practices such as cropland management, management and improvement of pastureland, management of organic soils, restoration of degraded land, livestock management, manure management and bioenergy (Smith et al., 2007). Many management strategies can also contribute to adaptation benefits, as they can result in better plant nutrient contents and increased water-retention capacities, leading to higher yields and greater resilience (Campbell-Lendrum et al., 2014; Rosenzweig and Tubiello, 2007). However, Arslan et al. (2015) finds that activities such as a minimum of soil disturbance and crop rotation have no significant impact on maize yields. Other examples, including manure management and the avoidance of methane production from biomass deterioration, particularly in rice farming and livestock management, have significant mitigation potential, while also offering adaptation benefits through food security and diversification, enhanced productivity, the reduced risk of droughts and floods and improved livestock-based livelihoods (Klein et al., 2007a; Linger, 2014; Locatelli, 2011; Pandey et al., 2016; Steenwerth et al., 2014). Moreover, households with tree-based home gardens in Ethiopia have higher species diversification compared to households with non-tree gardens (Linger, 2014). Linger (2014) points out other benefits, such as a reduction in the cost of fertiliser, as well as improved social relationships and reduced hunger among children caused by direct access to fruit in the garden, all of which increases the adaptive capacity of the household. Another example in Brazil involves pasture rotation systems and legume intercropping, which can form part of the mitigation strategy for livestock GHG emissions and can also provide adaptation benefits by increasing farmers' capacity through food security for livestock (Steenwerth et al., 2014). Finally, windbreaks are a well-known example of a mitigation contribution with adaptation benefits, as they are established in the fields to protect crops from dehydration and contribute organic material to the soil, thereby increasing soil fertility (Seck et al., 2005). To sum up, the examples of mitigation activities above contribute adaptation benefits that raise the socio-economic and biophysical adaptive capacity of communities, crops and the environment.

2.2 Agricultural Adaptation Activities that Lead to Mitigation Benefits

For crops like maize, rice and wheat, which are grown in tropical and temperate regions, climate change will mainly have negative impacts on production if temperature increases by two or more degrees Celsius (Porter et al., 2014). This will necessitate farmers adjusting the way they manage crops and livestock to secure the long-term stability of production (Havlik et al., 2014; Porter et al., 2014; Tubiello and Velde, 2011).

Several adaptation practices can positively support carbon sequestration in relation to land management under specific conditions. Specific adaptation activities targeted at crop diversification (such as home gardens with trees, legume intercropping, trees providing shade in tea and coffee plantations) can increase income options and lead to mitigation benefits, such as increased carbon sequestration below and above ground (Ashardiono and Cassim, 2014; Linger, 2014; Rahn et al., 2014). Improving soil fertility through increased inputs of organic matter will not only improve the nutrient status and water.- holding capacity of the soil, it can also reduce soil erosion and sequester carbon (Blanco et al., 2009). Other agricultural practices, such as soil and water conservation, crop diversification and improved or no tillage practices, can also make agricultural systems more resilient to climate change and improve the organic material in the soil, its water-holding capacity, nutrient availability and carbon sequestration (Matocha et al., 2012). For livestock farmers, adaptation strategies can include changing the composition of livestock from cattle to poultry and goats (Jacobi et al., 2015) or from cattle to camels, which are more adapted to periods of water scarcity and can provide milk (Steenwerth et al., 2014). On the other hand, certain adaptation activities may have negative outcomes. For example, increasing irrigation and increased use of cooling and ventilation systems will require more energy, resulting in more emissions, unless the energy comes from non-fossil fuel sources (Klein et al., 2007).

2.3 Integrated and Synergetic Activities

Agriculture has great potential for accomplishing both mitigation and adaptation (Smith and Olesen, 2010), specifically activities such as reducing soil erosion, reducing GHG emissions from agricultural processes, conserving soil moisture (where species and crops are improved through assortment and rotation) and improving microclimate to protect crops from temperature extremes and provide shelter. Other synergetic activities related to land use could be re-cultivating abandoned or exhausted farmland, avoiding cultivating new land, or even preventing the clearing or degradation of forests (Smith and Olesen, 2010). Examples of restoring exhausted soil, increasing food crop yields, household food security and incomes, increasing adaptive capacity and avoiding deforestation and the cultivation of new land can be found in Zambia, Niger and Burkina Faso (Garrity et al., 2010).

Food security is directly linked to the adaptive capacity of farmers and households to bounce back from climate change shocks or impacts. Agricultural activities can be categorised as contributing to high or low food security and a high or low mitigation potential, which results in four categories of agricultural activities with varying food security and mitigation potentials (Figure 2). Activities with high food security and high mitigation potential include restoring degraded and exhausted land, introducing agroforestry to increase food and income options and increase carbon sequestration, and micro-activities such as establishing tree-based home gardens, mulching and the use of organic fertiliser. Activities with low food security potential and low mitigation potential include the cultivation of fallow and bare land, overgrazing by livestock and ploughing on slopes, which can result in soil degradation and exhaustion. The possible trade-offs between biofuel production and food production should particularly be noted, as often these two compete for land, with increases in retail food prices being linked to increases in biofuel production as a result. Moreover, biofuel production can conflict with food supply and water management specifically in the tropical areas of the world (Steenwerth et al., 2014).

<table>
<tr><th colspan="4">Food Security Potential</th></tr>
<tr><th rowspan="3">Mitigation Potential</th><th></th><th>High</th><th>Low</th></tr>
<tr><th>High</th><td>• Restoring degraded and exhausted land
• Lowering energy-intensive irrigation
• Agroforestry and the use of cover crops to increase food and income options, and above- and below-ground carbon sequestration
• Establishing tree-based home gardens
• Mulching
• Using organic fertiliser to increase yields and reduce GHG emissions</td><td>• Reforestation/afforestation
• Restoring/maintaining organic soils
• Expanding biofuel production
• Agroforestry options with limited impact on yield</td></tr>
<tr><th>Low</th><td>• Expanding agriculture to marginal land
• Expanding energy-intensive irrigation
• Expanding energy-intensive mechanised systems</td><td>• Cultivation of fallow and bare land
• Overgrazing
• Slope ploughing</td></tr>
</table>

FIGURE 2 OVERVIEW OF THE EFFECTS OF AND RELATIONS BETWEEN FOOD SECURITY POTENTIAL AND MITIGATION POTENTIAL (BRANCA ET AL., 2013; LINGER, 2014).

The synergetic effects of JAM are in many ways already evident where sustainable agriculture or CSA is being implemented, because the activities needed for achieving adaptation and mitigation are similar (Harvey et al., 2014). As already mentioned, adaptation and mitigation are often pursued separately, especially in agriculture, where there are several examples of how this can lead to negative trade-offs on both the temporal and spatial scales (Rosenzweig and Tubiello, 2007; Smith and Olesen, 2010). For example, increasing the use of agrochemicals in order to increase agricultural productivity when faced with climate change can increase the crop yields, but it may also increase overall GHG emissions (Kandji et al., 2006). Conversely, increasing the use of fast-growing tree monocultures or using biofuel crops may enhance carbon stocks and have a positive effect on emissions reductions, but it can also reduce water availability downstream and thereby degrade areas appropriate for agriculture (Huettner, 2012.; Kongsager et al., 2013).

Some of the trade-offs can very well originate from the fact that climate change adaptation is often a result of the individual farmer's attempt to support his or her family (Mbow et al., 2014), therefore other objectives, such as mitigation and sustainability, are prioritised less or excluded. Short-term objectives such as these may therefore conflict with the longer term perspectives needed when considering sustainable development (Mbow et al., 2014). Nevertheless, initiatives such as payments for environmental services (PES) can be one way to pursue climate resilience and sustainable development. Such payments contribute directly to farmers to help manage risk and at the same time offer incentives to invest in and protect the natural resource base, which in turn contributes to mitigation potential through environmental services such as carbon sequestration and watershed regulation (see Box 4).

Box 4. What are Payments for Environmental Services (PES)?

PES, also known as Payments for Ecosystem Services, was originally defined by Wunder (2005: 3) as (1) a voluntary transaction where (2) a well-defined environmental service (or corresponding land use) (3) is 'bought' by a (minimum of one) buyer (4) from a (minimum of one) provider (5) if and only if environmental service provision is secured (conditionality).

Essentially PES is an approach designed to improve livelihoods and sustainable environmental management in a cost-effective way, rewarding custodians of the land for the provision of ecosystem services, such as watershed protection, soil stabilization and carbon sequestration.

Therefore, the potential synergetic effects of approaching adaptation and mitigation simultaneously, especially at the landscape level, and thus avoiding the trade-offs above, should not be ignored. Approaching JAM at the landscape level can catalyse diversification in the agricultural landscape through crop diversification, agroforestry, the restoration of riparian areas, including natural habitats and forest patches, the introduction of silvopastoral systems, livestock diversification and management, taking into consideration where livestock production can be intensified, and land management, including avoiding fragile areas for cultivation or pastureland (see Box 5). Harvey et al. (2014) specifically mention the potential for adaptation and mitigation at the landscape level in relation to the implementation of Farmer-Managed Natural Regeneration (FMNR) practices (also known as Faidherbia farmland) in several places in Africa. Here farmers encourage the systematic regeneration of existing trees and shrubs by re-growing and managing them from felled stumps, sprouting root systems or self-sown seeds. FMNR is an agroforestry system that involves nitrogen-fixing acacia trees. The trees only grow leaves during dry periods and drop them in wet periods, thus contributing to fertilising the soil. The adaptation benefits for farmers include income diversification, water regulation (improved infiltration), possible protection from landslides, increased fodder production during critical times and fuel wood supply, while the mitigation benefits are enhanced storage of carbon both above and below ground (Harvey et al., 2014). A similar initiative is the Ngitili, a traditional fodder bank system used to conserve pasture for the dry season in Tanzania, where it demonstrates both adaptation and mitigation effects, as it involves the regeneration and conservation of trees on land for cropping and grazing (Pye-Smith, 2010).

Box 5. JAM at the landscape level

Integrated landscape management, or climate-smart landscapes, is an effective solution to climate change (Hart et al., 2015; Locatelli et al., 2015; Scherr et al., 2012), being an approach where the landscape is increasingly seen as a multi-functional space specifically supporting food production, ecosystem conservation and rural livelihood across the entire landscape (Scherr et al., 2012). Locatelli et al. (2015) describe JAM at the landscape level as involving social adaptation, ecological adaptation and climate mitigation, thus identifying opportunities between adaptation and mitigation and minimizing the trade-offs between these outcomes.

A holistic approach to JAM at the landscape level, based on the known interactions between adaptation and mitigation (see Figure 1), will reduce the risk of climate change impacts and support ecosystem services, as well as increase biodiversity and carbon stocks at the landscape level. A landscape approach can further prevent fragmentation of the landscape and enable connectivity for floral and faunal migration under climate change (Locatelli et al., 2011). In particular, the restoration of agriculture landscapes is seen as an effective solution to climate change. However, pursuing JAM at the landscape level should not only consider the agriculture landscape, but the entire landscape, including the consideration and benefits of forest and riparian areas, watershed managements and other natural habitats contributing ecosystem services and benefits that exist and co-exist with the agricultural landscape.

Further JAM at landscape level captured at the field, farm or local or even regional levels creates the possibility to nurture a mosaic of habitats and ecosystems. This increases diversity, contributing to climate change resilience, adaptation and mitigation, and reducing the ecological risk otherwise found in homogeneous crop covers in an agricultural landscape (Scherr et al., 2012). Achieving JAM at the landscape level demands changes to current institutional arrangements, policies and funding options designed to support the implementation of climate-smart approaches in agricultural landscapes (C. A. Harvey et al., 2014; Locatelli et al., 2015; Mbow et al., 2014). It therefore requires management decisions or strategies to be made at the landscape level, but with appropriate care to ensure that the decision-making authority and influence are not taken away from the individual farmer. Pursuing JAM at the landscape level in a thoughtful manner will also provide the benefits of both adaptation and mitigation initiatives together to local beneficiaries, ensuring that negative trade-offs between different initiatives are minimised, and balancing the level of intervention needed compared to costs and benefits.

Scherr et al. (2012) finds three key benefits from focusing on the landscape approach: (1) through climate-smart practice, increase the benefits at the field level; (2) conservation of ecosystem functions; and (3) increasing climate change mitigation. To achieve the optimal outcome of pursuing JAM at the landscape level, it will be necessary for stakeholders to understand the opportunities they have in introducing a landscape approach, and then to identify, negotiate, prioritise and manage the landscape in that direction (Scherr et al., 2012).

A disadvantage of the landscape approach is that in some cases multi-stakeholder involvement could slow the implementation of initiatives, unnecessarily complicating implementation and creating incentives to pursue joint activities at any cost, thus neglecting fruitful initiatives that deliver only one outcome (Locatelli et al., 2015). Moreover, a lack of empirical knowledge and experience of the effects of JAM at the landscape level and of best practice in overcoming the barriers to implementing JAM at this level can create less-effective outcomes until more experience on implementing activities at this level is acquired.

Table 2 provides an overview of the different practices and actions in agriculture, outlining the effects in three different columns: *1) Effect on agricultural adaptation*, explaining the positive or negative effects of the practices and actions on agricultural adaptation; *2) Effect on people's adaptation*, explaining the positive or negative effects of the practices and actions on farmers' adaptation, that is, how they help farmers adapt to climate change impacts through agriculture; and *3) effect on mitigation*, explaining the positive or negative effects of these practices and actions on mitigation.

In summary, table 2 shows that many of the agricultural practices and actions that are showcased in the literature can have many positive effects on agricultural adaptation and farmers' adaptation as well as mitigation. This points to the need to improve understanding of the barriers to and opportunities for operationalising joint activities in order to evaluate the cost-effectiveness and accelerate the pursuit of joint activities in the future.

TABLE 5 OVERVIEW OF AGRICULTURAL PRACTICES AND ACTIONS WITH ADAPTATION AND MITIGATION BENEFITS

Practices and Actions	Effect on Agricultural Adaptation	Effect on Farmers Adaptation	Effect on Mitigation	References
		Crop management		
Heat- or drought-resistant seeds **Changing sowing, planting and harvesting times** **Changing crop type or varieties** **Shifting cultivation**	• Increased capacity and resistance to climate stress	• Increased yields • Spreading risks through diversified crops, leading to more secure harvests		(Branca et al., 2013) (Li et al., 2015)
Cover crops **Inter-cropping**	• Increased fertility and nutrient level in the soil • Enhance biodiversity	• Increased yield • Income diversification • Food security	• Increasing carbon sequestration below and above ground	(Branca et al., 2013)
Composting of manure and kitchen waste (vermicompost/vermiculture)	• Increased fertility and nutrient level in the soil • Increased water retention capacities of the soil	• Increased yield • Increased income from vermicompost	• Increasing carbon sequestration below ground	(Sushant, 2013)
Mulching	• Preserving moisture in the soil	• Increased yield	• Protection of existing carbon poo	(Li et al., 2015)
		Water management		
Water-harvesting and conservation **Increase irrigation**	• Increased capacity and resilience to climate stress	• Increased yield	- Increased energy requirements (depending on the	(Li et al., 2015)

Groundwater exploration for irrigation	- unsustainable, if groundwater is a finite resource		energy sources)	
		Landscape and land management		
Management of organic soils **Restoration of degraded land**	• Better plant nutrient content • Increased water retention capacities of the soil,	• Increased yield • Greater adaptation capacity	• Protection of existing carbon pool	(Campbell-Lendrum et al., 2014) (Rosenzweig and Tubiello, 2007)
Soil-conservation techniques (organic fertilizer, reduced tillage and deep ploughing)	• Better plant nutrient content • Increased water-retention capacities of the soil	- decreased yield in (short term)	• Increased carbon sequestration below ground •	(Branca et al., 2013)
Diversification of the agricultural landscape (e.g. crop diversification, agroforestry, tree cover, crop rotation) **Including natural habitats and forest patches**	• Risk reduction in relation to climate change impacts • Enhance the availability of ecosystem services • Resilience to pest and diseases among crops and livestock • Enhance biodiversity	• Income diversification • Food security	• Increase landscape carbon stock • Increased carbon sequestration above and below ground • Protection of existing carbon pool	(C. A. Harvey et al., 2014) (Branca et al., 2013)
Planting of windbreaks and shade trees	• Protections of crops and livestock from climate stress • Increased soil quality and fertility • reduce Soil erosion and risk of landslides	• Income diversification • Food security • Protect people from climate stress	• Reduce carbon loss • Increased carbon sequestration above and below ground • Protection of existing	(C. A. Harvey et al., 2014) (Seck et al., 2005) (Jacobi et al., 2015) (Matocha et al., 2012)

	• Enhance biodiversity		carbon pool	
Tree based home garden	• protecting of smaller crops in the home garden from climate stress; sun, rain, wind etc. • Enhanced biodiversity	• Income diversification • Food security • Protect people from climate stress • Reduce hunger among children, because of the direct access to fruit	• Increased carbon sequestration above and below ground	(Linger, 2014)
		Livestock		
Silvo-pastural system **Rotation pasture**	• The natural resources of the landscape are included as a measure of adaptation • Enhanced biodiversity	• Climate-tolerant legumes can be an alternative fodder source • Food security • Income diversification • Reduction in cost of fertilizer for the fields, because of access to manure	• Protection of existing carbon pool • Increasing carbon sequestration below ground • Elimination of use of fire in pasture management	(Jarvis et al., 2011) (Linger, 2014) (Steenwerth et al., 2014)
Converting livestock to more heat- or drought-tolerant species **Diversification of livestock** **Changing from crops to livestock**	• Increased adaptive capacity to climate stress • increased mobility	• Food security • Income diversification • Increased mobility for the household if they are forced to move • Faster income reliefs in case of climate shocks	• Manure management to avoid emissions • Mortality reduction of animals • Reduction of deforestation and pasture burning through PES	(Steenwerth et al., 2014) (Li et al., 2015)
Manure used for fertilizer	• Increased fertility and nutrient level in the soil	• Increased crop yield • Cost savings on fertilizer,	• Increased carbon sequestration below	(Steenwerth et al., 2014)

	• Increased water-holding capacity,		ground	
External support				
Farmers organisations	• Increased knowledge and knowledge sharing	• Social capital • Increased capacity and resilience		(Steenwerth et al., 2014)
Insurance of crops and livestock	• Create incentives for investment and income diversification - Risk of corruption among insurance verifiers	• Capital relief	• Avoid exhausting soils • Avoid deforestation and invasions of new land for agricultural areas • protection of existing carbon pool	(Jarvis et al., 2011) (Steenwerth et al., 2014)
Subsidies	• Create incentives for investment and income diversification - Risk of corruption among program implementers	• Increased adaptive capacity and resilience	• Avoid exhausting soils • Avoid deforestation and invasions of new land for agriculture • protection of existing carbon pool	(Steenwerth et al., 2014)
Extension services	• Increased knowledge and knowledge sharing • Create incentives for new initiatives - Risk of corruption among staff implementing the extension services	• Increased adaptive capacity and resilience • Increased awareness	• Avoid exhausting soils • Avoid deforestation and invasions of new land for agriculture • protection of existing carbon pool	(Steenwerth et al., 2014)
PES or other income	• Enhanced biodiversity	• income diversification	• Avoid exhausting of soils	(Steenwerth et al.,

generating carbon schemes	- Risk of corruption among program implementers	• Increased adaptive capacity and resilience	• Avoid deforestation and invasions of new land for agriculture	2014)

3. JAM in Forestry

Forests cover 31 per cent of the earth's land surface (FAO, 2010), and climate change is likely to have a wide range of impacts on the socio-economic systems that surround forests and the natural ecosystems of forests. In terms of biophysical impacts, forests are likely to experience range shifts, changes in patterns of tree growth, changes in insect and disease susceptibility and distribution, changes in disturbance regimes such as fire, and changes in soil properties (Evans and Perschel, n.d.; Yuan et al., 2011). This will reduce the capacity of natural sinks to absorb carbon and increase natural sources of CO_2. Agriculture, Forestry and Other Land Use (AFOLU) activities have a feedback link to climate change in that these activities can reduce or accelerate climate change, affecting biophysical processes such as evapotranspiration and albedo (Yuan et al., 2011). Studies reviewed by the IPCC show that climate change may increase the frequency and severity of droughts in peatlands in particular and become a source of GHG (Yuan et al., 2011).

In terms of socio-economic impacts, shifts in natural ecosystems will influence how communities use and depend on forests. The potential for forest resources to contribute to rural households is becoming increasingly apparent, as studies of the contribution of forest and wild products to the household income porfolio show that forest products on average represent 22 per cent of household incomes (Angelsen et al., 2014). Indeed, in general forests can fulfil three important roles: (1) support current consumption; (2) provide a safety net in cases of shocks and crises and fill gaps during seasonal shortfalls; and (3) represent a means to accumulate assets and provide a path out of poverty (Angelsen et al., 2014). Furthermore, today the livelihood of millions of people, particularly the rural poor, are inextricably linked to forests (Angelsen and Wunder, 2003; Cammack, 2004). The consequences of shifting ranges and the distribution of forests and their products, as well as other disturbances, can thus leave the forest-dependent poor particularly vulnerable.

The IPCC has calculated that forestry and other land uses accounted for about one third of anthropogenic CO_2 emissions from 1750 to 2011 and for 12 per cent of emissions from 2000 to 2009, with a large proportion of that coming from changes to land use, mainly deforestation (Smith et al., 2014). Forest-related mitigation activities are therefore a relatively quick win in the race to slow down the rate of carbon emissions. However, the socio-economic and biophysical impacts of climate change on forests and vice versa significantly affect forests' ability to function as a carbon sink. According to the latest Emissions Gap Report by the UNEP (2015), forest-related mitigation activities, which include avoiding deforestation and reducing degradation, afforestation and reforestation, have the technical potential to mitigate up to 9 $GtCO_2$ by 2030 if all forest-related activities that degrade or clear the carbon sink were stopped today.

Several characteristics specific to this sector can also have a bearing on the pursuit of JAM activities in this sector. First, the gestational period of forestry projects from idea to implementation tends to be quite long, and the benefits of mitigation cannot be harvested until many years later. This affects the permanence of carbon stocks, but it also makes it more susceptible to issues of land-tenure security, particularly since forests are often formally owned by states, but managed by local communities (Ravindranath, 2007). As mentioned above, forests are also a source of food, shelter, medicine and income, but returns are often low, and forest-based livelihoods rely heavily on the subsistence use of resources (Elias et al., 2014; Ravindranath, 2007). Hence, although challenging, achieving JAM in this sector is both socially and economically important.

3.1 Forest-Related Mitigation Activities that Lead to Adaptation Benefits

Forests play a particularly important role in mitigation, mainly due to their capacity to sequestrate and store carbon. Deforestation and forest degradation are believed to have contributed 12.5 per cent to global GHG emissions from 1990 to 2010 through tropical deforestation (Houghton et al., 2012). The main mitigation activities within forestry are afforestation, reforestation and avoiding deforestation (IPCC, 2000). Nevertheless, mitigation projects have the potential to facilitate adaptation by reducing pressure, conserving biodiversity (through conservation) and enhancing connectivity (Locatelli et al., 2011).

Forestry mitigation projects, largely in the form of forest conservation, can facilitate the adaptation of forests to climate change by reducing the anthropogenic pressure on forests, enhancing the connectivity between forest areas and conserving biodiversity hotspots (Locatelli, 2011). Forestry mitigation projects can also reduce vulnerability and promote adaptation through forest conservation, protected area management and sustainable forest management, but they can also have consequences for adaptive responses and/or the development objectives of other sectors (for example, expansion of farm land) (Smith et al., 2014). Importantly, forestry mitigation activities, including conservation actions, are relatively more cost-effective, safe and easy than other mitigation actions (in other sectors) and are therefore seen as a critical strategy in reducing emissions (Nabuurs et al., 2007; Ravindranath, 2007; Turner et al., 2009). Given the limited need to rely on technological development, it has been argued that ecosystem restoration will remain the only realistic large-scale climate change mitigation mechanism for the coming decades (Turner et al., 2009). However, strict conservation alone can also have negative effects, such as restricting access to land and forest resources, as well as encouraging dependence on external funding (Locatelli, 2011). The resilience of a natural diversified forest ecosystem is much greater than that of a monoculture plantation, as the former is more resilient to disturbances and provides important ecosystem services, such as water and microclimate regulation (Turner et al., 2009).

Plantation establishment through afforestation or reforestation can also be an effective way of sequestering carbon and preventing other environmental disasters, such as desertification, just as it can represent a useful source of income. The Carbon Farming Initiative, developed by the Australian government, is a voluntary carbon offset scheme rewarding farmers and landholders through the carbon credits system for actions to store carbon on their land (afforestation or reforestation) or to reduce GHG emissions (Commonwealth of Australia, 2013). However, other concerns related to plantation establishment, such as preserving biodiversity, are only incorporated as safeguarding measures (van Oosterzee, 2012). Indeed, , if plantations reduce biological diversity, they may also reduce the capacity of people to adapt to climate change. Furthermore, monocultures are often more vulnerable to climate change than other cultures (Campbell-Lendrum et al., 2014).

3.2 Forest-Related Adaptation Activities that Lead to Mitigation Benefits

Forests play an important role in adaptation. ‘Adaptation for forests’ refers to the adaptation needed for forests to maintain their function (Locatelli et al., 2011). Such adaptation strategies for forests can include the anticipatory planting of species along latitudes and altitudes, assisted natural regeneration, mixed-species forestry, species-mix adapted to different temperature tolerance regimes, fire protection and management practices, thinning, sanitation and the intensive removal of invasive species, surplus seed banking, altering harvesting schedules and other silvicultural practices. Moreover, it can include the in-situ and ex-situ conservation of genetic diversity, drought and pest resistance in commercial tree species, the adoption of sustainable forest management practices, increasing protected areas and linking them, when possible, to promote the migration of species, forest conservation and reduced forest fragmentation enabling species migration, and finally energy-efficient fuelwood cooking devices to reduce the pressure on forests (Millar et al., 2007)).

Strengthening the resilience of forests also increases the permanence of carbon (Malhi et al., 2009). 'Forests for adaptation' refers to how forests can support households in their adaptation to climate change and in coping with climatic change by acting as safety nets, gap-fillers and providers of local environmental services in response to climate-related fluctuations with lower food availability (Locatelli et al., 2011). Ecosystem-based adaptation is one example of this (see Box 6). Pramova et al. (2012) provide an overview of five cases where forests and trees contribute to adaptation. First, forests and trees can represent goods to local communities facing climate impacts. Second, trees on farms can regulate the soil, water and microclimate, thus facilitating more climate-resilient forms of production. Third, forested watersheds regulate the water and protect the soil. Fourth, mangrove forests can protect coastal areas. Fifth, urban forests can regulate the temperature and water of

Box 6. Ecosystem-based adaptation (EbA)

EbA projects are characterised by integrating the use of biodiversity and ecosystem services into an overall strategy to help people adapt to the adverse impacts of climate change, can contribute to mitigation by increasing or maintaining carbon stocks in forests (Colls et al., 2009). Though EbA encompasses many different types of ecosystems, forests play a central role as they are often major providers of ecosystem services (Locatelli et al., 2010). The costs of maintaining ecosystems may be lower and the end results can be more effective than for more sophisticated adaptation measures. Although clearly a human-oriented adaptation strategy, there are clear mitigation benefits of conserving forests and avoiding emissions. Within EbA, mitigation approaches such as REDD+ or PES can also be utilised to ensure that project objectives also focus on mitigation (Rizvi et al., 2015).

EbA can also be used to ensure the provision of particular ecosystem services that are crucial for human adaptation, for example water regulation (Locatelli et al., 2010). For example, sustainable watershed management is recognised as crucial in stabilising water supplies to African cities, which will face water scarcity in the future (Mafuta et al., 2011). At the same time, conservation of forested areas ensures the preservation of carbon stocks. Further examples of EbA can be found in the tsunami-affected areas of South and Southeast Asia, where coastal ecosystems were rehabilitated with mangroves and other coastal vegetation, increasing the carbon storage potential (Wetlands International Report, 2011). Mangroves also dissipate wave energy, rendering the impact of storms and other climatic events less severe for both people and the coastline. Another example is forest fire management in West Arnhem Land in Northern Australia. Mitigation benefits include limiting or preventing wildfire emissions, but the initiative also increases the adaptive capacity of forests to extreme climatic events, which may lead to increased fire frequency and intensity (ProAct, 2008).

cities. Rural households are destined to be among those that are most affected by the changing climate, including impacts such as decreased rainfall and increased storms and damage that threaten resource-based livelihoods, including agriculture. With intensified impacts of climate variability in other sectors such as agriculture, water and energy, forests may come to play an even more important role as safety nets (Angelsen et al., 2014; Nkem et al., 2010). For example, 'trees on farm' systems are used to provide shade, reduce temperatures and lessen the impact of hard rainfall and wind, both for certain crops (agroforestry systems) and livestock (silvipastoral practices) (Verchot et al., 2007). Conversely, climate shocks can enhance people's harvesting of forest products, thereby degrading the forest base, particularly if climate shocks become more frequent and intense (Locatelli, 2011). Adaptation and forestry mitigation projects can be linked by incorporating standards for adaptation into forest carbon certification and strengthening the capacities of project developers to accommodate both components (Kongsager and Corbera, 2015). National and international policies can also create conditions to facilitate the development of JAM activities (Locatelli, 2011).

3.3 Integrated and Synergetic Activities

Activities contributing to conservation and reduced deforestation can have mitigation benefits through carbon sequestration and carbon storage, as well as a range of adaptation benefits. For example, reduced deforestation can be achieved by reducing the dependence on land-based economic sectors (for example, agriculture and livestock) and by creating environments that facilitate such development (for example, removing the subsidies that encourage aggressive land-clearing). REDD+ aims to reduce carbon emissions from deforestation and forest degradation and covers both sustainable forest management and the enhancement of carbon stocks. It has become an important policy tool that will allow forest-rich countries to offset their carbon emissions. REDD+ has gained increasing traction, but it was only in the recently signed Paris Agreement (2015) that it was recognised as a viable path to reductions in CO_2 emissions. Though REDD+ was originally envisioned as an international PES scheme (see Box 1 for example, Angelsen et al., (2009), it is now apparent that emerging REDD+ initiatives are continuing integrated conservation and development strategies (Sunderlin et al., 2014a). Indeed, less than half of the 23 incipient REDD+ projects reviewed by Sills et al. (2014) were making conditional payments for actions to reduce deforestation and degradation. Nevertheless, adaptation benefits from such payment programmes can contribute to enhancing households' economic resilience, while also achieving mitigation benefits through preserving carbon stocks. In the cases reviewed by (Caplow et al., 2011), positive income and employment benefits were found; particularly in the Noel Kempff Mercado Climate Action Project in Bolivia, mitigation activities have produced positive livelihood impacts through the promotion of livelihood activities supporting conservation and sustainable management. The same project, however, suffered from poor inclusion and project coordination, largely due to the scale of the area involved, similar to the issues that concern conservation and development projects (May et al., 2004). Another example is the Bolsa Floresta programme (also known as the Forest Allowance programme) in the Amazon, which emphasises sustainable livelihood development, while achieving mitigation benefits through forest conservation (Börner et al., 2013).

Expanding or establishing protected areas can also lead to mitigation and adaptation benefits for forests, biodiversity and people. For instance, conservation corridors enable wildlife to migrate between areas for food and shelter. Intact forests lead to increased ecosystem resilience and the provision of regulating environmental services, such as water-cycling and microclimate regulation. Finally, greater ecosystem resilience achieved through conservation can conserve biodiversity and reduce susceptibility to disturbances such as fire. People also benefit from such activities by being less affected by disturbances, having access to a resource base and regulating ecosystem services that can help them adapt to climate change. Indeed, conservation actions are increasingly relevant to forest-dwelling communities, which may rely on forest products to diversify income streams in times of need or on forests for current consumption. Another coping strategy is harvesting of forest products (Fisher et al., 2010), which may serve an important function in the face of the increasingly unstable climate and its impact on food supply. Enhanced soil fertility and soil protection can increase the productivity of small-scale agriculture, which may in turn lead to reduced land-clearing. Nevertheless, overharvesting and forest degradation can become problematic if the severity and frequency of climate shocks increase (Locatelli et al., 2011). On the other hand, designating protected areas and placing restrictions on forest use may limit the consumption of forests and forest products, as well as restrict access to resources that people may depend on (Streck, 2009).

Activities aimed at reducing degradation may focus on sustainable forest management activities or practices that reduce the risk of disturbances such as fires or pests. Sustainable forest management, defined as 'a dynamic and evolving concept aiming to maintain and enhance the economic, social and environmental values of all types of forests for the benefit of present and future generations' (UN, 2008), represents a holistic approach to forest management. The failure to manage forests in a sustainable way drastically reduces their adaptive capacity; this includes benefits such as increasing ecosystem resilience to climate change, soil erosion protection, soil fertility enhancement and even watershed and microclimate regulation, depending on the degree of restoration (Locatelli et al., 2010). Clearly, a reduction in forest disturbances will positively benefit people's ability to adapt to climate change and reduce the impact of that on household economy and productivity. Fire management practices can have important adaptation benefits, especially in the hotter and drier climates of fire-prone areas, as well as mitigation benefits, as carbon stocks are preserved or maintained (Matocha et al., 2012). However, some adaptive measures, such as reducing rotation times or suppressing fires, can jeopardise the permanence or decrease carbon stocks in the long run. Sustainable forest management can also be implemented with mitigation as the main objective, for instance, in fire management. While fires are necessary for some ecosystems to maintain their function, in others the results can be devastating, leading to slow regrowth, lost biomass and reduced ecosystem services (Elias et al., 2014). More frequent and intense fires can make systems such as the Amazon rainforest reach a tipping point beyond which the forest cannot bounce back, resulting in a transition to grassy savannah-type environments (Nepstad et al., 2008).

Activities associated with afforestation and reforestation can lead to the direct mitigation benefits of restoring carbon stocks. Adaptation benefits for people include the provision of wood fuel to meet current resource demands and thereby reduce pressure on other natural forest areas. Environmental services such as water regulation, flood and erosion control can result in improved water availability and water regulation, soil conservation and increased arable land (Somorin et al., 2012). This is particularly true of water-abundant regions or areas that experience intense rainfall seasons interspersed with long dry spells (Locatelli et al., 2011). Such soil and water conservation benefits can reduce the impacts on tree growth. For forests, short-rotation species in commercial or industrial forestry or silvicultural practices, for example, sanitation harvests, can reduce susceptibility to pests and disease. However, afforestation and reforestation activities have certain negative effects. In semi-arid and arid regions, the demand for water can be high and will increase in hotter climates, while forestry is more water-demanding than other land uses (FAO, 2008; Klein et al., 2007a). Other concerns are land use and availability. For instance, reforestation plans may conflict with future demands for land for cultivation in the face of climate changes and, thereby, land productivity (arable land). Biodiversity can also be affected through monocultures in afforestation and reforestation, which promote fast-growing alien species (Klein et al., 2007). To minimise trade-offs, afforestation and reforestation activities can ensure the use of diverse tree species or native tree species (Ravindranath, 2007) or planting in degraded or marginalised lands, thus enhancing sustainable forest management (Duguma et al., 2014).

Overall several synergetic or integrated activities can be achieved within forestry, leading to greater cost and project efficiency (Somorin et al., 2012). An overview of integrated and synergetic practices and actions in forestry that result in mitigation and adaptation benefits is given in Table 3. The three columns note the positive and negative effects of these practices and actions on 1) forest adaptation, that is, how practice contributes to or detracts from building forest resilience to climate change impacts; 2) people's adaptation, that is, how practice contributes to or detracts from building people's resilience to climate change impacts, particularly forest-dependent people; and 3) mitigation.

TABLE 6 OVERVIEW OF PRACTICES AND ACTIONS IN FORESTRY WITH ADAPTATION AND MITIGATION BENEFITS

Practices and Actions	Effect on Forest Adaptation	Effect on People's Adaptation	Effect on Mitigation	Reference
		Conservation and reduced deforestation		
Avoided/reduced deforestation of forests, e.g. changes in policies, economic growth sectors	• Increase in ecosystem resilience to climate changes • Soil erosion protection and soil fertility enhancement • Watershed regulation • Microclimate regulation	• Microclimatic regulation for people, livestock, crops and wildlife • Coastal area protection • Increase in crop resilience	• Increase and enhance carbon sequestration above and below ground • Protecting against watersheds can benefit hydropower and clear energy	(Locatelli et al., 2015) (Malhi et al., 2009)
Avoided deforestation through REDD+/payments for environmental services		• Payments can contribute to household welfare, improve economic resilience		(Campbell, 2009) (Jarvis et al., 2011)
Expansion or formation of protected areas	• Linking areas through corridors • Reduced impact logging • Conserving biodiversity • Reducing disturbances, e.g. fire	• Preserving resource base as household safety net • Preserving ecosystem services, e.g. water regulation • Diversify livelihoods and incomes - Competition for land/ decreased access to land - overuse of forest resources for coping with climate shock, can lead to degradation of the forest		(Brown et al., 2011) (Mustalahti et al., 2012) (Alexander et al., 2011) (Locatelli et al., 2011) (Athanas and McCormick, 2013) (Stromberg et al., 2011)

Reduced degradation				
Fire management and protection	- Shortened rotation times to adapt to CC can decrease carbon stocks - Fire suppression can jeopardise permanence of carbon stocks • Early warning and improved fire fighting	• Microclimatic regulation for people and crops • Increase in crop resilience • Preserving resource base as household safety net • Preserving ecosystem services, e.g. water regulation • Diversify/uphold livelihoods and incomes	- Decrease in carbon stocks - Permanence of carbon stocks • Reduced/limited GHG emission as a result of reduced intensity	(Couture and Reynaud, 2009) (ProAct, 2008) (Swart and Raes, 2007)
Sustainable forest management, including pest/disease management	• Restoring degraded natural forest land through regeneration of native species and natural regeneration of degraded land • Increase in ecosystem resilience to climate change • Reduce disturbances, e.g. through fire-protection regimes • Soil-erosion protection and soil-fertility enhancement • Watershed regulation • Microclimate regulation		Increase and enhance carbon sequestration, and carbon storage above and below ground	(Ravindranath, 2007) (Duguma et al., 2014)
Sequestration				
Afforestation	• Reduce susceptibility to pest/disease through e.g. short	• Meeting current resource demands, e.g. wood fuel	• Increase and enhance	(Ravindranath, 2007) (Duguma et al., 2014)

	rotation species in commercial or industrial forestry or silvicultural practices, e.g. sanitation harvests • Reduce adverse impacts on tree growth through e.g. soil and water conservation measures	• Regulation of environmental services, e.g. water • Stabilise slopes and reduce flooding • Lower vulnerability to heat stress	carbon sequestration, and carbon storage above and below ground - Some trees may not be as effective in sequestering carbon	(Dang et al., 2003) (Klein et al., 2007a)
Reforestation	- Reduced ecological adaptation (fast-growing monocultures are more vulnerable)	- Decreased food security - Compete for land - Short-term benefits for few - Reduction in water availability in arid regions - Reduced ecosystem resilience resulting from monocultures		(Stringer et al., 2012) (Beymer-Farris and Bassett, 2012) (Schrobback et al., 2009) (D’Amato et al., 2011)

4. Barriers and Opportunities to Joint Activities in Agriculture and Forestry

4.1 Institutional and Policy Barriers and Opportunities

Institutional and policy barriers and opportunities can both hinder and facilitate the development of JAM activities. At the national level, Locatelli et al. (2011) found that in Latin America national policies are rarely set up to accommodate the integration of adaptation and mitigation activities, the strongest focus still being on mitigation activities. They also found that in CDM projects in Colombia the government recognised the lack of an adaptation requirement in the approval process. At the national level, adaptation and mitigation were managed by separate ministries or institutions, largely due to differences in sectoral focus and geographical scales of implementation. Policies that are uncoordinated and, at times, conflict in the areas of climate change mitigation and adaptation, food security and economic development can generate perverse incentives that can unintentionally lead to the unsustainable use and overuse of resources and conflicting goals, hindering a more all-inclusive approach to joint activities (Campbell et al., 2011; Hoffmann, 2011). For example, the fragmentation of mandates and tasks by different government agencies is one of the main challenges in moving REDD+ projects ahead in Vietnam and Indonesia (Thuy et al., 2014).

At the international level, the story is similar to the country-specific one above. The UNFCCC treats mitigation and adaptation as separate policy measures (Duguma et al., 2014), though recognition of joint adaptation and mitigation measures has been growing. International agreements have had a strong focus on mitigation, for example, setting emissions targets under Kyoto (Locatelli et al., 2010), while adaptation is viewed as a means to achieve mitigation (Duguma et al., 2014). Adaptation and mitigation are addressed through different processes and are discussed in corresponding policy debates that are rarely linked and that can involve different constituencies and funding sources (Harvey et al., 2014; Verchot et al., 2007).

Reasons for this may be because in many cases policy planning is short term, whereas the integration of adaptation and mitigation goals requires long-term planning as a result of their varying time scales for implementation and effect (Harvey et al., 2014). For instance, in some cases policies supporting conventional agricultural practices predominate over those supporting climate-smart agriculture. However, promoting multi-stakeholder planning across local, regional, national and business interests could avoid this barrier by raising awareness among policy-makers and other decision-makers about activities with adaptation and mitigation goals – for instance, (i) developing NAPAs, NAMAS and REDD+ strategies that include JAM practices, or (ii) securing high-level commitments to conservation agriculture, agroforestry and other climate-smart agriculture practices

(Harvey et al., 2014), as well as incorporating JAM objectives directly into sector policies (e.g. forestry (Locatelli et al. 2015).

4.2 Knowledge and Capacity Barriers and Opportunities

The fundamental divide between mitigation and adaptation also affects the way project developers think of their projects, as is evident from the large number of projects that can potentially contribute win-win outcomes for both adaptation and mitigation, but fail to do so (Locatelli et al., 2011).

Empirical studies of the synergies in forestry and agriculture are few, and more research is needed to explore these linkages in forests at the levels of landscapes, projects, countries and international agreements (Naidoo et al., 2008). Methods for assessing the magnitude of the ecosystem services that are generated through forest conservation and reforestation are needed, as are methods for measuring the role of ecosystem services in reducing the vulnerability of communities to climate change (Locatelli et al., 2011; Naidoo et al., 2008). The difficulty associated with documenting and collecting data on the benefits of ecosystem services amongst users often plays a central role (FAO, 2015) (FAO, 2015).

Moreover, at the individual level, farmers may face another level of barriers, namely tradition and the social acceptability of change, which can ultimately affect their willingness to adopt new initiatives. This results in the need for awareness and communication of the need for and benefits of climate change adaptation initiatives (Smith and Olesen, 2010). Related to this, capacity barriers have become increasingly relevant. The failure of extension services in some African countries restricts the ability to upscale innovations in agroforestry for improved land-use systems (Mbow et al., 2014). Specifically, knowledge of advanced cultivation methods and technical support is necessary before farmers can add trees to cropping systems and/or animal production, and it may also promote the swift adoption of agroforestry techniques (Matocha et al., 2012).

There is a technical difference between mitigation and adaptation concerning their physical evaluation, where single-metric GHG emissions exist for mitigation, but not for adaptation (Watkiss et al., 2015). Moreover, there are no metrics for evaluating the synergetic benefits of mitigation and adaptation (Duguma et al., 2014). The synergetic effects have only recently begun to be described, and there is still some scientific uncertainty as to what constitutes the optimal mix of adaptation and mitigation, when the goal is to achieve the best benefits of different kinds of synergies (Klein et al., 2005). Moreover, both adaptation and mitigation suffer from other methodological challenges: there are high levels of uncertainty and large costs involved in measuring and monitoring emissions reductions, including complications in establishing a baseline. REDD+ projects in particular face significant methodological challenges with regard to linking co-benefits to carbon benefits, as common measures for evaluating biophysical and welfare outcomes still need to be developed (Caplow et al., 2011). At the landscape level it is essential to track and monitor the diversity of farming and the changing impacts and threats facing farming (e.g. of agricultural production, ecosystem services and human welfare) in order to monitor the synergies and trade-offs of different agricultural development scenarios and inform future sustainable agricultural development (Sachs et al., 2010).

To solve the existing technical, knowledge and capacity-building barriers, Harvey et al. (2014) have argued that it is necessary to develop tools for policy-makers and other decision-makers to visualise the potential outcomes of different joint strategies concerning mitigation and adaptation, food production, energy, incomes and other related objectives. More analytical assessments of ongoing JAM initiatives and projects can therefore provide the evidence for when and where pursuing adaptation and mitigation simultaneously is more beneficial and cost-effective than implementing them separately. Also knowing the impact of future climate change on current joint activities is essential, for example, knowing how tree species distributions will change in future climate scenarios, particularly if agroforestry relies on a certain tree species. Importantly, there is a large gap in our knowledge of how mitigation can benefit from adaptation (and vice versa) and of the added value of integrated strategies. Also, certain contextual factors should be in place that can largely determine whether mitigation and adaptation should be pursued separately or combined, but this knowledge also needs to be acquired (Locatelli et al., 2015).

4.3 Funding and Other Barriers and Opportunities

Funding bodies often look at mitigation and adaptation separately, and current funding of adaptation and mitigation projects rarely takes synergies into account (Duguma et al., 2014; Kongsager et al., 2015). In addition, many mitigation and adaptation projects have been on a small to medium scale; hence, identifying the project-level capacity of JAM can perhaps be achieved by first identifying the adaptation co-benefits of mitigation projects or vice versa (Illman et al., 2012). Project standards such as the Voluntary Carbon Standard only consider the livelihood impacts of mitigation activities, not of adaptation. However, a concept like PES and payment schemes such as REDD+ and co-investment schemes (Namirembe et al., 2014) show increasing potential when it comes to incorporating adaptation activities. The Climate Gold Level of the CCB Standards' Third Edition adopts an optional criterion, which can be used to identify and promote projects that provide significant support to communities and/or biodiversity with regard to adapting to anticipated climate change impacts and risks (Namirembe et al., 2014). This is a starting point for the joint funding of JAM activities.

Even though there are indications that certain climate management practices generate savings over their lifecycle, many also involve upfront costs and short-term risks (FAO, 2009; Hoffmann, 2011; McKinsey, 2009). For example, soil and water conservation infrastructures can require large upfront costs in terms of labour and external efforts (FAO, 2009). Although the financial incentives for some mitigation practices may take the form of agricultural carbon credits, and some only benefit smallholders, a number of issues need to be taken into consideration here to enhance the options for carbon incomes to create incentives for adaptation initiatives and thus overcome the barrier of underfunded adaptation initiatives.

The lack of joint coordinated funding streams for adaptation and mitigation is another key constraint (Buchner et al., 2013; FAO, 2013). The private sector and carbon finance represent the main sources of funding for mitigation activities, whereas public funds, NGOs and donors often prioritize poverty alleviation, food security or disaster relief, which tends to complement adaptation priorities (Lobell et al., 2013; Schalatek et al., 2012). This traditional separation of funding sources (and funding eligibility criteria) has created silos in the implementation of adaptation and mitigation measures on the ground (Schalatek et al., 2012), as well as hindering the adoption of integrated landscape-level approaches (Harvey et al., 2013; FAO, 2013).

In REDD+ projects, tenure security poses a major barrier (Kongsager and Corbera, 2015; Sunderlin et al., 2014a). Without secure tenure and rights to use forest resources, the potential of forests to support local communities and our chances of further developing REDD+ will be limited (Sunderlin et al., 2014a). Recent evidence has shown that transfers of ownership of large areas of forest commons to communities coupled with carbon payments can both contribute to mitigation and introduce livelihood improvements (Chhatre and Agrawal, 2009). Moreover, the twenty to thirty-year time scale of REDD+ projects creates uncertainty when it comes to evaluating whether such projects will indeed have positive outcomes (Caplow et al., 2011).

5. Conclusion

The present review of the concepts and practices of joint adaptation and mitigation in agriculture and forestry highlights the complexity and challenges involved in both defining and operationalising joint activities. Issues such as the differences between adaptation and mitigation activities in terms of scale of implementation, time horizon for implementation, availability of funding for mitigation versus adaptation and the metrics to measure mitigation versus adaptation pose significant challenges to the pursuit of joint activities.

Land use is one of the key sectors that has great potential for creating synergies between mitigation and adaptation actions, potentially achieving both objectives at little or no extra cost. Importantly, mitigation and adaptation in two of the major land uses – agriculture and forestry – have interconnected effects on agriculture or forest ecosystems and on society, making the pursuit of joint activities even more complex, but at the same time offering mutual benefits. The positive benefits of adaptation can also be mutually beneficial for development, and often positive development benefits are likely to contribute to positive effects on people's adaptive capacity. Moreover, the positive nature of these benefits, showcased by empirical studies in Tables 2 and 3, emphasises the need to pursue joint activities and further research to understand the barriers and opportunities to operationalisation.

The current coverage of joint adaptation and mitigation in the literature has also been piecemeal, as there is no one definition of a joint adaptation-mitigation activity. At best, scholars have attempted to describe the linkages, interrelationships, complementarity, substitutability, synergies and trade-offs that currently exist in empirical examples in agriculture and forestry, among others. From this we have compiled the major activities that can be categorised into mitigation activities with adaptation benefits, adaptation activities with mitigation benefits, integrated or synergetic activities, and importantly their effects on agriculture or the forest ecosystem and on society.

The paper has also highlighted existing barriers and opportunities within agriculture and forestry in pursuing JAM – this is the first step in highlighting the specific areas that suffer from policy, financial, knowledge and capacity barriers and opportunities that hinder or facilitate the pursuit of JAM activities. This also provides insights into where efforts can be focussed to ensure the further development of JAM activities and the tools necessary for succeeding. Examples include making funding available for joint adaptation and mitigation activities, encouraging collaboration in order to challenge the current policy division between mitigation and adaptation, and promoting further documented research measuring the impacts of joint activities, their cost-effectiveness and their synergies within the complex setting of risks and uncertainty concerning the magnitude of climate change impacts.

Moving forward, in the pursuit of joint adaptation and mitigation activities, it is important to keep in mind the objectives of pursuing JAM activities simultaneously in order to provide cost-effective, sustainable solutions that capitalise on the mitigation and adaptation effects of a particular activity to the mutual benefit of both. Simply striving for win-win outcomes for the sake of doing so may put at risk other activities which may achieve important adaptation- or mitigation-only benefits, thereby diminishing the effective use of limited climate funding (Klein et al., 2005).

Indeed, identifying an optimal mix of adaptation and mitigation is a slow and tedious process, one that is likely to vary between countries and over time (Klein et al., 2015). Thus, country-specific and context-adapted responses are vital to the design of JAM activities and their eventual success. In particular, the enabling conditions that can facilitate the pursuit of joint activities also need to be understood, enhanced and/or established in order to support the full pursuit of joint activities where relevant and thus complement the fulfilment of national ambitions highlighted in the INDCs, as well as in global targets such as the Sustainable Development Goals and the Paris Agreement, thus ultimately setting the world on track to a low-carbon and climate-resilient future.

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7. References

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Paper 2

Estimating the Benefits of the Interrelationship between Climate Change Adaptation and Mitigation - A Case Study of Replanting Mangrove Forests in Cambodia

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Abstract

The paper demonstrates welfare benefits of climate change adaptation leading to mitigation in a case study of mangrove forest replanting in part of the coastal wetland areas of the Peam Krasaop Wildlife Sanctuary in Cambodia. The community is suffering from storm damage which is expected to be increased by climate change. Replanting mangrove forests is a means to adapt to climate change, which protects the local community. Based on information on income, climate change and expected changes in the mangrove area, we simulate development in the mangrove forest area and the associated welfare economic consequences in terms of income loss and mitigation benefits. We estimate the adaptation benefit based on an expected damage cost approach and the mitigation benefit based on the amount of carbon sequestrated in the replanted area as well as a carbon price.

For a wide range of scenarios and assumptions, the paper concludes that the welfare benefit of replanting is positive if one looks at adaptation alone and even more so if mitigation is included. Consequently, considering adaptation and mitigation benefits jointly leads to higher replanting intensities than considering adaptation alone. Payment for mitigation needs to be implemented if it is to attract private decision makers.

1 Introduction

Climate change adaption and mitigation are two different approaches to handle climate change; mitigation is mostly seen as a global public good, reducing the cost of adaptation, and adaptation is mostly seen as a local and also often private good (Ingham et al. 2013; Kane & Shogren 2000), that reduce the need for (and thereby the marginal cost of) mitigation. As they are interrelated, if we want to maximise welfare, we need to look at both – assuming that climate change stays below a threshold where a mix of adaptation and mitigation is possible. (Watkiss et al. 2015).

Technologies for adaptation and mitigation have largely been advanced individually due to the large variation of the spatial and temporal characteristics and different stakeholders and implementation approaches (Watkiss et al. 2015). Consequently, also much of the literature focuses on only one of them (Canadell & Raupach 2008; McGray et al. 2007; IPCC 2007) as does the United Nations Framework Convention on Climate Change (UNFCCC) and policy-oriented programmes in this framework such as the clean development mechanism (CDM), Nationally Appropriate Mitigation Action (NAMA), National Adaptation programmes of Action (NAPA), and Reduced emissions from deforestation and forest degradation in developing countries (REDD+). IPCC (2014b) finds that research into interrelationships between climate change mitigation and adaptation is fragmented, and examples from real life (Matocha et al. 2012; Verchot et al. 2007; Laukkonen et al. 2009) question the findings in the theoretical approaches (Felgenhauer & Webster 2013) highlighting a need for research regarding interrelationships between climate change adaptation and mitigation (Klein et al. 2007; Locatelli et al. 2011; Ingham et al. 2013; Kane & Shogren 2000; Watkiss et al. 2015; Locatelli et al. 2015).

Therefore, the area is still in need of in-depth, empirical and local knowledge to understand the interrelationships and complexity of climate change adaptation and mitigation and for methodologic development and tools for implementation. This requires case specific information, which in many cases is not available. In this paper we illustrate how far we can get with establishing such a model, based on empirical data when available, and otherwise reasonable assumptions. We do so by looking at a local case study of adaptation by replanting mangrove (*Rhizophora apiculqator Bl.*) forest in Cambodia. We quantify the possible welfare economic benefits of replanting and address unintended side-effects of interrelationship between climate change adaptation and mitigation (Locatelli et al. 2015). We do so by looking at two different replanting strategies – a fast and a slow – and three different climate change scenarios and estimate the avoided expected damage cost by replanting.

The underlying assumption is that adaptation is the main objective of local decision makers. However adaptation in the form of replanting may also contribute to mitigation as unintended benefits. This can ideally promote investment in adaptation through carbon funding and ecosystems services, which thereby potentially increases welfare. This is a situation in which the two measures complement each other. If a drop in the cost of adaptation or mitigation occurs, the ideal reaction will be to increase both (Ingham et al. 2013). This definition comes from Klein et al. (2007). Whether adaptation and mitigation are substitutes or complements is a much discussed area (Ingham et al. 2013; Kane & Shogren 2000; Felgenhauer & Webster 2013). Economic models have found that a mixture of adaptation and mitigation tends to be optimal from a substitution perspective (Ingham et al. 2013) while the policy literature reports that adaptation and mitigation tend to be complements (Locatelli et al. 2015).

Approaching adaptation and mitigation as complements allows us to assess whether a combination of climate change adaptation and mitigation at a local case level can contribute to greater welfare compared to initiatives in which adaptation and mitigation are addressed separately in response to climate change. If this is the case, there may be situations in which adaptation is not worth pursuing itself, but it may be worth pursuing if mitigation is also considered.

2 Literature on the Quantification and Valuation of Adaptation and Mitigation

One of the great barriers to understanding the interrelationships between adaptation and mitigation is the lack of quantitative indicators for adaptation (Lecocq & Shalizi 2007; Warren et al. 2012). One approach is the ‘expected damage cost’ (EDC) approach (Hanley & Barbier 2009; Barbier 2007), which looks at values directly. The EDC approach values storm protection in terms of the avoidance of future damage from storms (Barbier 2007) and falls in the category of ecosystem services valuation. Fisher et al. (2009) conclude that the number of papers addressing ecosystem service valuation is increasing exponentially. However, a search of the literature has shown that there are relatively few case studies based on the EDC approach even though some of the integrated assessment models (IAM) (Warren et al. 2012), such as the Dynamic Integrated Climate-Economy model (DICE) and the Regional Integrated model of Climate and the Economy (RICE) (Nordhaus 2014; Nordhaus 2011), are based on it. A number of studies refer to the ability of mangrove forests to protect communities and inland areas from storms and surges (Brauman et al. 2007; Das & Vincent 2009; Quisthoudt et al. 2012; Quisthoudt et al. 2013; Khan & Amelie 2015; Brisson et al. 2014; Sanford 2009) or they refer to the production function as an option for ecosystem service valuation (Fenichel et al. 2013; Liu et al. 2010; Sauer & Wossink 2013; Brauman et al. 2007; Jenkins et al. 2010). Barbier (2007) also mentions that the method have been used regularly in risk assessment and health economics - looking at how changes in assets affect the probability of a damaging event occurring. This method requires us to use the ecosystem as an input, developing a "production function" (Dupont 1991) for the mangrove's ability to protect the community against storms. EDC is generally considered a valid approach for estimating the lower boundary of the value of avoided damages cost by mitigation of damages (Boutwell & Westra 2015), as it captures the full value of an ecosystem providing a service. It is not dependent on consumer preferences like other ecosystem service valuation methods (Brauman et al. 2007). Errors may appear with this method if the case is not well-defined or the quality of the data is poor (Boutwell & Westra 2015). In the current paper, we will use the EDC approach; and, because we focus on a very narrow case (as opposed to the larger climate models), the method of our study allows us to evaluate carefully the assumptions behind it and thereby point out knowledge gaps. This is of particular importance in a developing country context where data is often limited, but where decisions area, of course, made. Consequently, judging the reasonability of the assumptions is crucial. We will return to this in section 6.

In this paper, the replanting of mangrove forests as a mitigation of climate change activity will be addressed through an estimation of the carbon sequestrated and emitted in the replanted area, based on the IPCC (2014b) guidelines for calculating carbon sequestration in coastal wetlands. To estimate a value hereof, the social cost of carbon (SCC)[1] is appropriate. The SCC is the net present value of one more or one less tonne of CO_2e emitted (van den Bergh & Botzen 2015). SCC can be found from IAM (Warren et al. 2012). Hope (2013) suggests an SCC of USD 106 per tonne of CO_2e for 2010, which is a mean estimate of an integrated assessment model (IAM) and considerably higher than the USD 81, which is used by the Stern review (Stern 2007). As Hope (2013) highlights, one has to be aware of the assumptions behind, e.g., discount rates, equity weight assumptions, socioeconomic scenarios, and climate sensitivity. Nordhaus (2011) estimates a cost of USD 12 per tonne of CO_2e at 2015 prices, including uncertainty, equity weighting, and risk aversion, based on the IAM RICE-2011 model, and the DICE-2013R model suggests USD 18.6 per tonne of CO_2e at 2005 prices (Nordhaus 2014). Tol (2008) did a meta-study based on 200 estimates of SCC with a mean of USD 25 per tC or USD 6.8 per tCO_2e, followed by other studies (Tol 2013; van den Bergh & Botzen 2014; van den Bergh & Botzen 2015). Van den Bergh and Botzen (2014) conclude that a cost of USD

[1] Sometimes, a price per unit is used; sometimes, per unit CO_2e. One can be obtained from the other by recalculating the price based on the molecular weight of CO_2 compared to a carbon molecule.

125 per tonne of CO_2e represents the lower bound if one gives weight to the potential impact of climate change. As see, there is wide variation among these authors of the cost level – based among other things on disagreements of how to handle data (see, e.g., the editorial note in the vol. 29, no. 1 of the *Journal of Economic Perspective* (Anonymous 2015)).

An alternative to using SCC is to use the price of carbon traded on one of the existing markets. In an ideal world, where politicians take future generations fully into account and can agree on a social optimal amount of credits, this marketed price should reflect SCC. Though this is highly unlikely, it can be argued that it is the value current politicians can agree on assigning to it. Furthermore, such a market price is closer to potential compensation paid to local communities for the global public good of carbon sequestration, and may thereby better reflect potential local complements of adaptation. Consequently, we will use a range of such market prices from related markets, thereby obtaining a conservative estimate of the value of carbon mitigation – from a welfare economic point of view.

3 Mangrove Forests and Climate Change

The mangrove forest is a forest type with the ability to survive in salty and brackish waters under influence of tidal water and an ability to colonize in a large range of habitats along ocean coastlines and estuaries throughout the tropics with a rather monoculture and inaccessible nature (Tomlinson 1986; Donato et al. 2011; Alongi 2008)

Mangrove forests play a key role for the livelihood of people living there, as a supplier of food, timber, fuel, and medicine (Alongi 2008). Mangrove forests also contribute to global biodiversity as a breeding and nursing ground for marine organisms (Gilman et al. 2008). The mangrove forest is one of the major carbon pools in the tropics, four to six times higher than boreal and tropical upland forests (Donato et al. 2011).

Climate change that impacts the mangrove forest may be such things as rising sea-level, increase in temperature, change in precipitation pattern, increase in storm frequency and intensity, and increased atmospheric CO_2 concentration (Gilman et al. 2008). The impact on the mangrove ecosystem is diverse; an increase in storm intensity and frequency can lead to increased damage to and mortalities of the forest (Alongi 2008), and other impacts may increase productivity and dynamics in the stand (Gilman et al. 2008; Alongi 2008). Mangrove forest ecosystems can be vulnerable to rising sea levels (Gilman et al. 2008). If the system cannot keep pace with the changing sea level compared to the change in elevation of the mangrove sediment, it can cause increased mortality among the trees (Gilman et al. 2008). Donato et al. (2011) state that it is unclear whether mangroves manage to keep pace with the sea-level rise, and Alongi (2008) argues that the mangrove can cope with rising sea levels by moving inland and that deforestation is more likely to exterminate mangrove forest. To know the scale of the devastation from a rise in sea level, site-specific knowledge is necessary (Gilman et al. 2008). The mangrove forest's response to climate change is very much dependent on the landscape dynamics and other ecosystem factors such as salinity and the level of nutrients; and, in many cases, it will respond positively (Alongi 2008).

In this paper we use the increased frequency of storms as a measure of the impact of climate change on the mangrove forest. Damage will be determined as hectares (ha) of destroyed mangrove forest. We do not consider the rise in sea level since data at the local level were not available.

The argument for considering the replanting of mangrove forests as adaptation is that it is very likely that increasing the area of mangrove forests will strengthen the resilience of the local community by protecting them from storm surges and natural hazards. Replanting will also contribute with a global mitigation benefit by carbon sequestration.

3.1 The Case

The case study for this paper is the Peam Krasaop community located on the coast of Cambodia in the Koh Kong province, close to the border of Thailand. The Peam Krasaop community contains a mangrove forest (2,324.4 ha) and open water (2,300 ha). In addition, there are 5 ha of villages on the mainland, 16 ha of floating villages, and 15 ha of open land, which is being managed by 5 households, which support themselves on agriculture. The Peam Krasaop community is located inside the Peam Krasaop Wildlife Sanctuary, which is an area of approximately 26,000 ha. We focus on two townships within the Peam Krasaop community, the floating village and the new village. Both villages belong to the Peam Krasaop community.

Peam Krasaop has a population of 1,318 people distributed among 277 households (CCCA 2012). Their main occupations are based on ecosystem services from the mangrove forest such as coastal fishing, selling souvenirs, and providing tour guides.

The community in Peam Krasaop is very vulnerable to storms, and by climate change the storm frequency is expected to increase. Salt water is intruding on the freshwater supply in the villages, damaging their livelihoods and threatening human safety. Another threat is flooding of the floating villages that are built on stilts near preferred fishing areas - on the edge of the mangrove forest and close to the open sea but, at the same time, close to the mainland. (CCCA 2012). Both types of villages will benefit from storm protection. The threats from storms have forced many to move from the floating village to the new village on the mainland. Many fishermen prefer to stay in the floating villages when they go fishing - to save money on fuel, but in periods with less fishing intensity they stay in the village on the mainland. The local fishermen are dependent on their boats for access to fishing grounds and to transport tourists. Not all the fishermen own their own boat. Some rent boats from others (Nielsen 2014).

The communities in Peam Krasaop are already exposed to the effects of storms and floods because of the vulnerability of their bad housing and fragile boats (CCCA 2012), and they have limited coping strategies with respect to storms. The community's vulnerability to storm is increased by the poor infrastructure in the area (CCCA 2012). An indication of the size of the problem can be seen from data from 2011 where there were 11 incidents of winds above 12m/sec. 38 houses, two fishing boats, and 1.4 ha of mangrove forest were destroyed as a consequence hereof.

The ecosystem services for the Peam Krasaop community are very sensitive to climate change since the sea grass beds and coral reefs in relation to the mangrove forest serves as breeding grounds for fish, mussels, crabs and other marine wildlife found in the area, which are vulnerable to increased sedimentation as a result of rising sea levels, storms, surges, and other natural hazards or changes in the ocean current. This leaves the entire local community extremely exposed if it does not adapt to climate change.

In October 2013, 15 ha of mangrove forest were replanted just outside the boundary of Peam Krasaop as a climate change adaptation initiative to protect and increase the community's resilience to climate change. The project was financed by the European Union, national development aid programmes from Sweden and Denmark (SIDA & DANIDA) and, United Nation Environmental Programme (UNEP), and United nation Development Programme (UNDP) as a part of a larger project of vulnerability assessment and adaptation programmes in the coastal zone of Cambodia. The initiative is to replant 60 ha, which will not only strengthen the community's resilience to climate change but also improve the conditions for the ecosystems services on which the community is so dependent. The initiative was implemented by hiring local people to gather mangrove seeds and plant them in the designated area. Only the replanting activities and damage from storms are considered in the case study.

In the following we will describe an estimation of the expected damage costs to assess the adaptation and mitigation benefits. We do so by considering two different scenarios of replanting – one where a certain area is replanted at once (corresponding to a project approach), and one where replanting occurs (to a smaller amount) every year over 100 years (corresponding to a situation where the problem is tried solved by small inputs available from daily management). For each situation, we calculate social welfare as the discounted sum of the avoided damage cost and the mitigation benefit, subtracted by the replanting cost – considering a range of replanting intensities. As there is large uncertainty about the impact of climate change on storm risk, we analyse the replanting scenarios for three different climate scenarios.

4 Modelling the Welfare Benefits of Interrelationships

4.1 General Model and Model Assumptions

To answer the research question of whether a combination of adaptation and mitigation can lead to higher welfare, we focus on a marginal valuation approach. How marginal valuation approach relates to EDC. So, we look at the benefit of replanting one extra hectare of mangrove forest. This allows us to identify the optimal area to replant (given the assumptions of the model). We assume that a social planner has a utility function $U_i(A,M,H)$ from the mangrove forest under the impact of climate change in scenario *i*. U_i is a function of *A*, *M* and *H*, where *A* is the benefit of climate change adaptation, i.e., the ability of the mangrove forest to protect the local community from economic damage; *M* is the benefit of the climate change mitigation, i.e., the value of carbon storage in the replanted mangrove forest; and *H* is the possible co-benefit of adaptation and mitigation, such as increased welfare. Furthermore, there is a cost of replanting, *Z*. Each differs depending on when they occur. As mitigation primarily is a global good and adaptation is a local, it makes sense to assume additivity and linearity in input, we can express the utility of a given mangrove forest over a finite period *T,* discounted by *r* representing the preference for the present over the future at time *t*:

$$\boldsymbol{U_i(A, M, H) = \int_{t=0}^{T} \ (A_t + M_t + H_t - Zs_t)\, e^{-rt} dt}, \qquad (1)$$

Where *A*, *M*, and *H* depend on the area of mangrove forest; whereas *Z* depending solely on the replanted area (s_t, = the replanted area of mangrove forest at time *t).* Replanting can have positive effects on both mitigation and adaptation. Thus, potential interrelationships between mitigation and adaptation may occur and only in the form of positive interrelationships, i.e. the two measures are complements to each other. Let S_t be the area of mangrove at a given point in time, l_t the area lost at time *t*, and s_t the replanted area of mangrove forest at time *t.* The timeframe of *t* is one year. Under climate change scenario *i* at time *t,* the mangrove forest area (ha) may be written as:

$$\boldsymbol{S_{t,i} = S_t + s_t - l_t} \qquad (2)$$

l_t is a function (*g*) of the current overall area of the mangrove forest (S_t) impacted by the climate change (C_{it}) in the current climate change scenarios (*i*) at time *t*:

$$\boldsymbol{l_t = g(S_t, C_{it}),\ l_t \geq 0} \qquad (3)$$

Notice that this implies that we assume that a replanted and an existing hectare of mangrove have the same value. Without a spatially-specific model, this is a reasonable assumption at the margin.
In the following section, we shall look at how *A*, *M, H*, and *Z* are estimated.

4.1.1 The Benefit of Adaptation (*A*)

We estimate the increases of welfare benefit by replanting (s_t). This activity can increase the overall area of mangrove forest (S_t).

To estimate the ability of the mangrove forest to protect the local community, we use an 'expected damage function' (EDF), which will give us the option of calculating the marginal EDC, taking our point of departure in Barbier (2007) and Hanley and Barbier (2009). The EDF is derived from the 'production function' (PF) by which the environment is valued as an input in the creation of assets that increase the utility for the local community. In our case, the EDF describes the relationship between damage caused by storm and the loss of the mangrove forest and, thereby, production. Whereas Barbier (2007) and Hanley and Barbier (2009) deal with a static model, we have a dynamic model because this better captures the key attributes of climate change – the continuous change in conditions.

We use the aggregated households from this study site to represent the entire community and, thereby, the preferences of the social planner. The aggregated households' expenditure function is expressed as $m(P,C_i,U_i)$. U_i is the utility level for a given climate scenario *i*, and U_i^0 indicates that no replanting is done in climate scenario *i*. Notice that, with climate change, the utility may vary over time and, thus, will not reflect today's consumption possibilities. *P* is a price vector for acquired goods consumed by the householdss. C_i represents the impact of climate change under the climate scenario *i.*

The EDC, E[D(C)], is the welfare loss caused by changes in the number of acquired goods in the expenditure function, i.e., the minimum income needed to offset the change. This is a result of the expected damage to the households due to the shift of C. If we let C^0 denote the consequences of a 'no change' scenario and *K(C)* the minimum income for a household to maintain the initial utility level, then we can say:

$$\boldsymbol{E}[\boldsymbol{D}(\boldsymbol{C})] = \boldsymbol{m}(\boldsymbol{P^x}, \boldsymbol{C^0}, \boldsymbol{U^0}) - \boldsymbol{m}(\boldsymbol{P^x}, \boldsymbol{C_i}, \boldsymbol{U^0}) = \mathbf{K(C)} \quad (4)$$

This will provide a measure of compensating surplus. We are assuming that the total area of mangrove forest may have a direct effect, i.e., a reduction in the impact of storms and other natural hazards in terms of damage to the local community, and this positive effect will also be strengthened by replanting the mangrove forest. Thus, the PF for the damage caused by storm may be represented as (see equation 5):

$$\boldsymbol{C} = \boldsymbol{C}(\boldsymbol{S}), \boldsymbol{C}' < \mathbf{0}, \boldsymbol{C}'' > \mathbf{0}' \quad (5)$$

By this, we are assuming that the damage caused by storm in relation to climate change increases with the decrease of the remaining mangroves, which is reasonable.

We can define the marginal willingness to pay (*W(S)*) for protection services of the mangrove forest in relation to the marginal impact of mangrove forest changed based on expected damage caused by storms and other natural hazards (Barbier 2007):

$$\boldsymbol{W}(\boldsymbol{S}) = -\frac{\partial \boldsymbol{E}[\boldsymbol{D}(\boldsymbol{C}(\boldsymbol{S}))]}{\partial \boldsymbol{S}} = -\boldsymbol{E}\left[\frac{\partial \boldsymbol{D}}{\partial \boldsymbol{C}}\boldsymbol{C}'\right], \boldsymbol{W}' < \mathbf{0} \quad (6)$$

This is analogous to the Hicksian compensated demand function for market goods (Freeman III et al. 2014).

Because the risk of damage depends on the total area *S* at a given point in time, any mangrove loss (or increase) influences future potential damage. Thus, the aggregated value of an adaptation measure such as replanting an area of s_t can be calculated as the integral of the reduced damage at all points in time – discounted:

$$\boldsymbol{V}(\boldsymbol{A}) = -\int_{\boldsymbol{\tau}=\boldsymbol{t}}^{\boldsymbol{T}} \int_{\boldsymbol{S}_{\boldsymbol{t},\boldsymbol{\tau}}}^{\boldsymbol{S}_{\boldsymbol{t},\boldsymbol{\tau}+\boldsymbol{s}_{\boldsymbol{t}}}} (\boldsymbol{W}(\boldsymbol{S}_{\boldsymbol{\tau}})\boldsymbol{dSd\tau})\boldsymbol{e}^{-\boldsymbol{rt}} \quad (7)$$

We want to estimate the marginal value (in present value terms) of the last replanted hectare of mangrove forest in the context of climate change adaptation ($MV^{V(A)}$). We can express this as the marginal EDC:

$$MV^{V(A)} = \frac{(V(A)\ \ )}{(S_\tau - S_0)} \tag{8}$$

4.1.2 The Benefit of Mitigation (*M*)

The benefit of mitigation is calculated as the monetary value of the carbon sequestration in the replanted mangrove forest at time *t*, as the trees sequestrate CO_2 from the air and capture it as carbon in the wood. From a social planner perspective, the monetary value could be seen as the SCC. The benefit of mitigation at time M_t can be expressed as a function of $\dot{S}_t$ over the time period we are considering:

$$M_t = L(\dot{S}_t), \tag{9}$$

where *L* is the function for captured CO_2e in the mangrove forest.

This can be rewritten as equation 10; S_t is reduced out of the function, since we are assuming that the existing mangrove forest is a closed system that does not contribute any additional carbon sequestration or emission. The mitigation benefit will be calculated on basis of the area of mangrove forest lost at time *t* (l_t) and the replanted area at time t (s_t):

$$\dot{M}_t = -l_t + s_t \tag{10}$$

Aggregating and discounting over time, we have the contribution to equation 1, and the marginal value of mitigation can be obtained in a manner similar to equation 8 for adaptation.

4.1.3 Co-benefits in Relation to Replanting the Mangrove Forest (*H*)

The benefits that are achieved in addition to the benefits of climate change adaptation and mitigation are referred to as the co-benefits of replanting the mangrove forest (see equation 1). These co-benefits are related to the increased welfare that may be a result of an improvement of the breeding conditions and the natural habitat for fish, dolphins, coral, etc., for this specific case study. It is a welfare gain because of the enhanced economic activities that are dependent on the mangrove forest for the local community/fishery and tourism. The case we are considering is coastal fishery and open access fishery. Therefore, the fishery in the area is not optimally managed and also suffers from unsustainable fishing. The consequence of open access is that, if any profit is apparent, it will draw the attention of new fishermen, who will then establish themselves in the community, which will equalise any producer surplus. However, it will still affect the welfare through its influence on consumer surplus (Barbier 2007). We are assuming that the co-benefits are positive and increasing with S_t. However, the data required to estimate the influence of co-benefits is limited in our case. Therefore, they are assumed to be zero (H_t=0) in our case study, but the model could easily be expanded.

4.1.4 Replanting Costs (Z)

The cost of replanting the mangrove area, *Z*, is assumed to be constant per hectare. We assume that the cost of replanting the mangrove forest as an adaptation initiative is equal to the cost of replanting mangrove forest as a mitigation initiative. Thus, if the cost has been accounted for in estimating the benefit of adaptation, it will not be necessary to account for the cost again in estimating the benefit of mitigation.

4.2 Simulation

With the utility function described above and specification of the components, we can now describe the simulations performed. To analyse the welfare consequences under different scenarios and strategies for adaptation to and mitigation of climate change, we are operating with three damage scenarios and two replanting strategies. We carried out the simulations in the MATLAB2013 environment.

4.2.1. Damage Scenarios as a Consequence of Climate Change

When the wind speed reaches 12 m/sec, damage occurs (CCCA 2012). Therefore, in the following, we shall refer to this as a storm even if it is not defined so in technical terms. From 1979 to 2012, wind speeds over 12 m/sec were measured at two points outside Cambodia's coast. These historical data have provided us with an opportunity to calculate the daily probability of storms for each month of each year (Nielsen 2013). It is sometimes argued that storm frequencies and strength in some locations will increase. However, according to IPCC 5th assessment report (Hijioken et al. 2014), there is currently no indication that the frequency of storms will increase or decrease off the coast of Cambodia; however, coastal and marine systems will suffer from climatic and non-climatic drivers, as strength and impacts of storms. Therefore, we base our simulation on the historical data, simulating day-specific risk of wind speeds higher than 12 m/sec for a 100 year period. Developing three damage scenarios illustrating how the PF for a damaged mangrove forest will develop under the influence of the storms. The PF for the damage scenarios, equation (5), is partly based on the assessment of the destroyed mangrove area in Peam Krasaop from 2011(CCCA 2012), assuming that ecosystem services do not respond linearly to changes in habitat size (Barbier et al. 2008).

To comply with the uncertainty regarding the expected climate change for the study area, and that no detailed data exist, consequently we set up three scenarios that can demonstrate a range of possible changes. The first is a baseline scenario, reflecting the climate of today; the second contemplates greater destruction; whereas the third has stronger storm occurrences once in a while, damaging the resilience of the system. The three damage scenarios are described by equation 11:

$$\boldsymbol{C_i(S) = b * e^{-aS}}, \qquad (11)$$

Damage Scenario 1: Is based on our knowledge of storm occurrences in 2011, and we simulate the start of the first storm by removing 0.08 ha of mangrove forest, based on equation 11, where a = -0.001770 and b=5. This reflects an almost 'no change' scenario (as compared to today). However, the amount of mangrove forest removed per storm increases slowly but exponentially because of the assumption made in equation 5.

Damage Scenario 2: Is based on that 1 hectare of mangrove forest will be removed each time a storm occurs to start with, and then it develops exponentially. Equation 11 was fitted based on this assumption: a = 0.00099 and b=10. The destruction of the mangroves develops exponentially.

Damage Scenario 3: Is based on damage scenario 1 and an obstruction of, for each 30 storms, one typhoon will occur. The typhoon is assumed to destroy 50 ha of mangrove forest each time. The typhoon's destruction of 50 ha is not influenced by the replanting strategies of mangrove forest under the simulation, as damage scenarios 1 and 2 are. The simulated typhoon's destruction reflect a severe incident but without causing complete destruction.

Figure 1 shows how the three damage scenarios will destroy the existing 2,324.4 ha of mangrove forest over time, assuming there is no replanting to delay the destruction. Under damage scenario 1, the destruction is minimal compared to damage scenario 2 in which everything will be destroyed by year 60 and damage scenario 3 in which everything will be destroyed by year 63. The reason the two curves cross is that the obstruction in damage scenario 3 over time delays the total destruction compared to damage scenario 2. From around year 50, damage scenario 2 start to go beyond 50 ha of destruction. It is assumed that no regeneration of the storm-damaged areas will occur.

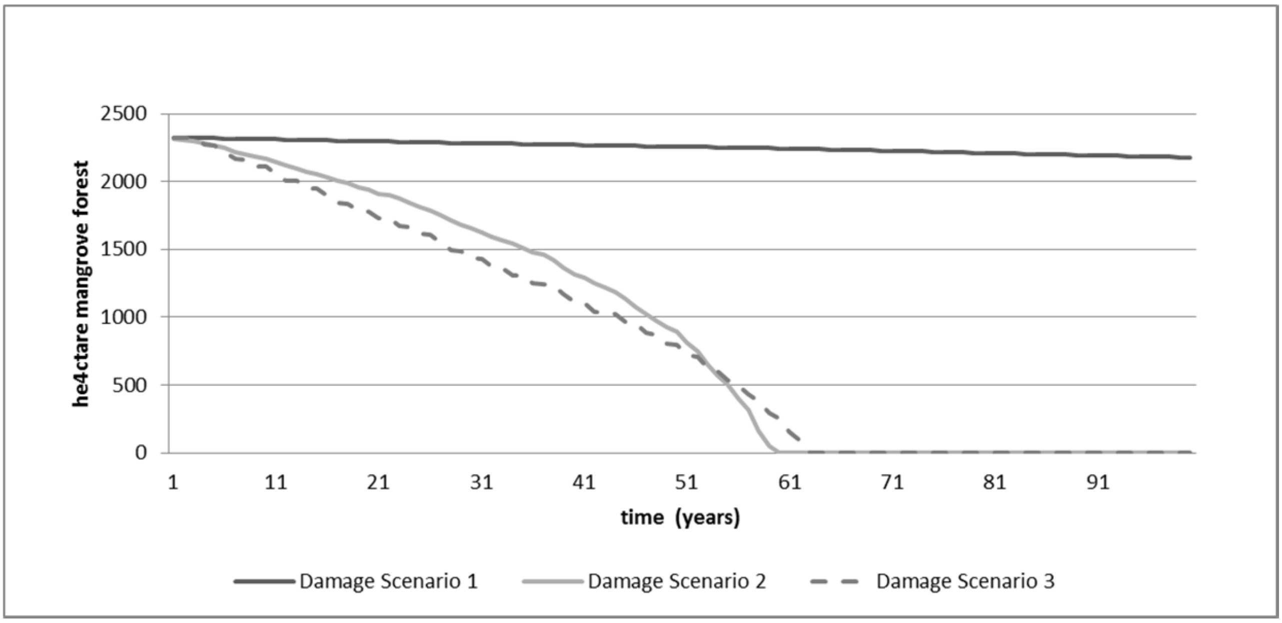

Figure 1 the destruction of the mangrove forest from year 1 to 100 in the three damage scenarios without any replanting of the mangrove forest.

4.2.2. Replanting Strategies

We operate with two replanting strategies for adaptation that differ in terms of the time when the replanting occurs. The replanting strategies are meant to reflect two extreme approaches. While early replanting is, *ceteris paribus*, favoured compared to later because of the increasing destruction rate, it may not always be feasible due to limitations in the availability or access to knowledge, capital, and labour. The two replanting strategies for simulations are defined as follows:

Replanting Strategy A: One-shot replanting of mangrove forest at intervals of 1 ha from 0 to 500 ha, where replanting is only carried out in year 1 of the 100 year period of the simulations. This reflects the fastest possible action.

Replanting Strategy B: Continuous replanting of mangrove forest at intervals of 0.25 ha from 0 to 15 ha, where replanting is carried out each year in the 100-year simulation period. This reflects a situation in which, e.g., labour availability is limited and, therefore, constrains the magnitude per year.

4.3 Data and Functional Forms

In this section, we describe the data and various assumptions for the concrete simulation. The Cambodia Climate Change Alliance (CCCA) carried out a vulnerability assessment of the community's risks from climate change in 2012. The CCCA obtained data through informal questionnaires and facilitated group discussions with the communities concerned. In January 2014, we visited the 15-

hectare replanting site and the community of the fishermen just outside the city of Koh Kong in the Peam Krasaop Wildlife Sanctuary. Exploratory interviews with fishermen and other member of the community were conducted in which the information obtained through the CCCA (2012) was confirmed. For the simulations, the replanted mangrove area is assumed to be located inside the Peam Krasaop community border. Areas in which climate change is having an impact on the mangrove forest were also visited along with two park rangers and an interpreter. Information about cost and expenses in relation to the replanting site was also obtained through the project coordinator (VAAP LDCF 2013) along with additional information about the fishermen's use of equipment, commodities, and belongings (Nielsen 2014).

4.3.1 Replanting Cost

The cost of replanting was obtained through the CCCA, which was responsible for replanting the 15 ha of mangrove, costs include gathering seeds for new plants, renting boats, hiring people from the community for seed-gathering and planting mangrove seedlings, monitoring, and later replanting, if necessary. The cost also include an event to raise awareness of the project in the community (CCCA 2012). The cost does not include soil preparation. The total cost of replanting 15 ha was USD 16,441 (or USD 1,096 per hectare). The cost of replanting the mangrove forest used in the simulation, excluding the awareness event, is estimated to be USD 896 per hectare.

4.3.2 EDC

The annual EDC is calculated based on the income lost. Thus, apart from the information on the area of damaged mangrove depending on the remaining area, we also need information of household income and assets. The 277 households in the community can be divided into three different categories of poverty, where 51% belongs to the two poorest groups[2]. The community's aggregated income as USD 445,416 per year (CCCA 2012).

To assess the annual damage costs as a function of remaining mangrove, data from tree situations were considered. The first one is an estimated cost of USD 49,400[3] of storm damage in 2011 where 2023 ha mangrove was left (CCCA 2012). The second one is an estimation of the loss of a total destruction of the community, which we assume will occur when 2/3 of the mangrove is destroyed

[2] the two lowest income groups are characterized by not having their own home, living on land illegally, having their own house but very far from the main road or having a very low income but living close to the main road (CCCA 2012). Other indicators of these groups are that they have lost family income, faced food shortages, have sold properties, or borrowed money from people within the last 12 months (CCCA 2012).

[3] This is an aggregated value for the whole community. It is biased towards the poorer income groups due to their low-quality houses and boats.

(770 ha is left). Here the fishing options present around the mangrove forest are no longer assumed sufficient to sustain livelihood. The average household earns 1608 USD/year (CCCA 2012), so the aggregated income for the 277 households is USD 445416. Adding the value of their assets[4] (taken from (Nielsen 2014), results in a loss of UDS 1.2 million. Finally, we use a lower bound estimate of damage of USD 1,800 as it is unlikely that storm damage can be completely avoided because of the poor quality of houses and boats. Based on these three points, an exponential function of the EDC depending the area (ha) of mangrove forest remaining each year is estimated as:

$$\boldsymbol{D}(\boldsymbol{S}) = \boldsymbol{c} * \boldsymbol{e}^{\boldsymbol{gS}} \qquad (12)$$

where c = 14,726,276.0915 and g = -0.00291. To avoid extraordinary large damage costs when little mangrove is left, we set an upper boundary of USD 1.6 million.

The expected damage cost is calculated on an annual basis. When no mangrove is left, livelihood options corresponding to the annual income are lost – every year, forever. This is of course only true to the extent that people cannot move away and find other ways to sustain themselves. In the other extreme, we can assume that they just find another living, and thereby there is no income loss present once people move away. Given the limited livelihood options in the area, and the importance of the mangrove not only in this village but for larger areas, this may also be unrealistic. Consequently, we use the one extreme – calculating the annual loss as present every year after destruction. The other extreme, zero cost once the mangrove is destroyed was also calculated but results are not shown. But we will refer briefly to these results in the result section.

4.3.3 Calculating Carbon Sequestration under the Influence of the Damage Scenarios and Replanting Strategies

The IPCC tier 1 guidelines have been used (IPCC 2014a; IPCC 2006) to estimate the possible carbon sequestration and emission in the mangrove forest, with respect to the remaining, replanted and damaged mangrove forest.

[4] This is not equally distributed. But as we work with aggregated values, the distributional aspect does not matter for the estimation.

The area of mangrove forest destroyed under the three damage scenarios will count for the full destruction in the year it occurs, creating an emission of 129 tonnes of carbon per ha/year (IPCC 2014a).

The time span for calculating the carbon sequestration in the replanted mangrove forest is based on Alongi (2008). Alongi (2008) uses long-term data from French Guinea, which indicates that a mangrove forest stand follows a series of successive stages: rapid early development, a maturity stage, and, finally, a stage of senescence in which the stand breaks down and a new stand is regenerated and colonised. In the calculation of the possible carbon sequestration, we limit the influence of gap dynamics only to consider how much of the mangrove forest is left in each scenario of the simulations.

At first, the replanted mangrove forest will create carbon emissions of 1.62 tonnes ha/year (IPCC 2014a), this stage of rapid early development will lasts five years (Alongi 2008; Fromard et al. 1998). After that, the replanted mangroves will reach the maturity stage and create sequestration in the amount of 6.65 tons carbon ha/year (IPCC 2014a), which we estimate will last approximately 65 years in the replanted area (Alongi 2008).

Replanting strategy B in which replanting is done every year will contribute consistently to carbon sequestration from year 6 until 0 ha is left, but the act of replanting will only be done until the threshold of 770 ha left mangrove forest is reached. However, even if the threshold of 770 ha is reached, CO_2 emission will continue from mangrove destruction until 0 ha mangrove is left none is left.

Human collection of fuel wood and other wood removal leading to deforestation should also be included in the estimation of the carbon sequestrated for the area. Data availability on this subject is very poor for the Peam Krasaop community. Therefore, the net emissions from fuel wood and wood removal have not been included in the calculation.

The benefit of climate change mitigation is estimated on the basis of the amount of carbon sequestrated and converted to tons CO_2-equivalent (tCO_2e) under the constraints and assumptions mentioned above for the calculation of the amount of tCO_2e, which we then assign a monetary value. We are using three different CPs to give the carbon sequestration a monetary value; we use prices from existing markets, to reflect what local decision-makers will take in to account. The first CP (CP1) represents the price for the 'certified emission reductions' (CERs) under the 'clean development mechanism' (CDM), under the Kyoto protocol. The price for trading CERs on 10 February 2014 was USD 0.54[5] per tCO_2e (Fenhann 2014). The second carbon price (CP2) refers to the social cost of tCO_2e. We apply the very low SCC price of USD 6.8 per tCO_2e, referring to Tol (2008)[6], who bases this estimate on over 200 estimates of the SCC. The third CP (CP3) is the average price of CERs traded between 21 May 2007 and 10 February 2014 (Fenhann 2014), which is EUR 9.66 or USD 13.18 (XE 2014). The CPs are multiplied by the amount of tCO_2e sequestrated or emitted for the specific year and in the specific replanting stage for each of the replanting strategies and damage scenarios. Therefore, they will have a negative monetary value if more CO_2e is emitted than sequestrated. Appendix C illustrates the consequence of SCC in the range of USD 50-200 (not part of the submitted paper).

4.3.4 Calculation of the Marginal Value of Climate Change Adaptation, Mitigation and Replanting Cost

If we know the annual EDC for the three different damage scenarios combined with the two replanting strategies, including the cost of replanting for each adaptation initiative, and the monetary value of the mitigation initiative (carbon sequestrated and emitted in the mangrove forest), it is possible to calculate the present value of each adaptation and mitigation initiative under each of the replanting strategies. In this way, we can calculate the expected marginal EDC for each replanting and damage scenario and, thereby, evaluate the different strategies. To reflect the preference for the present over the future, we made the simulations with four[7] different discount rates: 4% and 12% is presented in the paper. This reflects the choice that the decision-makers have to take, and what priorities they have (Arrow et al. 1996). The four discounts rates contribute to a sensitivity test of the expected marginal EDC for each replanting and damage scenario. Discount rates at 4% or lower reflect a private planner or an alternative investment in a developed country, whereas 12% or higher reflect the private actor in a developed country. Specific for Cambodia can the discount rates for micro-loans reach 2-3.5% per month, cumulative equivalent to close to 50% per annum (CCCA 2012). Therefore, the discount rate most commonly used in developing countries is applied.

For each damage scenario and replanting strategy (and discount rate), we first calculate the present value of the cash flow of the EDC. Then, we summarise the present values over the 100-year period

[5] The CP for CERs on February 10 2014 was EUR 0.40 (for exchange rates, see XE (2014)).
[6] Converted to tCO_2e from his reporting of USD 25 per tC
[7] The marginal EDC and mitigation values in relation to the replanting cost under influence of 2% and 20% discount rates is available in Appendix B.

in each of the different stages of the replanting strategies. This is used to calculate the marginal value as given by equation 8. Because storms are random, the exponential development of the strengths and destructive power of the storms in the three damage scenarios, the estimated expected damage, is not smooth. So, to calculate the slope, different approaches were used, depending on what fitted best. The model fitted for the adaptation under the replanting strategy A was a two-term exponential function by which the derivative function gives the marginal value of one extra ha mangrove forest replanted. This fitted poorly for adaptation, mitigation and replanting costs[8] under replanting strategy B and mitigation under replanting strategy A. So, here, we used a moving average of 5 adjacent points of the present value, where the marginal value is found as the difference between two adjacent points of the moving average.

5 Results

5.1 Annual Values for Adaptation and Mitigation

In this section, we will first present the annual EDC, A_t, for the adaptation strategy for replanting strategies A and B, and the corresponding annual mitigation benefit (figures available in appendix A), M_t for the 100 year periode that we run the simulations over. These form the basis for the marginal curves for EDC and CP1, CP2, and CP3, which may be compared with the marginal replanting cost.

Figure 2 below shows the annual EDC, A_t, over time for replanting strategy A at three different levels of replanting - 0 ha, 250 ha, and 500 ha - and for the three different damage scenarios. It is seen that A_t increases over time as fewer mangroves remain but also that replanting delays destruction and, thereby, increases A_t. When the forest is total destroyed, A_t will be equal to USD 1.6 million, corresponding to the opportunity cost of the mangrove forest and the communities complete destruction. Under damage scenario 1, A_t is low compared to the two other damage scenarios. In fact, it is close to zero, and total damage will not occur. If replanting is done, A_t decreases from an average of USD 21,015 at 0 ha to USD 9,847 at 250 ha and USD 4,997 at 500ha – a change that is not visible in figure2. In damage scenario 2, total destruction will occur in year 52 if no replanting is done, and replanting 250 and 500 ha, respectively, may postpone this for 17 and 37 years, respectively. For scenario 3, total destruction will occur in year 51, and replanting 250 or 500 ha may

[8] Notice that, because replanting in scenario B occurs over time, the marginal cost of one extra hectare is not constant – e.g., replanting stops in the scenarios when the mangroves are completely destroyed.

postpone this for 10 and 18 years, respectively. Thus, the more severe the damage, the smaller is the effect of major replanting now.

Figure 3 shows a similar picture as figure 2, just for replanting strategy B. For replanting strategy B, the replanting cost is incurred each year as the mangroves are replanted until only 770ha of mangrove forest are left. The no-replanting strategies are identical to Figure 2, and we also find that replanting under damage scenario 1 has a small effect, though larger than under replanting strategy A. In damage scenario 2, replanting 15 ha per year may delay the increase in annual damage cost, so that total destruction is not reached. For damage scenario 3, replanting 15 ha a year will result in total destruction in year 89. The overall the picture for figure 3 is that replanting delays the increase in A_t and that replanting of 15 ha a year makes a significant difference in this regard, especially in damage scenario 2 in which the mangrove forest is not destroyed within the 100-year simulation period.

The results for the annual mitigation values show that, for replanting strategy A for all three CPs, damage scenario 1 has a positive mitigation value from year 6 to 76. After year 76, the mitigation value becomes slightly negative, which is caused by the limited destruction of mangrove forest in damage scenario 1 and further slowed down due to the termination of replanting. For the damage scenarios 2 and 3, it is clear that the destruction of the mangrove forest has a negative impact on the annual carbon sequestration (see figure A1, A3 and A5 available in appendix A).

Mitigation values for replanting strategy B, damage scenario 1, is the one less influenced by destruction, whereas damage scenarios 2 and 3 are both heavily influenced by the destruction of the mangrove forest, which creates a large amount of emissions that influence the monetary value of mitigation negatively. Similar to the annual damage costs (A_t)(figures 2 and 3), it is possible to see that replanting has a significant influence on the mitigation in damage scenarios 2 and 3, as it delays the point of complete destruction. When no forest is left, no carbon is sequestrated or emitted (see figure A2, A4 and A6 available in appendix A).

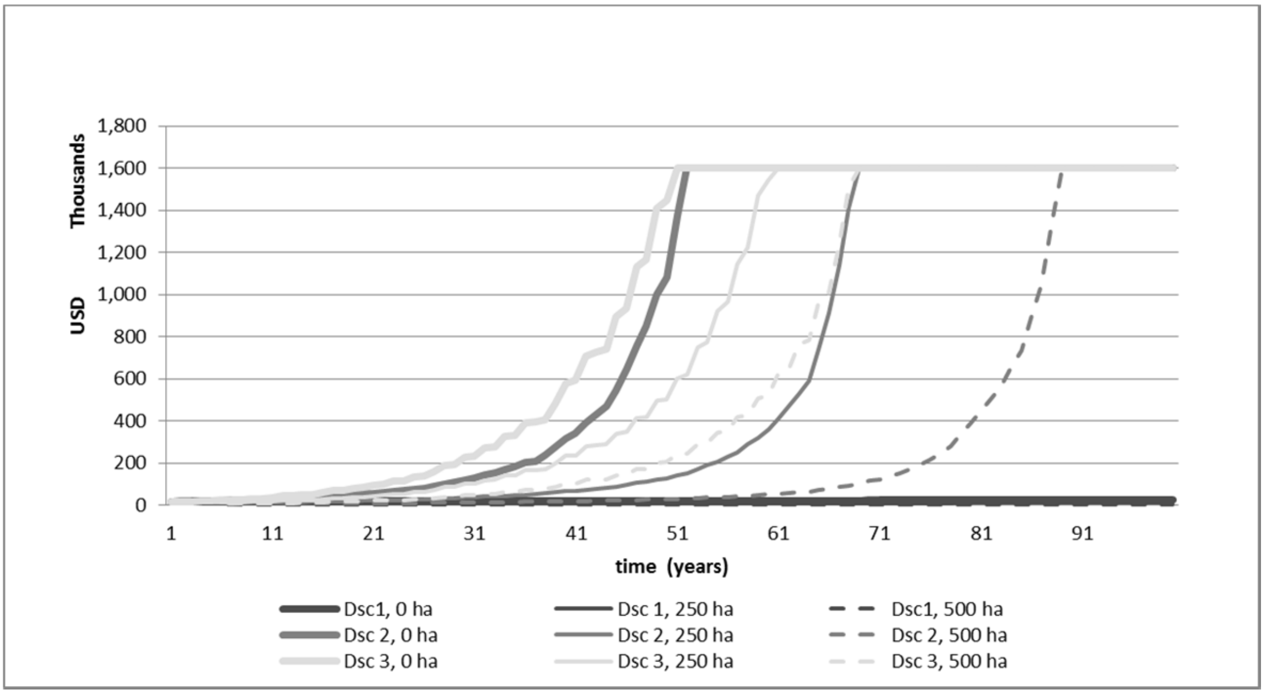

Figure 2. Simulated annual expected damage cost, A_t *(x-axis)*, over the 100-year period (y-axis) for replanting strategy A and three different levels of replanting (0 ha, 250 ha, and 500 ha) influenced in the three damage scenarios.

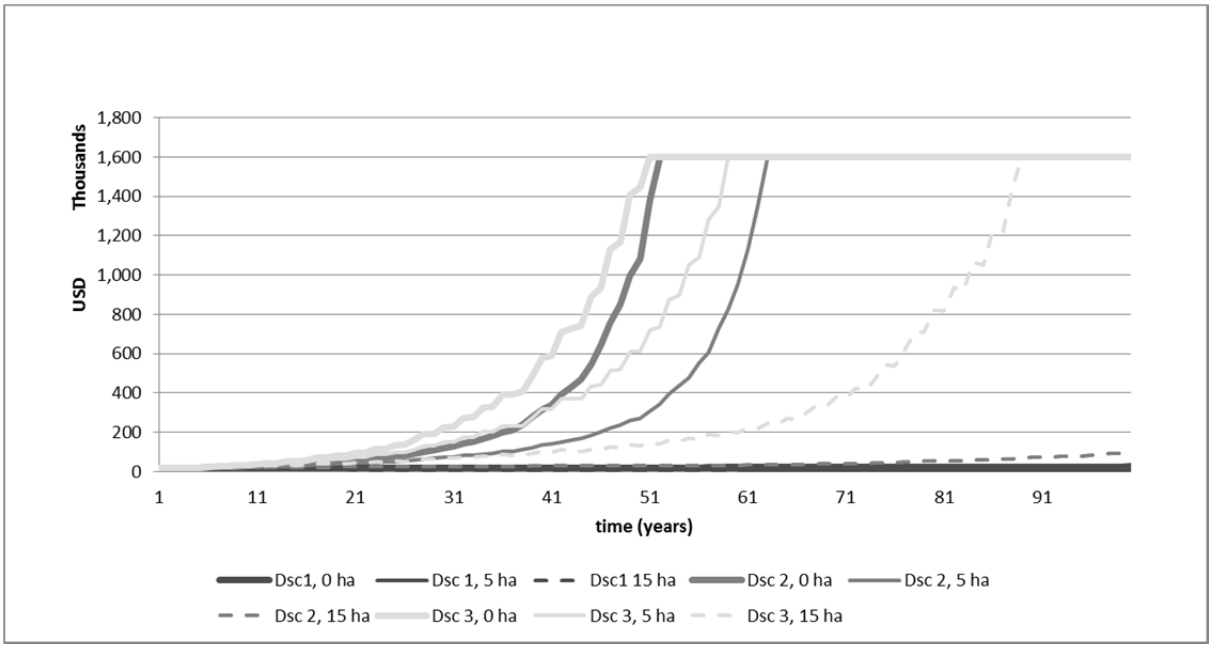

Figure 3 Simulated annual expected damage costs, A_t *(x-axis)*, over the 100-year period (y-axis) for replanting strategy B and three different levels of replanting (0 ha, 5 ha and 15 ha) influenced in the three damage scenarios.

5.2 Marginal Values

Figure 4 shows the aggregated present value of damage costs as the marginal EDC (i.e., the damage costs avoided by replanting one more hectare) at a discount rate of 4% for replanting strategies A and B along with the present value of the marginal mitigation value and the marginal replanting costs at the three CPs. We see that, for both replanting strategies, the marginal EDC in damage scenario 1 is around the same size as the marginal replanting cost – they intersect at 68 ha for replanting strategy A and 2.25 ha for replanting strategy B. However, if mitigation is included, it will be worth doing the replanting. If the price is high (CP2 or 3), the curves never intersect; but, if the price is low, we see that looking at mitigation and adaptation jointly will lead to an optimal replanting of 209 ha in replanting strategy A and 5 ha per year in replanting strategy B. For damage scenarios 2 and 3, the EDC is well above the marginal replanting cost. So, replanting is beneficial. If mitigation were considered as a single product, it would only be worthwhile to do replanting if prices were above the low price scenario (CP1). A similar pictures may be seen if we apply a discount rate of 2% (see appendix B, figure B1).

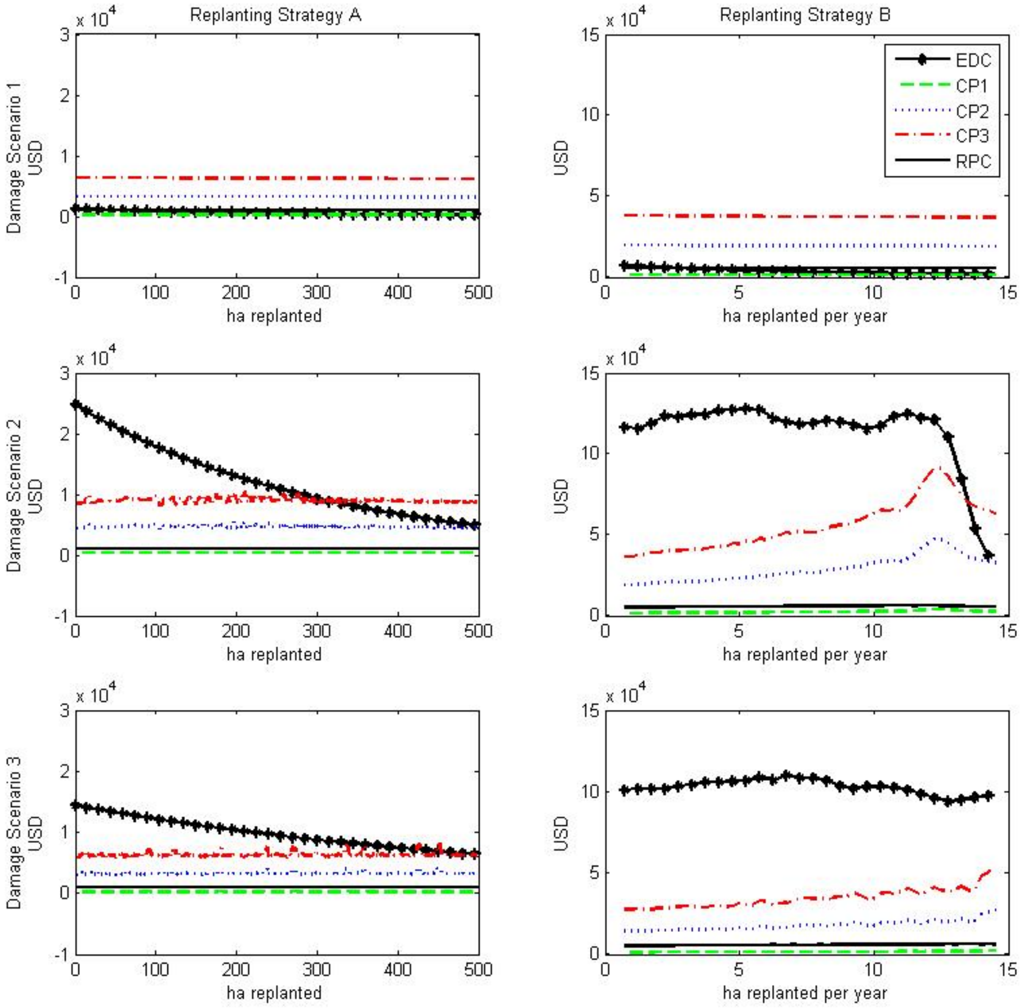

Figure 4 The marginal avoided EDC for the two replanting strategies A and B (adaptation initiatives) in each of the three damage scenarios (the black solid lines with dots), together with marginal mitigation values for the three CPs: CP1 = USD 0.54 per tCO_2e, CP2 = USD 6.8 per tCO_2e, CP3 = USD 13.18 per tCO_2e (the dashed lines). The thin black line shows the marginal replanting costs. All assume a discount rate of 4%.

These results assume a 4% discount rate –reflecting the discount rate of a social planner. A higher discount rate might reflect the decisions of a private actor – if incentives are provided for public good mitigation. Figure 7 shows the results for a 12% discount rate. Here, we see that, in damage scenario 1, the marginal EDC is considerably below the marginal replanting costs, and only CP2 and CP3 are high enough to justify replanting. In damage scenarios 2 and 3, however, we see that the EDC and the replanting cost intersect, so that, looking at adaptation alone in damage scenario 2, optimal replanting intensities are 243 ha under replanting strategy A and 10 under replanting strategy B. In damage scenario 3, we see that, for replanting strategy B, replanting more than 15 ha/year is optimal; whereas, for replanting strategy A, the optimal replanting is 132, i.e., below the optimal for damage scenario 2. This is because the benefit of replanting is higher in damage scenario 2. This can also be seen from Figure 2, where the integral of the difference between replanting 250 ha and 500 ha is larger in damage scenario 2 than damage scenario 3.

Looking at mitigation, we see that, for the lower discount rate, price scenarios CP2 and CP3 pay off the replanting costs fully – it is more pronounced than for lower discount rates. If the discount rate is increased to 20%, the replanting costs exceed the mitigation values (see appendix B, figure B2).

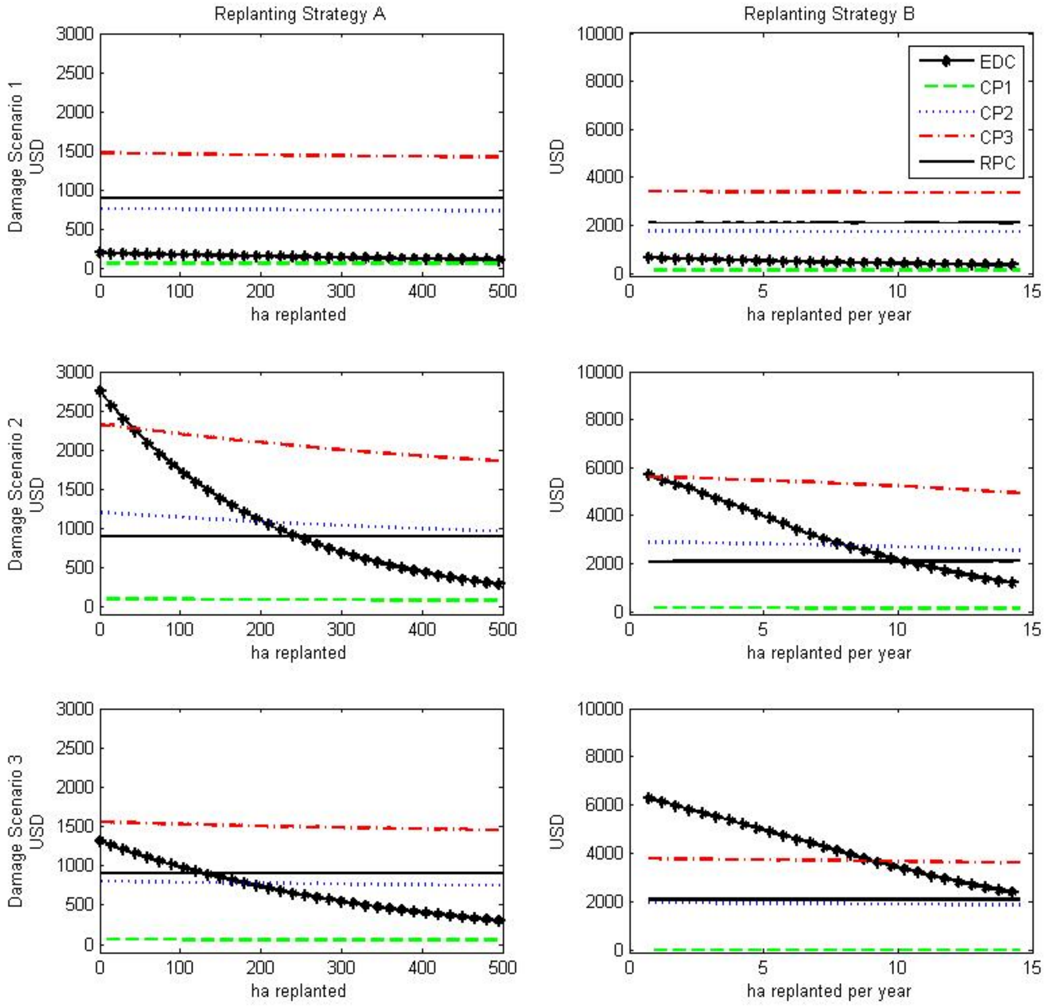

Figure 5 The marginal avoided EDC for the two replanting strategies A and B (adaptation initiatives) in each of the three damage scenarios (the black solid lines with dots), together with marginal mitigation values for the three CPs: CP1 = USD 0.54 per tCO_2e, CP2 = USD 6.8 per tCO_2e, CP3 = USD 13.18 per tCO_2e (the dashed lines). The thin black line shows the marginal replanting costs. All assume a discount rate of 12%.

Two assumptions are crucial for the above shown results, namely the choice of assuming continued loss once the mangrove is left, and the choice of using relatively low carbon prices compared to many of the SCC estimates which should be used in welfare economic analyses. Assuming that people just find other livelihood options if the mangrove is destroyed would reduce the expected damage cost. In the case of a 4% discount rate this would still result in the expected damage cost being larger than the replanting costs for damage scenario 2 and 3. For a discount rate of 12%, damage scenario 2 and replanting strategy A, the EDC and the replanting costs, would intersect each other at 220 ha, i.e. around 100 ha less than in the scenarios shown. For the corresponding replanting strategy B, the benefits from around 8 ha of replanting will offset the costs. This pattern is repeated for the other scenarios. Consequently, while the area optimal to replant is reduced, an effort is still beneficial. And if mitigation benefits are included it is even more so. This leads to the second sensitivity – namely, what is a high SCC of carbon was used: in that case, it would be beneficial from a welfare economic point of view to replant the maximum area analysed for all scenarios.

6 Discussion

6.1 Main Findings

The aim of this paper was to analyse the interrelationships of the benefits of climate change adaptation and mitigation. We do so by looking at the marginal value of replanting in a small case study in which causes and effects are visible and, thereby, possible to interpret in a broader context.

The overall assumption is that there is a joint benefit from climate change adaptation and mitigation; thus, they complement each other. From a social planner's point of view, adaptation alone makes replanting mangroves beneficial as the adaptation benefits are larger than EDC. Mitigation emphasises this. Our results show that even for the highest replanting intensities we have analysed (500 ha from the beginning or 15 ha per year over 100 years), replanting is worth the effort. If the discount rate is high, 12%, we find that adaptation by replanting is only beneficial to some extent – in damage scenario 2, replanting 250 ha from the beginning or 10 ha per year over the next 100 years is optimal, and in damage scenario 3, replanting 140 ha from the beginning or 15 ha per year over the next 100 years. So, in conclusion, the study shows that, looking at adaptation alone only makes replanting the mangroves worth the effort if increases in storm frequency occur. If mitigation is included, prices as low as in CP2 (6.8 USD per tCO_2e) makes the highest replanting intensity worth the effort. Consequently, looking at both adaptation and mitigation, makes replanting worth the effort even if there is no increase in storm frequency. Notice that this cost estimate is well below most estimates of SCC. van den Bergh and Botzen (2014) indicate that an SCC should not go below USD 125 per tonne CO_2e. Applying such high values would just make the emphasis on including mitigation in adaptation more pronounced, as the marginal mitigation benefits in Figures 4 and 5 would be very much above the marginal replanting cost (see Appendix C, not part of the submitted paper). If we are thinking of paying for carbon sequestration through a market price in a carbon emission trading scheme, it is much more likely that we lie in the lower end of CPs – unless there is political will to have the amount of quotas to reflect the SCC.

From a private decision maker's point of view, only adaptation is relevant – unless mitigation is paid for. And a higher discount rate would very likely also apply. In the study here, we operated with a

12% (real) discount rate; and, in that case, the area it would be optimal to replant would be smaller than in the social planner case for all damage scenarios. However, if payment for mitigation is implemented to reflect an increase in public good provisions together with the adaptation component, replanting would still be optimal – also from a private decision maker's point of view. An increase to 20% makes the whole thing a bit more impervious for investors, since the replanting cost exceeds the marginal benefits of mitigation and the EDC.

Comparing the two replanting strategies, we see that, if we assume that storms always destroys mangroves, a continuous replanting (replanting strategy B) may, in many instances, be beneficial – as it can halt ongoing destruction. Replanting strategy A delays destruction of the mangrove. But, will still lead to total destruction. Consequently, a mixture of the two strategies is probably best – a large replanting initially to reduce the risk level and, then, continued replanting of what is destroyed to make sure that the high risk levels are not reached again.

Boutweel and Westra (2015) argue that the values revealed by the EDC method are at the lower boundary compared to other ecosystem valuation methods. Consequently, the adaptation estimates in this study may be considered conservative, even though we do not consider alternative livelihood options.

6.2 Policy Implications

The complexity of climate change will also need a complex response; a benefit from implementing both adaptation and mitigation is shown, and a mix of the two replanting strategies is suggested.

A mixture of the two replanting strategies is suggested as the optimum for interlinkages between adaptation and mitigation from a social planner perspective, thereby reducing risk by replanting a large area to start with and then continuously replanting to maintain the acquired level of reduced risk. If payment for mitigation were included, this might motivate private investors to pledge money to replant in a manner similar to replanting strategy A. The investment should avoid being a "one-time wonder" in which the level of risk reduction from adaptation is seen long before the impact of climate change. By creating a mixture of the replanting strategies, it is possible to see long-term results from the investment, enforced by including stakeholder involvement and awareness of the mangrove forest and climate change. This could create the motivation for the community to continue replanting the mangrove forest (similar to replanting strategy B) and strengthen their resilience to climate change by learning to recognise the importance of natural resources to sustain their livelihoods, an aspect already reflected in the high replanting costs from the CCCA project. This is an investor opportunity to signal social responsibility that would be beneficial both locally and globally and, from a long-term perspective reduce risk.

The arguments for pursuing both climate change adaptation and mitigation for maximising welfare, is reinforced by that there is a limit for climate change adaptation, therefore a threshold for the mix of adaptation and mitigation (Watkiss et al. 2015). If climate change exceed this threshold, the cost of adaptation will only be a burden to future generations (Laukkonen et al. 2009). This enhances the arguments for the mixture of replanting strategies suggested, since the benefits of both adaptation and mitigation will have the large impact now but secure future risk reduction on a local scale.

Laukkonen et al. (2009) argue that local stakeholders should be persuaded to enhance their response to climate change. To do this, not only academic information but also the empirical knowledge - such as fishermen's knowledge about tidal water and the mangrove forest - is needed. From the exploratory interviews of fishermen in Peam Krasaop, it was easy to track awareness of the mangrove forest, since the forest sustains their livelihoods. However, there is a large gap between this awareness and the knowledge of how they could participate in protecting the mangrove forest and the co-benefits they derive from it. For example, when the tide is high, fishing is possible in the replanted area, so boats propellers destroy new seedlings, which delays the developing of the newly planted seedlings. Laukkonen et al. (2009) underline that stakeholder involvement should not be a top-down process but a process that strengthens the feeling of collective responsibility. Through this process, it will also be possible to address other factors that cause damage and degradation to the mangrove forest. For example, the community has recognised the income opportunities from tourists visiting the mangrove forest. This is an important issue to address since the fight against climate change is not always the first priority among local communities (Warren et al. 2012; McGray et al. 2007). Therefore, it is also important to support sustainable development, which is necessary since climate change will continuously provide challenges (Laukkonen et al. 2009). The use of local initiatives may, in the long run, strengthen and reinforce regional or national strategies (Laukkonen et al. 2009).

This strengthens the argument to pursue climate change adaptation and mitigation simultaneously from a social planner perspective. For this specific case, one could argue that adaptation and mitigation are complementary but with a known contradictory example (Matocha et al. 2012; Laukkonen et al. 2009): it is easy to imagine situations with a free-rider effect - fishermen who do not participate in the replanting or who damage newly planted seedlings. Once again, this underlines the need to make awareness and sustainable development a part of the adaptation and mitigation project.

6.3 Caveats

This paper is based on a case study in Cambodia in which data have been collected from locally-available knowledge. The quality of such an approach lies in its connection to decisions actually being taken. It can also be seen as a starting point for stakeholder involvement. However, there are some obviously caveats to the estimation. The economic data are based on the best available knowledge, and it is not considered whether, e.g., replanting costs could be lower. Another element it would be relevant to include is other threats from climate change - especially, rising sea levels but also temperature increases and changes in precipitation. Adapting to an increased number of storms may be worthless if the mangrove forest is flooded by rising sea levels. However, for the current study, this data was not available. Therefore, we leave it to future research.

The EDC approach is also applied in large climate change models and IAM (Warren et al. 2012) such as the RICE and DICE models (Nordhaus 2014; Nordhaus 2011). An advantage of using it on a local scale, such as here, is that its limitations become quite clear: results are not better than the data and assumptions behind them. Nevertheless, using it at a local level, where processes are clear, makes it possible to identify drivers affecting the trade-offs between costs occurring now and damage avoided in the future. In the current case, it has been demonstrated to be highly sensitive to the intensity of storm risks. Another consequence of the assumption is that replanting strategies that are not continuous will, in the long run, lead to destruction. While this may be correct in the near future, one could hope that, as the ecosystem becomes resilient, it will no longer be the case.

7 Conclusion

Methodological developments for handling the interrelationships between climate change adaptation and mitigation demand innovative thinking. The paper combines general economic theory with case-specific knowledge obtained from stakeholders, contributing with empirical knowledge. This paper is a step on the way towards developing a methodology to estimate the interrelationships between climate change adaptation and mitigation. Thus, it illustrates how, we can evaluate different strategies for adaptation and mitigation.

This case from Cambodia shows that, from a social planner perspective, there are positive benefits from replanting mangroves taking only adaptation into consideration but even more when mitigation is included. Consequently, looking at adaptation and mitigation jointly leads to higher replanting intensities than looking at adaptation alone. For this to motivate for private decision makers to pledge money for investment, payment for mitigation needs to be implemented. But the price levels do not need to be very high for replanting to be beneficial. To avoid private investment from becoming "one-time wonders", it is argued that private investments should include a learning element and involve stakeholders from the local community if we are to see a long-term effect through sustainable development, since the preference is to mix the two replanting strategies in order to reduce risk and secure the level of risk obtained.

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Appendix A:

Mitigation values for carbon sequestration and emissions over a 100-year period, for replanting strategy A and B.

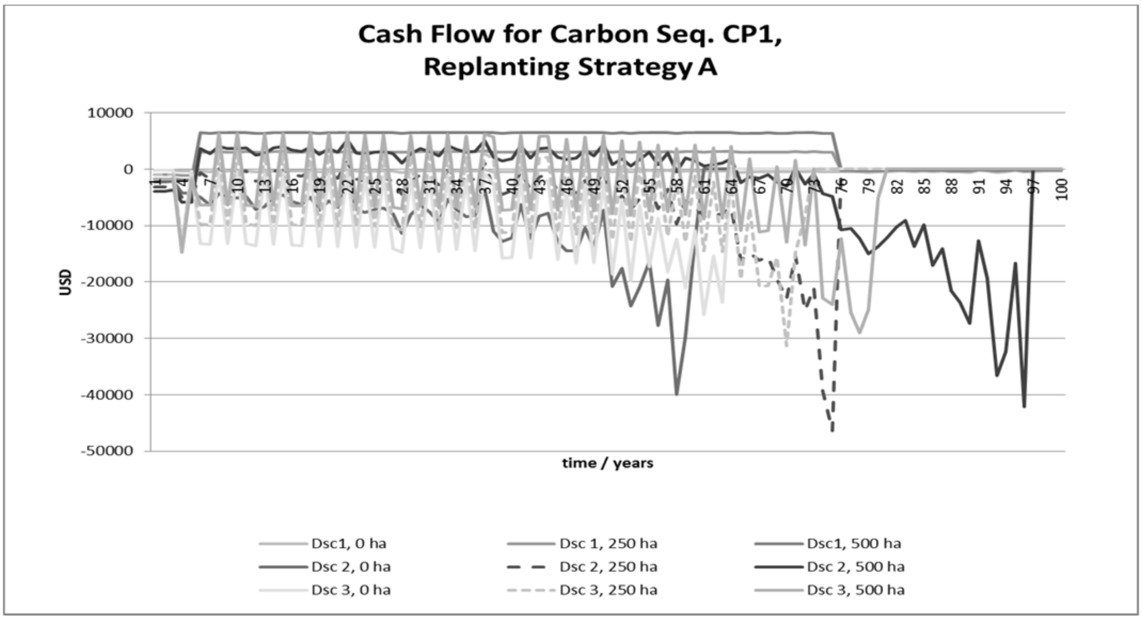

Figure A1 Shows the simulated annual mitigation values, M_t *(x-axis)*, for carbon sequestration and emissions over the 100-year period (y-axis) for replanting strategy A and three different levels of replanting (0, 250. and 500 ha) influence on the three damage scenarios. M_t is based on CP1= USD 0.54 per tCO_2e.

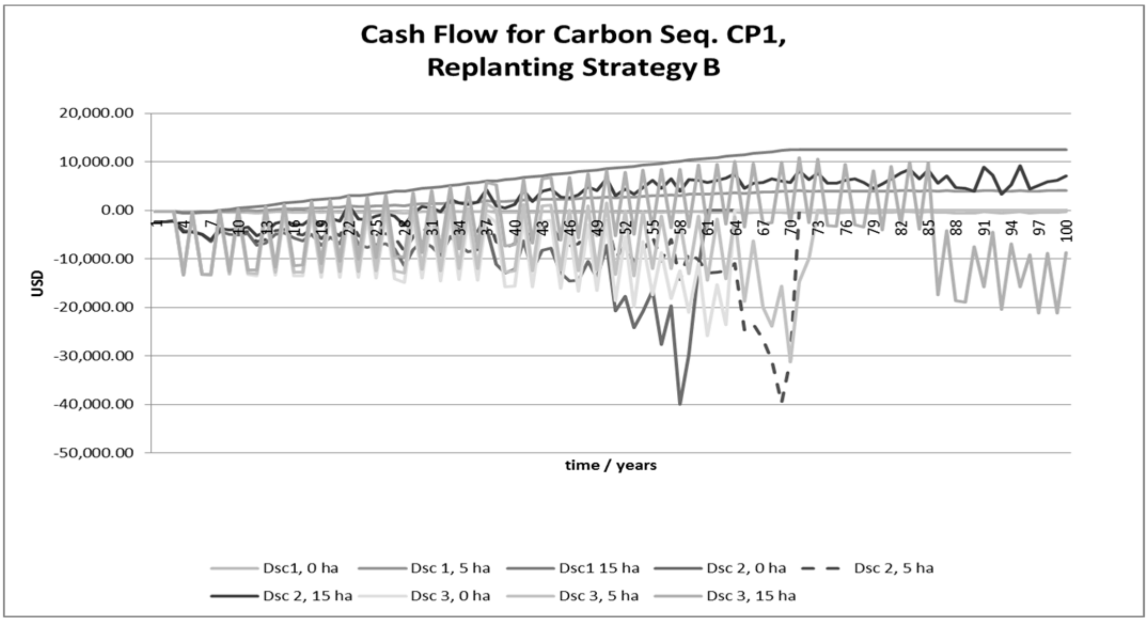

Figure A2 Shows the simulated annual mitigation values, M_t *(x-axis)*, for carbon sequestration and emissions over the 100-year period (y-axis) for replanting strategy B and three different levels of replanting (0, 5, and 15 ha a year) influence on the three damage scenarios. M_t is based on CP1= USD 0.54 per tCO_2e.

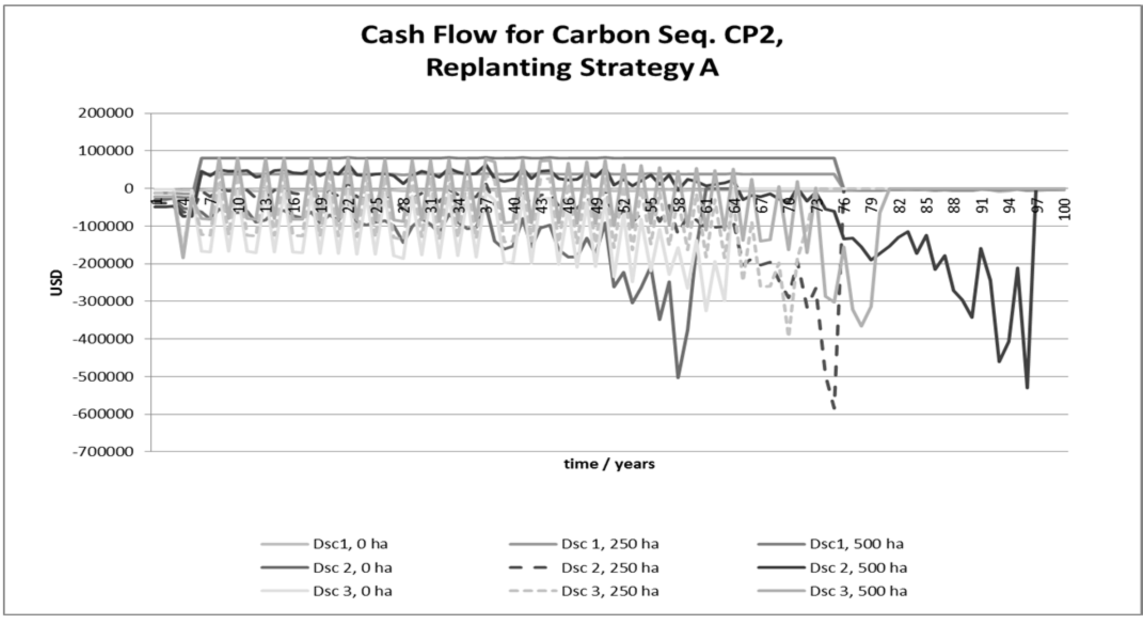

Figure A3 Shows the simulated annual mitigation values, M_t *(x-axis)*, for carbon sequestration and emissions over the 100-year period (y-axis) for replanting strategy A and three different levels of replanting (0, 250. and 500 ha) influence on the three damage scenarios. M_t is based on CP2= USD 6.8 per tCO_2e.

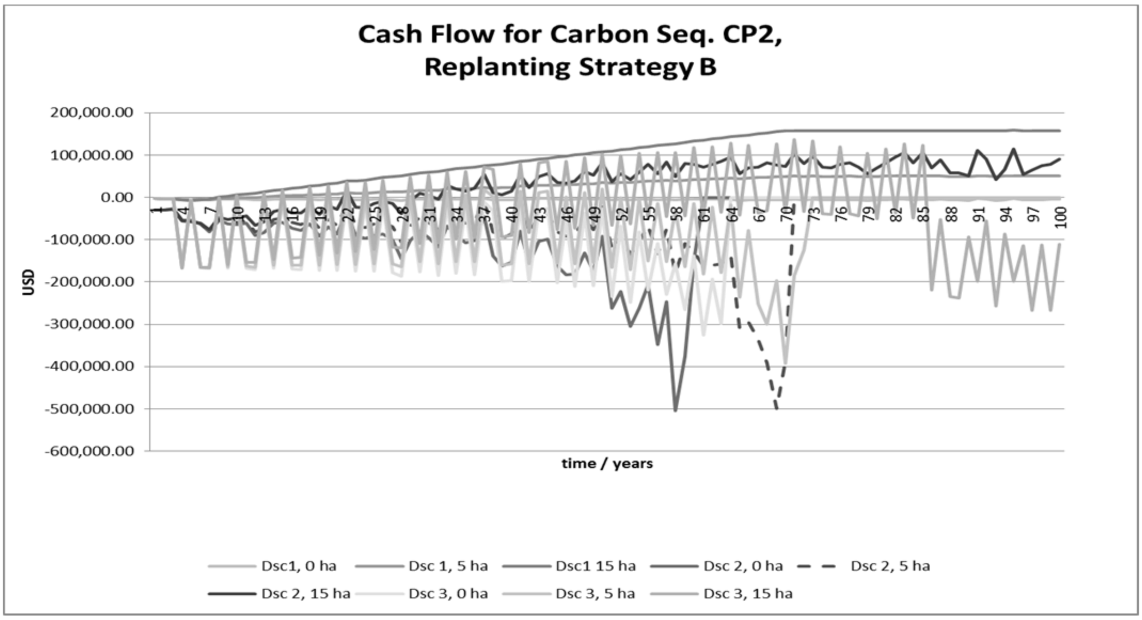

Figure A4 Shows the simulated annual mitigation values, M_t *(x-axis)*, for carbon sequestration and emissions over the 100-year period (y-axis) for replanting strategy B and three different levels of replanting (0, 5, and 15 ha a year) influence on the three damage scenarios. M_t is based on CP2= USD 6.8 per tCO_2e.

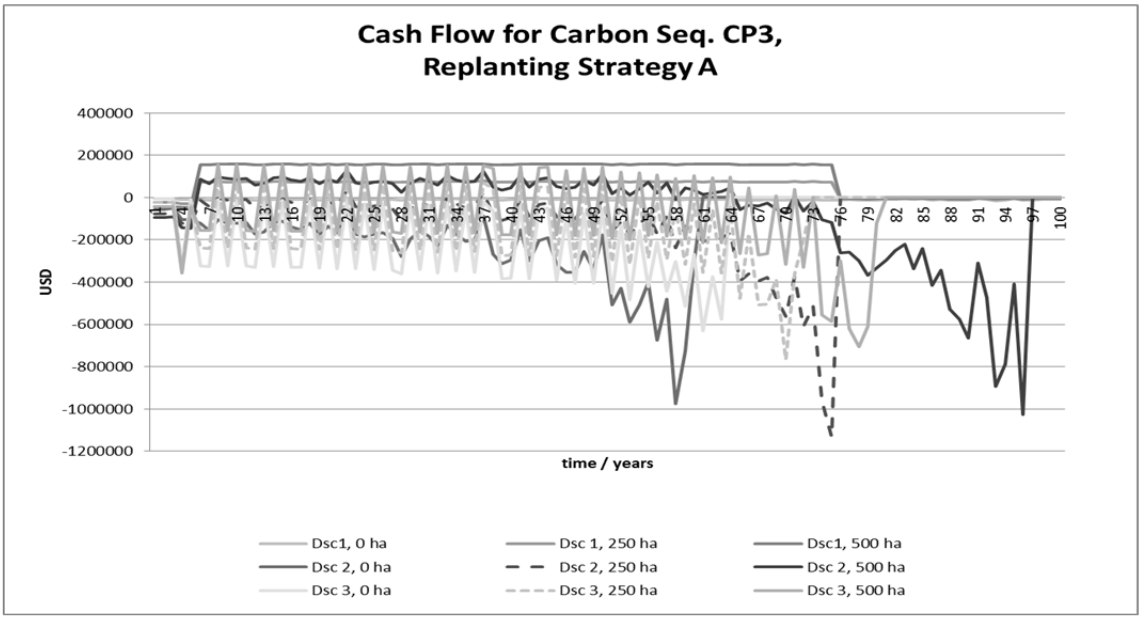

Figure A5 Shows the simulated annual mitigation values, M_t *(x-axis)*, for carbon sequestration and emissions over the 100-year period (y-axis) for replanting strategy A and three different levels of replanting (0, 250. and 500 ha) influence on the three damage scenarios. M_t is based on CP3= USD 13.18 per tCO_2e.

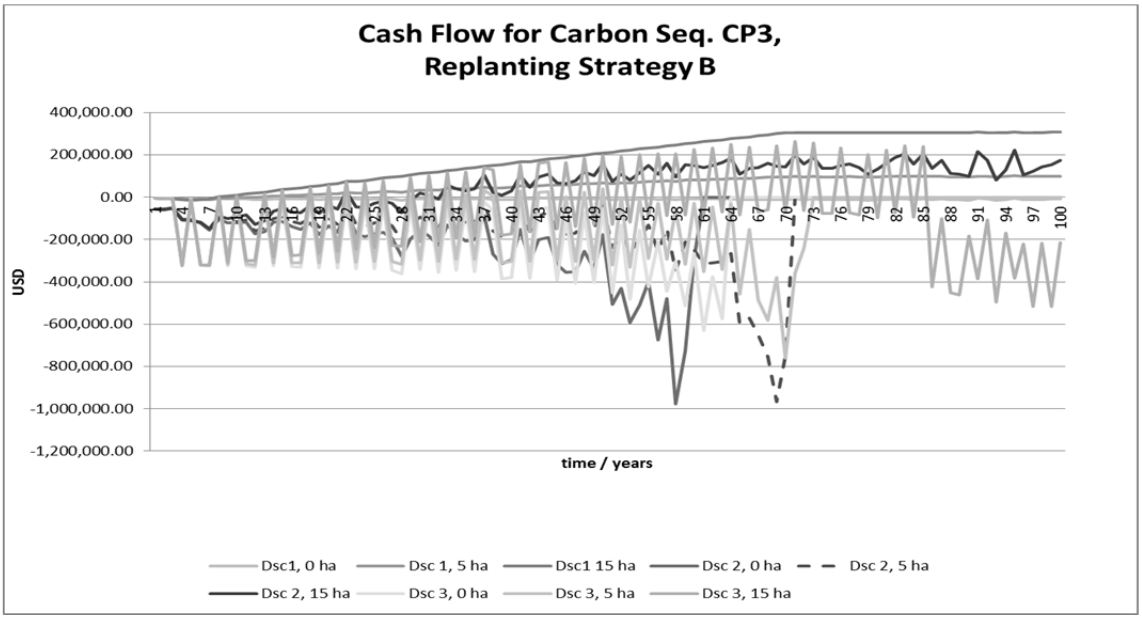

Figure A6 Shows the simulated annual mitigation values, M_t *(x-axis)*, for carbon sequestration and emissions over the 100-year period (y-axis) for replanting strategy B and three different levels of replanting (0, 5, and 15 ha a year) influence on the three damage scenarios. M_t is based on CP3= USD 13.18 per tCO_2e.

Appendix B:
Marginal EDC and mitigation values for different interest rates

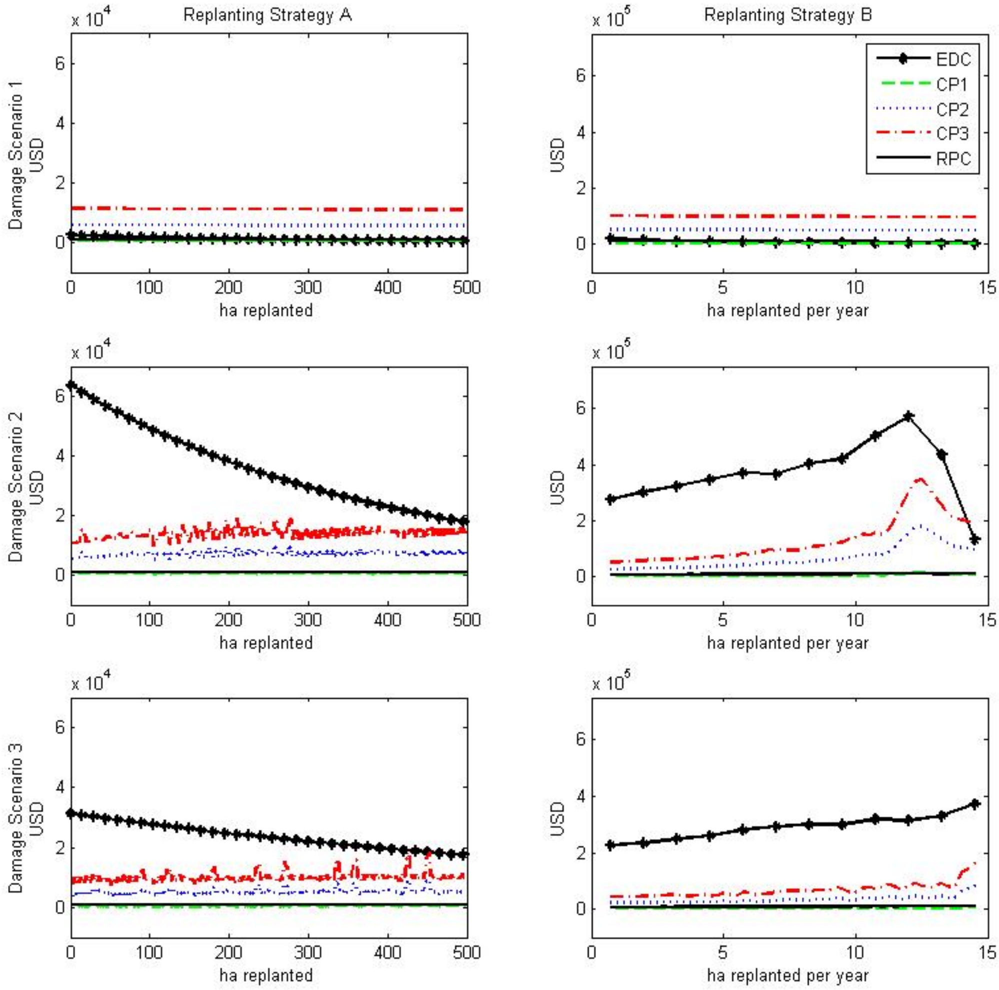

Figure B1 Present values for marginal EDC in replanting strategies A and B (adaptation initiatives) for each of the three damage scenarios, together with marginal mitigation values for the three CPs (CP1 = USD 0.54 per tCO_2e, CP2 = USD 6.8 per tCO_2e, CP3 = USD 13.18 per tCO_2e) and the replanting costs, assuming an interest rate of 2%.

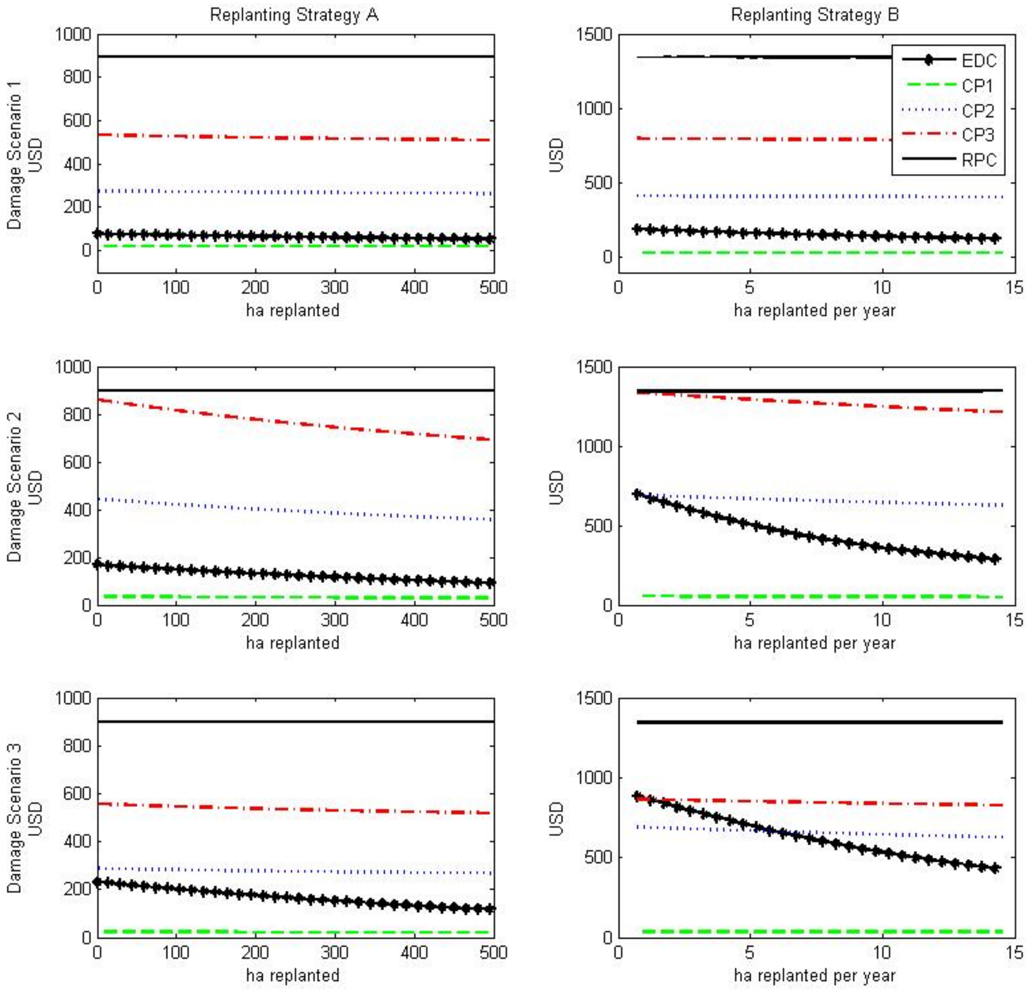

Figure B2 Present values for marginal EDC in replanting strategies A and B (adaptation initiatives) for each of the three damage scenarios, together with marginal mitigation values for the three CPs (CP1 = USD 0.54 per tCO_2e, CP2 = USD 6.8 per tCO_2e, CP3 = USD 13.18 per tCO_2e) at an interest rate of 20%.

Appendix C: *Not part of submitted paper*

Marginal EDC, extreme carbon prices and mitigation values for 4% and 12% interest rates

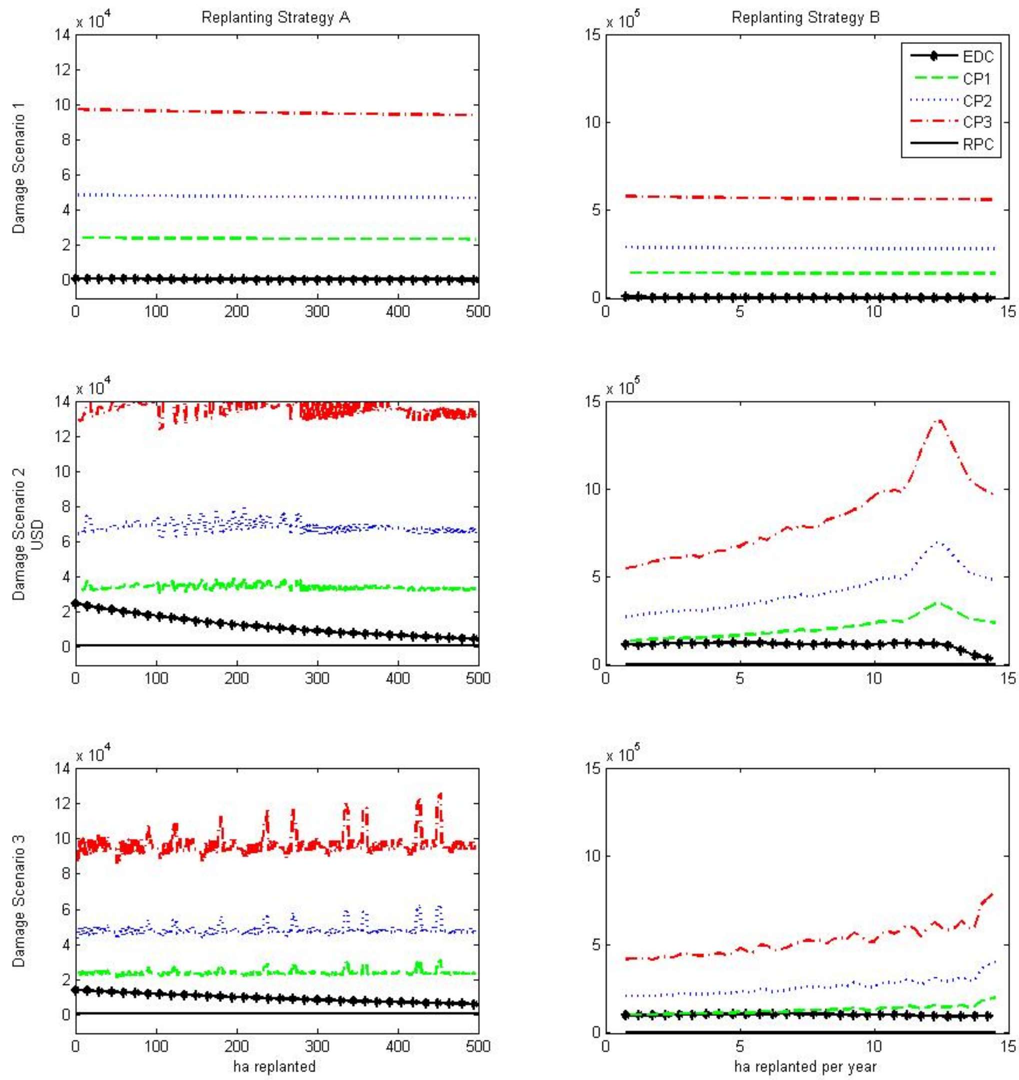

Figure C1 The marginal avoided EDC for the two replanting strategies A and B (adaptation initiatives) in each of the three damage scenarios (the black solid lines with dots) together with marginal mitigation values for the three CPs CP1 = USD 50 per tCO_2e, CP2 = USD 100 per tCO_2e, CP3 = USD 200 per tCO_2e (the dashed lines). The thin black line shows the marginal replanting costs. All assume a discount rate of four per cent.

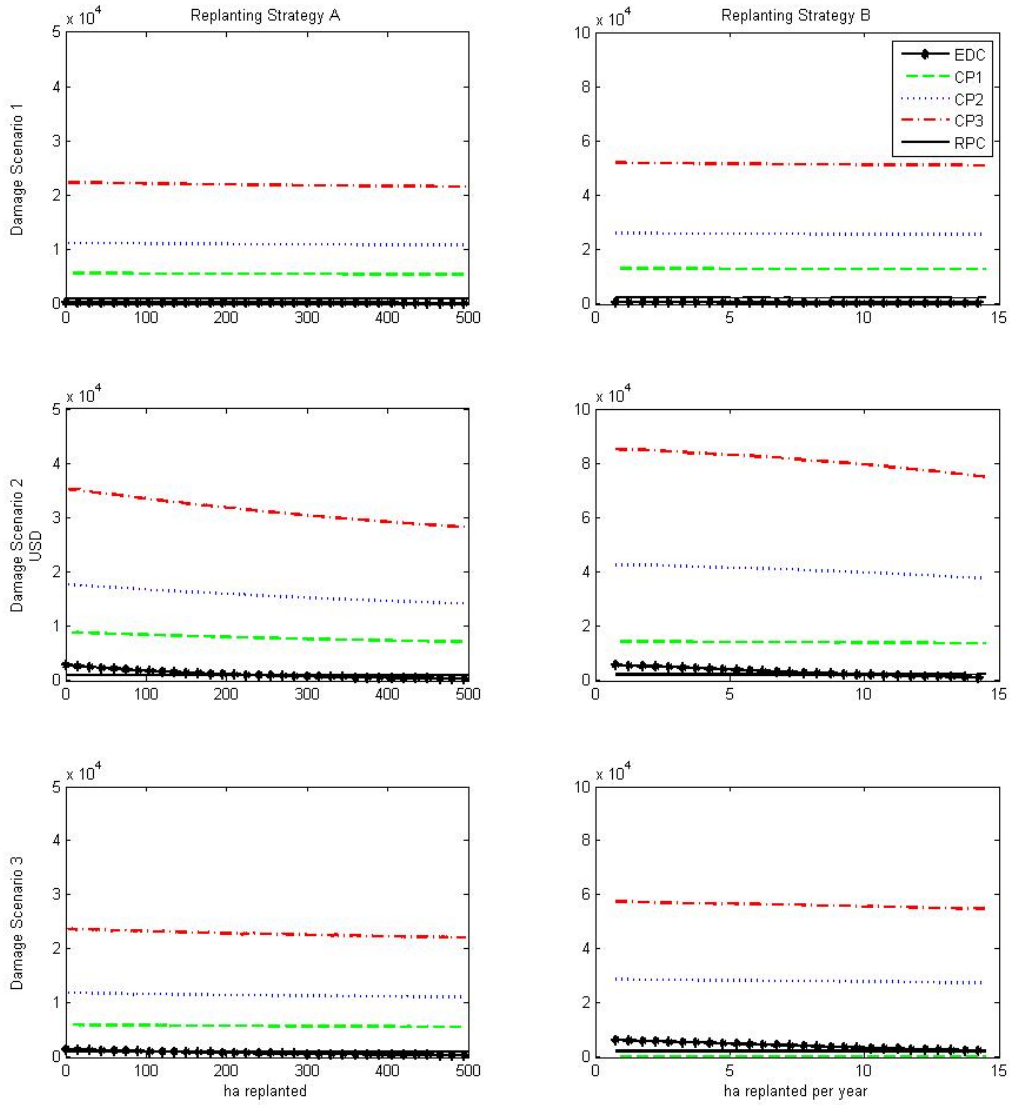

Figure C2 The marginal avoided EDC for the two replanting strategies A and B (adaptation initiatives) in each of the three damage scenarios (the black solid lines with dots) together with marginal mitigation values for the three CPs CP1 = USD 50 per tCO_2e, CP2 = USD 100 per tCO_2e, CP3 = USD 200 per tCO_2e (the dashed lines). The thin black line shows the marginal replanting costs. All assume a discount rate of 12 per cent.

Paper 3

Empirically Based Analysis of Households Coping with Unexpected Shocks in the Central Himalayas

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Key words: Coping, livelihoods, vulnerability, Nepal

Abstract
Climate change may significantly impact the large number of households in developing countries depending on agricultural production, not least through changes in the frequency and/or magnitude of climatic hazards resulting in household income shocks. This paper analyses rural households' responses to past experience of and future expectations to substantial and unexpected negative and positive agricultural income shocks. Empirical data is derived from an environmentally-augmented structured household (n=112) survey in the high mountains of central Nepal. Multinomial logit regression, using data on rural household demographics, assets (agricultural land, livestock), value of other assets such as furniture, bicycles, and agricultural implements), and income sources showed that household coping choices are determined by opportunities to generate cash. We argue that

public policies should enhance the ability of rural household to generate cash income, including through environmental products.

Introduction

Evidence of climate change is beginning to show. Developing countries are especially vulnerable to climate change due to a combination of substantial projected biophysical changes, strong reliance on climate-sensitive sectors such as agriculture, and widespread poverty (Adger et al. 2003, Dodman et al. 2009, Hijioken et al. 2014, Huq and Reid 2004). However, even without climate change, households engaged in agriculture experience weather related shocks – e.g. from draughts, floods, frost and hail storms, irregular snow, pest and diseases – resulting in production losses leading to lower total household income and possibly an increase in expenditures, e.g. to purchase new seeds. While rural households often have established strategies for coping with known challenges (Dodman et al. 2009) climate change is expected to represent additional challenges in the form of new climatic phenomena and/or changes in the frequency or magnitude of existing climatic hazards (Hijioka et al. 2014).

Coping constitutes the use of available skills, resources, and opportunities to address, manage, and overcome adverse conditions, with the aim of achieving basic functioning in the short to medium term; while coping capacity is the ability of people, organizations, and systems, again using available skills, resources, and opportunities, to address, manage, and overcome adverse conditions (IPCC 2012). A defining feature of coping is the focus on the short to medium term in contrast to adaptation, which refers to longer term responses. The two concepts are, however, related and Smit and Wandel (2006) define adaptation as the expansion of coping ranges. On the other hand, short-term coping strategies can also undermine or prevent longer-term adaptation and reduce the coping range, for example where shock responses, such as the sale of productive assets, leave households more vulnerable to future shocks (e.g. Smit and Wandel 2006). Coping may be proactive, e.g. when households reduce risk by diversifying income generating activities, avoid profitable but potentially hazardous actions, or pool risk through social and institutional networks (Wunder et al. 2014). Reactive coping responses depend on the size of the shock and include actions such as income and consumption smoothing, assets sales, resource reallocation (e.g. finding work off-farm, increasing labour time, taking children out of school that can contribute more labour) (Wunder et al. 2014). Household coping responses and choices of coping strategies are shaped by their access to resources and liberty of actions (Eriksen 2005, Sen 2003). Household resources can be divided into human, natural, financial, social, and physical capitals according to the sustainable livelihood framework (e.g. DFID 1999). Liberty of actions is inter alia influenced by households' priorities, past experiences, expectations for the future, and social and cultural norms limiting which responses are considered possible, appropriate, and acceptable (e.g., Adger et al. 2009, Coulthard 2008, 2012, Nielsen and Reenberg 2010).

In this paper, we analyse rural households' coping responses in relation to unexpected negative and positive shocks to their income from agricultural production in the high mountains of central Nepal, and relate their responses to household resources. We define negative shocks as substantial unexpected shortage from agricultural production, e.g. due to drought, too much rain, landslides, or irregular snowfall, causing an income loss. Positive shocks are defined as an unexpected large income from agricultural production as compared to a normal year. Rural households in the study area generally have limited economic resources, low levels of technology, low skill levels, poor infrastructure, and weak institutions (Rayamajhi et al. 2012) – factors which are expected to contribute to high levels of vulnerability (Wunder et al. 2014). Their liberty of actions (Sen 2003) is arguably limited by the low asset levels and macro-level constraints, including political instability and low levels of economic growth, even if new opportunities also emerge, such as through migration (Walelign et al. 2016).

We answer the two questions:

1. Which coping responses have rural households utilised in the past to overcome unexpected shocks, and which coping responses do they expect to use in the future?
2. How do households differ in their responses and how is this linked to their livelihood strategies and assets?

We hypothesise that: 1. Households choose coping responses that are complementary, and 2. Households' coping responses are shaped by their assets and livelihood strategies.

Methods

Study Area

The Lete and Kunjo Village Development Committees (VDCs – the smallest local administrative unit in Nepal) lie in the lower part of Mustang District (28°34'-28°41' N and 83°33'-83°44' E) in the Western Development Region of Nepal. The villages are located at an altitude of above 2,000 metres in a temperate to sub-alpine climate with occasional windstorms, hail, and snow. The annual average precipitation was 1242 millimetres and the yearly average temperature was 11.7°C (in 2006, unpublished data from Dept. of Hydrology and Meteorology). The study area is situated within the Annapurna Conservation Area (ACA), world famous for trekking tourism, and was recently connected to an all-weather road (Baral et al. 2007, Larsen et al. 2014). Land use is characterised by upper and higher elevation subsistence production type systems (Metz 1989, 1990, Olsen 1996): large areas of rain-fed fields, whose fertility is maintained through use of composted manure. Average per household land holding was 1.1 ha and the main crops are maize, barley, buckwheat, potato, and beans. Average livestock holding was 8.7 Tropical Livestock Units (TLU) dominated by cattle, sheep, and goats. About 5,017 ha are covered with forest, including natural forests, plantations, and shrubs; a similar area of grassland under community-based management was available (Larsen et al. 2014). Forests are dominated by *Pinus wallichiana* and some old-growth *Tsuga dumosa*, two valuable timber species. The main forest products are grass, bamboo, firewood, pine needle, and timber and can be collected or purchased on the basis of rules and restrictions made by the forest user groups (FUGs); only minor extraction of timber was permitted (Larsen et al. 2014).

The study area is characterised by low income levels and widespread poverty, with ca. 13 % of average total household income derived from crops, 16 % from livestock, 26 % from environmental sources, and 42 % from non-farm activities, e.g. remittances and gifts, self-owned businesses, off-farm wage labour, or government pensions (Rayamajhi et al. 2012). Environmental income plays a main role, especially for poor households, who collect non-timber forest products for sale while better off households rely on non-farm income (Rayamajhi et al. 2012). Recent research from the study area (Walelign et al. 2016) indicates that a common pathway out of poverty is household accumulation of assets through farming, petty trading, and migratory work. Environmental income has also been shown to reduce income inequality (Chhetri et al. 2015) while establishment of road infrastructure increased household incomes and decreased income inequality (Charlery et al. 2016).

Climate Change in Nepal

The few existing studies of meteorological records for Nepal show an increase in annual mean temperature over the past 30-50 years, with higher increases at higher elevations (Khan 2005, Marahatta 2009, McSweeney 2008, Shrestha et al. 1999). Analyses of precipitation patterns over the past 50 years show mixed results (Ichiyanagi et al. 2007, Kansakar et al. 2004, Khan 2005, Marahatta 2009, McSweeney 2008, Shrestha et al. 2000). The average temperature is predicted to increase from 1.3 to 4.3° C by the middle of the 21st century with the mountainous north experiencing the highest increase. With regard to precipitation, models tend to predict a summer monsoon increase and a winter precipitation decrease (Khan 2005, McSweeney 2008). Importantly, the likelihood of 'heavy rainfall' events is also predicted to increase. Future climate change risks in the study area, while uncertain and difficult to quantify, are thus increases in extreme event frequency and intra-annual rainfall variability. The latter may not be as dramatic as the former, but can make it difficult for farmers to plan activities such as sowing and harvesting or what to plant.

Data Collection

Data was collected using two survey instruments, both administered in 2009. The first was a structured household (n=186) survey using the Poverty Environment Network (PEN) protocol (Angelsen et al. 2011, Larsen et al. 2014) including annual surveys (at survey start and end) and four quarterly income surveys. The data collection period spanned a complete year from December 2008 to November 2009. The annual surveys registered asset data while the quarterly surveys included recording of all environmental, farm, and non-farm incomes. Allocation of own labour into different activities is difficult to disaggregate – a common phenomenon in the development literature – and was not subtracted from net incomes (Nielsen et al. 2013, Rayamajhi et al. 2012). In most cases, market prices were used to calculate income values; in cases with thin or missing markets, standard methods for estimating subsistence product values were applied (Rayamajhi and Olsen 2009, Wunder et al. 2011).

The second instrument was administered, alongside the survey end annual questionnaire, to elicit household-level responses to substantial unexpected shocks (negative or positive) in the past five years as well as their expected coping responses to a hypothetical shock in the coming year (the instrument is provided in Appendix 1). A number of households were excluded as they did not complete all the income surveys or could not be located at the time of interview; the survey included 112 households. Specifically, for the past five years, the survey recorded shocks and their impact on crop production (loss or gain) compared to the expected normal value for each year; we distinguished moderate shocks (< 50 % loss or gain) and substantial shocks (> 50 %), and used a discrete range (0-20 %, 21-80 % or 81-100 %) to measure the importance of responses, each counting as an observation. A similar approach was used to elicit responses to hypothetical situations taking place next year. This produced 663 and 501 observations for loss and gain in the past, and 795 and 787 observations for next year responses.

Data Analysis

To enable comparison between households, including the different predicted variables' influence on households' choices of coping responses, we accounted for household size and possible effects of economics of scale by reporting all monetary values per adult equivalent unit (AEU) following common practice (Cavendish 2002). The percentage of income loss or gain was calculated on the basis of the value that was obtained as the normal income value. The households' total income per AEU was calculated by summarising all net income types per household. Based on Rayamajhi et al. (2012), it is assumed that income level and quartile membership have a significant influence on choice of coping responses.

We applied multinomial logit (MNL) regression to analyse households' past behaviour and expected future behaviour in response to unexpected positive and negative shocks to agricultural income. Following the argumentation in Gebrehiwot and van der Veen (2013), the multinomial adaptation model is the correct choice when there are more than two alternatives. We assume that households' responses are rational and that they will choose the coping response that maximises their utility (McFadden 1973). This makes it possible to identify determinants of the households' choice of coping responses through discrete choice modelling. Assume that farmer *i* aims to maximise utility through his choice of coping response *j* (*j* = 1, 2,… *j*). He will choose coping response *j* rather than *k*, if the perceived benefit of *j* is larger than for *k*. The relative probability of the coping response variables is given by the log odds ratio (Eq. 1) (Green 2003):

$$ln\left[\frac{P_{ij}}{P_{ik}}\right] = x_i'\beta_j \qquad (1)$$

where x_i is a vector of household characteristics and β_j are the corresponding coefficients. The most preferred coping response is used as the base category for normalization, *k*. These coping responses are used as reference groups as they are assumed available to all households regardless of characteristics and status, e.g. income, land ownership, or debt. Reduced consumption and saving cash are used as references in the MNL regressions for loss and gain in income, respectively.

We account for clusters among the households by allowing for intragroup correlation, relaxing the requirement that the observations must be independent. We assume that observations are independent across households, but not within households, as our data contain repeated information on households' past and expected future behaviour in relation to income loss or gain from unexpected shocks.

The individual explanatory variables were tested using a Type III (Wald chi^2) test. MNL regressions were carried out using the statistical software, StataIC 11.

Results

Household Income and Asset Data

The overview of household income and asset values (Table 1) documents widespread poverty, e.g. the average total income is 1.6 USD/AEU/day (below the global poverty line of 1.9 USD/capita/day), ranging from 0.5 – 3.5 across the quartiles. Agricultural land is limited as is the number of livestock. The best-off quartile households own the most land; 9.9 % of households do not own any land and mainly belong to the 'Poorest' income quartile. Environmental income and wage income are the most important to the two poorer quartiles, while business income and remittances are more dominant for higher income households. When it comes to the size and composition of the households – male, female, children, elderly – households in most well-off quartile tend to be smaller than in the other three quartiles. Furthermore, literacy is high (83 %) and the mean adult educational level is 6.6 years of schooling (Rayamajhi et al. 2012).

Households' Coping Responses

The questionnaire on coping with unexpected loss or gain included 12 coping response options. To use the data in the MNL regressions, the response variables were aggregated in seven and eight groups, for loss and gain respectively, as specified in Tables 2-5 that also present the sequence of households' chosen coping responses.

Table 2 presents an overview of household coping responses to shocks reducing agricultural income. The most common first coping choice is to reduce household consumption (A, 37%), followed by obtaining loans or assistance (B, 38%) and spending savings (C, 51%). The most common responses are consumption reduction (done by 32% of households), spend savings (27%), and obtaining loans and assistance (21%).

Table 1 Household absolute mean asset and income across income quartiles. Net income figures in parentheses are share of annual total household income.

Description	Units	Poorest Lowest 25% n=28	Poor 25-50% n=28	Medium 50-75% n=28	Less poor top 25% n=28	Sample mean (SD) n=112	Min.-max. range
Household size	AEU	4.2	4.2	3.8	3.5	3.9 (1.1)	1-8
No. of adult females in HH		1.7	2.0	1.5	1.7	1.7 (1.0)	0-5
No. of adult males in HH		2.2	2.1	1.9	1.2	1.8 (1.2)	0-5
No. of children in HH		1.4	1.1	1.0	0.7	1.1 (1.1)	0-4
No. of elderly in HH		0.5	0.5	0.5	0.9	0.6 (0.8)	0-2
Farmland owned	Ha	0.7	0.9	1.2	1.5	1.1 (0.8)	0-3.4
Livestock	TLU per AEU	0.5	0.8	1.5	2.9	1.4 (2.6)	0-18.2
Net environmental income	USD per AEU	48.5 (24.6%)	74.8 (21.5%)	79.1 (14.8%)	132.3 (10.2%)	83.7 (95.3) (14%)	-237.6-648.7
Income: land rented out	USD per AEU	0.7 (0.3%)	2.0 (0.6%)	5.1 (0.9%)	12.8 (1.0%)	5.2 (22.1) (0.9%)	0-219.4
Net income from livestock	USD per AEU	63.8 (32.5%)	107.9 (31.0%)	137.5 (25.7%)	560.6 (43.3%)	217.5 (627.1) (36.6)	-107.3
Net income from crops	USD per AEU	21.8 (11.1%)	56.6 (16.3%)	78.8 (14.7%)	126.5 (9.8%)	70.9 (87.3) (12%)	-16.6
Net business income	USD per AEU	14.1 (7.2%)	27.7 (8.0%)	157.6 (29.5%)	301.5 (23.3%)	125.2 (233.9) (21.1%)	-30.4-1304.2
Net wage income	USD per AEU	24.6 (12.5%)	38.3 (11.0%)	21.7 (4.1%)	20.9 (1.6%)	26.4 (45.6) (4.4%)	0-225.5
Pension, support from NGO or government	USD per AEU	4.4 (2.2%)	11.1 (3.2%)	7.9 (1.5%)	3.4 (0.3%)	6.7 (23.5) (1.1%)	0-148.3
Remittance	USD per AEU	18.8 (9.5%)	29.4 (8.5%)	46.9 (8.8%)	136.8 (10.6%)	58.0 (136) (9.8%)	0-767.8
No remittance[A]	0-1	0.8	0.7	0.7	0.7	0.7 (0.4)	0-1
Net Total Income	USD per AEU	196.7 (100%)	347.8 (100%)	534.4 (100%)	1,294.9 (100%)	593.5 (736.6) (100%)	79.4-7,032
Savings in bank and jewellery	USD per AEU	346.0	314.9	585.6	1,775.7	755.6 (1,481.9)	0-12,348.4
Value of all assets	USD per AEU	1,496.5	1,537.8	3,025.4	5,786.9	2,961.7 (3,846.2)	-569.5-24,815
Cost of power for irrigation	USD per AEU	3.0	1.5	0.9	3.3	2.2 (5.3)	0-45.3
Debt	USD per AEU	179.7	290.5	410.1	384.1	316.1 (361)	0-1,695
Total expenditure	USD per AEU	337.0	344.6	477.1	711.7	467.6 (300)	144.2-1,703

[A] Dummy variable takes the value of 1 if the household does not receive remittance and 0 otherwise.

Table 2 Rural households' coping responses, over the past five years, following a substantial unexpected negative shock resulting in an agricultural income loss.

No.	Response variables	A	B	C	Total	Description
1	Spend savings	17%	11%	51%	27%	The HH spends savings and sells non-agricultural assets.
2	Remittance	3%	4%	2%	3%	The HH decides that a member will work outside the community to generate remittance.
3	Reduce consumption	37%	29%	29%	32%	The HH reduces consumption.
4	Loan or assistance	21%	38%	6%	21%	The HH takes a loan from a money lender or bank or get assistance from NGO or others.
5	Sell livestock or land	7%	5%	3%	5%	The HH chooses to sell livestock or land.
6	Work more	15%	13%	9%	12%	The HH does extra casual work, or harvests, uses or sells more environmental products.
	Total	100%	100%	100%	100%	

Household first choice in response to shocks increasing agricultural incomes (Table 3) is to increase consumption (A, 39%) followed by loan repayment (B, 32%) and saving up cash (C, 61%). The most common responses are to save cash (done by 31% of households) followed by loan repayment (25%), and increased consumption (24%). Other responses are not frequent.

Table 3 Rural households' coping responses, over the past five years, following a substantial unexpected positive shock resulting in an agricultural income gain.

No.	Response variables	A	B	C	Total	Description
1	Save cash	14%	14%	61%	31%	The HH saves cash.
2	Remittance stop	1%	15%	1%	5%	HH members stop sending remittances or return to the HH.
3	Increase consumption	39%	24%	11%	24%	The HH increases consumption and purchases goods.
4	Pay loan back	32%	32%	11%	25%	The HH pays back loans to money lender or bank, or sends gifts to others.
5	Purchase agricultural assets	5%	4%	3%	4%	The HH invests in land and livestock.
6	Reduce income activities	3%	3%	10%	5%	The HH stops doing extra casual work or limits the extent of collecting, using or selling environmental products.
7	Purchase other goods	7%	7%	4%	6%	The HH chooses to purchase or invest in other goods.
	Total	100%	100%	100%	100%	

Asked about their responses to a negative shock reducing income next year, households expected to reduce consumption (the dominant first and second choice: A, 30% and B, 30%) followed by spending of savings (C, 40%) (Table 4). The three most common responses are consumption reduction (27% of all households), savings spending (23%), and obtaining loans or assistance (23%). This response pattern is similar to that for past behaviour (Table 2); however, there seems to be an increased interest in pursuing remittances as a coping response (7% vs. 3%).

Table 4 Rural households' anticipated choices of coping responses in reply to an imagined substantial unexpected negative shock in the coming year resulting in an agricultural income loss.

No.	Response variables	A	B	C	Total	Description
1	Spend savings	14%	13%	40%	23%	The HH spends savings and sells other non-agricultural assets.
2	Remittance	11%	9%	2%	7%	The HH decides that a member will work outside the community to send remittance.
3	Reduce consumption	30%	30%	20%	27%	The HH reduces consumption.
4	Loan or assistance	25%	25%	20%	23%	The HH chooses to take a loan from a money lender or bank or get assistance from NGO or others.
5	Sell livestock or land	7%	8%	8%	8%	The HH chooses to sell livestock or land.
6	Work more	13%	15%	9%	12%	The HH does extra casual work, or harvests, uses or sells more environmental products.
	Total	100%	100%	100%	100%	

Table 5 shows the expected household responses to a positive shock resulting in an income gain. The most common first and second response choices are to increase consumption (A, 25% and B, 26%) followed by saving cash (C, 32%). The most common responses are loan repayment (done by 24% of households) followed by increased consumption (22%) and cash saving (20%). Again, this is similar to the past response pattern (Table 3) though expected responses seem more evenly distributed compared to past actual behaviour.

Table 5 Rural households' anticipated coping responses in reply to a substantial unexpected positive shock in the coming year resulting in an agricultural income gain.

No.	Response variables	A	B	C	Total	Description
1	Save cash	15%	11%	32%	20%	The HH saves cash.
2	Remittance stop	9%	3%	1%	4%	HH members stop sending remittance or return to the HH.
3	Increase consumption	25%	26%	15%	22%	The HH increases consumption and purchases goods.
4	Pay loan back	19%	23%	28%	24%	The HH pays back loan to money lender or bank, or sends gifts to others.
5	Purchase agricultural assets	15%	16%	14%	15%	The HH chooses to invest in land and livestock.
6	Reduce income activities	9%	12%	4%	9%	The HH stops doing extra casual work or limits the extent of collecting, using or selling environmental products
7	Purchase other goods	8%	8%	5%	7%	The HH chooses to purchase or invest in other goods.
	Total	100%	100%	100%	100%	

Results of the MNL Regressions

In the MLN regressions, the coefficients reflect the effects of the explanatory variables on the likelihood of the households choosing a coping response relative to the coping response used as reference. Each of the explanatory variables were tested against the response variables in a minor MNL regression (not presented) to determine if they independently influenced households' choice of coping response. If the probability of the chi^2 test ($P > chi^2 < 0.10$) for the MNL regression was equal to or below 10%, the explanatory variable was included. As each individual household answered questions with several answers, we estimate each of the presented MNL regression models as a cluster model with the household being the cluster. The Type III test was used to test each individual explanatory variable. Explanatory variables significant at the 10% level were included in the relevant final model. A total of 14 explanatory variables were significant to the households' past and expected future choices of coping responses in case of agricultural income loss or gain. Tables 6-9 show the significant explanatory variables for each of the four MNL regressions; the explanatory variables are listed in the same order and left blank if not relevant. Appendix 2 presents all results for the four MNL regressions (i.e. also insignificant explanatory variables).

Table 6 MLN regression results for coping responses to past situations with an unexpected agricultural income loss

No.	Coping responses / Explanatory variables	1 Spend savings Coef.	z	2 Obtain remittance Coef.	z	4 Loan or assistance Coef.	z	5 Sell livestock or land Coef.	z	6 Work more Coef.	z	chi^2 test P > chi^2
1	Household size (AEU)	0.147	1.45	0.529	1.92*	-0.112	0.79	0.149	0.58	-0.0987	0.35	0.0788*
2	No. of adult males in HH (AEU)	-0.337	3.2***	-0.0865	0.37	-0.229	1.68*	-0.117	0.47	-0.0493	0.27	0.0453**
3	Farmland owned (ha)											
4	Livestock(TLU/AEU)											
5	Net income from environmental products (USD/aeu)											
6	Income from land rented out											
7	Income quartile: 'Less poor' (4)[A]											
8	Net business income (USD/AEU)											
9	Pension, support from NGO or government (USD/AEU)	-0.007517	3.95***	0.0068381	0.58	-0.0189	3.06**	-0.009	0.56	-0.0018	0.28	0***
10	Remittance (USD/AEU)	-0.00135	2.44**	0.001958	2.02**	0.000	0.58	-0.005	1.97**	-0.0048	2.33**	0***
11	Value of all assets (USD/AEU)	-0.00004	2.08**	-0.000104	1.27	0.000	3.84***	0.000	1.06	-0.0004	3.83***	0.0002***
12	Cost of power for irrigation (USD/AEU)	-0.003424	0.41	-0.050797	0.77	-0.0550	2.29**	-0.271	1.91*	0.0088	0.34	0.0214**
13	Debt (USD/AEU)											
14	Size of shock [B]											
	Constant	0.1295677	0.41	-4.234237	3.88***	1.074	2.27**	-1.467	1.59	0.4951	0.48	
	Number of obs. = 663, Pseudo R^2 = 0.0504											

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Table 7 MNL regression results for coping responses to past situations with an unexpected agricultural income gain

No.	Coping response / Explanatory variables	2 Save cash Coef.	z	3 Increase consumption Coef.	z	4 Pay loan back Coef.	z	5 Purchase livestock Coef.	z	6 Reduce income activities Coef.	z	7 Purchase other goods Coef.	z	chi^2 test $P > chi^2$
1	Household size (AEU)													
2	No. of adult males in HH (AEU)	-0.663	2.75***	0.179	2.18**	0.0147	0.15	0.536	2.45**	0.0732	0.41	0.211	1.02	0.0002***
3	Farmland owned (ha)													
4	Livestock(TLU/AEU)													
5	Net income from environmental products (USD/aeu)													
6	Income from land rented out													
7	Income quartile: 'Less poor' (4)[A]													
8	Net business income (USD/AEU)													
9	Pension, support from NGO or government (USD/AEU)	0.0168	5.54***	-0.0119	1.91*	-0.001	0.27	0.00853	2.44**	0.00961	2.75***	-0.0026	0.28	0***
10	Remittance (USD/AEU)													
11	Value of all assets (USD/AEU)	-9.5E-05	1.43	1.9E-05	1.08	-0.0001	3.22***	0.00012	2.37**	-3.3E-05	0.64	7.1E-05	1.74*	0***
12	Cost of power for irrigation (USD/AEU)													
13	Debt (USD/AEU)													
14	Size of shock [B]													
	Constant	-0.862	1.71*	-0.552	3.02***	0.0299	0.13	-3.55	5.15***	-1.86	4.31***	-2.255	4.62***	
	Number of obs. = 501, Pseudo R^2 = 0.0286													

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Table 8 MNL regression results for coping responses to future unexpected agricultural income loss

	Coping responses	1 Spend savings		2 Obtain remittance		4 Loan or assistance		5 Sell livestock or land		6 Work more		chi^2 test
		Coef.	*z*	Coef.	*z*	Coef.	*z*	Coef.	*z*	Coef.	*z*	P > chi^2
No.	Explanatory variables											
1	Household size (AEU)											
2	No. of adult males in HH (AEU)											
3	Farmland owned (ha)	0.0913	0.6	0.125	0.57	0.382	2.58***	-0.156	-0.72	-0.305	1.30	0.0031***
4	Livestock(TLU/AEU)	0.00606	0.18	-0.111	0.91	-0.0675	1	0.150	2.43**	0.0643	0.85	0.0004***
5	Net income from environmental products (USD/aeu)	-0.00176	2.67***	-0.00577	3.1***	-0.00264	2.01**	0.000631	0.46	-0.000684	0.58	0.0001***
6	Income from land rented out	0.00176	1.08	0.0124	2.26**	0.00160	0.16	-0.0488	1.20	0.0119	2.54***	0.0028***
7	Income quartile: 'Less poor' (4)[A]	0.01765	0.1	0.557	1.52	0.0850	0.26	-0.594	1.51	-0.342	0.93	0.0781*
8	Net business income (USD/AEU)	0.000937	2.49**	0.000683	0.85	0.000864	1.45	-0.000132	0.13	-0.00214	1.60	0.03**
9	Pension, support from NGO or government (USD/AEU)	-0.00312	1.07	-0.0152	2.21**	-0.00820	2.41**	0.00361	0.91	0.000523	0.15	0.0021***
10	Remittance (USD/AEU)											
11	Value of all assets (USD/AEU)	-0.00009	2.78***	-0.000256	3.03***	-0.000297	4.85***	-0.00012	1.32	-0.000246	2.39**	0***
12	Cost of power for irrigation (USD/AEU)											
13	Debt (USD/AEU)	0.00004	0.2	-0.00079	1.57	-0.000394	1.28	6E-06	0.02	0.000444	1.42	0.0172**
14	Size of shock [B]	-0.232	1.49	-0.652	2.33**	-1.32	7.59***	-0.819	2.99***	-0.0523	0.25	0***
	Constant	0.166	0.87	0.229	0.61	1.202	4.95***	-0.421	1.28	0.0956	0.31	
	Number of obs. = 795, Pseudo R^2 = 0.0656											

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Table 9 MNL regression results for coping responses to future unexpected agricultural income gain

No.	Coping response / Explanatory variables	2 Save cash Coef.	z	3 Increase consumption Coef.	z	4 Pay loan back Coef.	z	5 Purchase livestock Coef.	z	6 Reduce income activities Coef.	z	7 Purchase other goods Coef.	z	chi^2 test $P > chi^2$
1	Household size (AEU)													
2	No. of adult males in HH (AEU)													
3	Farmland owned (ha)	-0.754	2.24**	-0.149	1.06	-0.0246	0.21	-0.0975	0.63	-0.591	1.96**	-0.0903	0.37	0.0994*
4	Livestock(TLU/AEU)													
5	Net income from environmental products (USD/aeu)	-0.00129	0.69	0.00169	2.37**	-4.4E-05	0.06	-0.00049	0.32	-0.00038	0.18	-0.0031	2.6*	0.0015***
6	Income from land rented out	0.0120	2.31**	-0.0116	2.5**	-0.00252	0.31	0.0026	1.33	0.00739	1.52	0.0046	1.01	0.0003***
7	Income quartile: 'Less poor' (4)[A]													
8	Net business income (USD/AEU)	-0.0012	0.9	-0.0004	0.72	-0.0005	0.75	-0.0012	1.91*	-0.0013	1.26	0.00107	3.57***	0.0046***
9	Pension, support from NGO or government (USD/AEU)													
10	Remittance (USD/AEU)													
11	Value of all assets (USD/AEU)	2.5E-05	0.2	5.8E-05	1.55	-9.7E-05	1.71*	5.4E-05	1.55	-2.5E-05	0.29	-4E-05	0.9	0.0672*
12	Cost of power for irrigation (USD/AEU)	0.00545	0.14	0.0242	1.77*	-0.0222	0.82	-0.0687	2.17**	0.0191	0.59	-0.0222	0.74	0.0009***
13	Debt (USD/AEU)													
14	Size of shock [B]	2.19	4.5***	-0.0367	0.21	1.018	5.13***	0.772	3.78***	0.826	3.07**	0.418	1.47	0***
	Constant	-2.15	4.11***	-0.0064	0.04	0.0653	0.33	-0.422	1.78*	-0.528	1.59	-0.915	3.3**	
	Number of obs. = 787, Pseudo R^2 = 0.0456													

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

In case of responses to agricultural income loss in the past five years (Table 6), ‘Household size’, ‘No. of adult males in HH’, ‘Pension, support from NGO or government’, ‘Remittance’, ‘Value of all assets’, and ‘Cost of power for irrigation’ were found to be significant explanatory variables. With increasing ‘Value of all assets’, the likelihood of choosing to obtain a loan or assistance, rather than reduce consumption, increases, reflecting improved repayment likelihood. A high number of adult males in a household increases the likelihood of consumption reduction over obtaining loan or assistance or spending savings. With increasing household size, households are more likely to choose to obtain remittances over reduction in consumption.

In case of responses to agricultural income gain the past five years (Table 7), ‘No. of adult males in HH’, ‘Pension, support from NGO or government’, and ‘Value of all assets’ were found to be significant. Households with a high ‘No. of adult males in HH’ are likely to choose purchasing agricultural assets or increasing household consumption over saving cash. Increasing income from pension, support from NGO or government is likely to choose to stop remittance over the saving cash response; such households are also likely to purchase agricultural assets or reduce income activities over saving cash. Increasing wealth, measured as value of all assets per AEU, is likely to make a household choose to purchase agricultural assets or other goods.

In case of responses to a hypothetical agricultural income loss in the coming year (Table 8), households with higher livestock assets are likely to sell livestock rather than reduce household consumption. A high amount of farmland owned makes it more likely that households choose to obtain a loan or assistance. However, increasing ‘Net income from environmental products’, ‘Pension, support from NGO or government’, ‘Value of all assets’, and ‘Size of shock’ increase the likelihood of reducing consumption over obtaining a loan or assistance. Households with ‘Income from land rented out’ are likely to work more or choose to obtain remittance over reducing consumption. Households with a high ‘Net business income’ are likely to spend savings over reducing consumption.

In case of responses to a hypothetical agricultural income increase in the coming year (Table 9), the higher the income from land rented out, the more likely households are to stop remittance over saving cash. The higher the unexpected income, the higher the likelihoods of choosing ‘Pay loan back’, ‘Reduce income activities’, and ‘Purchase agricultural assets’ over saving cash. Households with a high environmental income and high ‘Cost of power for irrigation’ prefer to increase household consumption over saving cash. Households with a high net business income are more likely to purchase agricultural assets or other goods over saving cash.

Discussion

The MNL regressions show that the preferred household coping response to agricultural income loss is obtaining a loan or getting assistance from an NGO, friends, or family rather than reducing consumption. The preferred coping response to agricultural income gain is to save cash. These findings support our first hypothesis that households choose complementary responses when facing agricultural income gains and losses: loans in case of losses, saving up in case of gains, both responses that enable cash spending. These results indicate that households try to save cash rather than make use of other response options such as environmental product harvesting, consumption, and sale. Saving cash can be seen as a flexible multi-purpose response, e.g. allowing households to pay for weddings or contribute to coping with devastating negative shocks like earthquakes, illness, and unemployment.

It should be noted that households may not have access to all response options, e.g. selling livestock requires ownership of livestock. There are also limits to how much households' can reduce consumption, if they already live in deep poverty. An overall impression from the MNL regressions is that households choose among the coping responses available given their asset and income situation. In addition, nominally similar options may differ in quality across households. For example, the quality of non-agricultural employment opportunities differs dependent on factors such as education, wealth and caste, with better educated, wealthier households belonging to upper castes typically able to access better paid non-agricultural jobs compared to less educated, poorer households belonging to lower castes (e.g. Seddon et al 1998). Household choices amongst available options are also likely to be influenced by other factors such as past experiences and expectations for the future (Coulthard 2012). If households assume that climatic or other shocks are only temporary and will be followed by a return to normal, coping strategies such as borrowing money may be seen as a good response option that can help bridge temporary shortfalls in food and income. The likelihood of increased frequencies and/or magnitude of climatic shocks may, however, mean that such strategies become maladaptive and risk leading households into spirals of deepening poverty where loans cannot be paid back and assets are eroded. For households which have the necessary resources to choose amongst different response options providing more information on expected climate changes may help them to avoid falling into these traps. However, as mentioned above, households may be limited in the resources and options available to them, and not all existing options may be deemed acceptable (e.g., Coulthard 2008, Nielsen and Reenberg 2010).

In the study area, environmental income in 2006 was as important as farm income for the rural households' total income, especially for the poorer quartiles (Rayamajhi et al. 2012). We find, however, that while the Wald chi^2 test for environmental income show significant influence on households' responses to agricultural income loss in the coming year (Table 8), the regression coefficients are negative for spend savings, remittances, and obtained loans. Households with increasing environmental income would choose to reduce consumption rather than work more - only households with increasing income from land rented out would choose to work more over reducing consumption. This limited importance of environmental income on coping was also reported by Wunder et al. (2014); the higher environmental income reliance of poorer quartiles (Table 1) indicates that they are less susceptible to agricultural income losses. It should be noted that there are additional important issues which the present analysis and MNL regressions are unable to analyses further due to lack of observations, e.g. if households with a large variety of crops are better able to cope with shocks than households practising monoculture (each crop is treated individually in the MNL regressions which showed an insignificant Type III test).

The above points to the importance of enabling rural households to earn cash incomes. Previous research has argued that the way out of poverty for rural Nepalese mountain households is through obtaining a non-farm income (Rayamajhi et al. 2012) and the positive household-level income effect of establishing roads has been documented (Charlery et al. 2015). Hence rural development policies should continue to improve infrastructure, e.g. in relation to tourism in the area, and should seek to dismantle barriers to trade. This includes agricultural marketing and through allowing trade in environmental resources, e.g. Meilby et al (2014) documented that forests in the study area are under-utilized and that household incomes from timber trade could be increased three-fold within sustainable harvesting limits. This indicates a need for less conservative environmental product management in the conservation area. This would enhance households' ability to generate cash and thus cope with shocks, while also making non-agricultural response options locally available.

Conclusion

The main objective of the paper was to analyse rural households' coping responses in relation to unexpected negative and positive shocks to their income from agricultural production in the high mountains of central Nepal, and relate their responses to household resources. MNL regressions showed that obtaining a loan or getting assistance from others was the main coping response in case of an unexpected negative shock while saving cash was the main coping response to unexpected positive shocks to agricultural production. We found that households chose complementary response options and that these are shaped by household assets. Findings complement other recent research findings in the study area and emphasize the importance of allowing rural households to generate cash incomes, not only through remittances and local business, such as in tourism, but also through enabling trade in environmental products such as timber.

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Appendix I

Household level information on Risk/Shocks (negative and positive; actual and perceived)

A. negative shocks

HH # ____________ Name: _______________________ PID # ________ Date: __________ Enumerator's name: _________________

In terms of agricultural production what was this year like?

Worse than normal (production less by)		Normal production	Better than normal (production higher by)	
50-100% less	10-50% less		10-50% high	50-100% high

In the last 5 years has your household suffered a substantial (unexpected) shortage/loss of agricultural product?

Year	Crop type	Quantification of value loss (in Rs)		Causes of shortage/loss (Code, 1= drought, 2a= too much rain, 2b= land slides, 3= pest and diseases outbreak, 4 = frost and hailstorm, 5= any other (specify), 6= storm, 7= irregular snow		How did you cope? * 1= spent savings, 2= reduced consumption, 3= sold livestock, 4= sold land, 5= sold other asset, 6= did extra casual labour work, 7= harvest, use or sold more forest products, 8= get loan from money lender, credit association, bank etc, 9= assistance from others (friends, relatives NGOs), 10= HH members work elsewhere sending remittance, 11=reduced unnecessary expenditure, 19= any other (specify)		
		loss value	normal value	Rank 1	Rank 2	Rank 1	Rank 2	Rank 3

* Specify how much each response contributed (a=0-20%, b=20-80%, c=80-100

B. Negative shocks (hypothetical situation)
Assuming in the coming year if household experience a substantial (unexpected) loss/decrease in total agricultural production?

Type of loss	Quantification of value loss (%, unit)	How will you cope? * 1= spend savings, 2= reduce consumption, 3= sell livestock, 4= sell land, 5= sell other asset, 6= do extra casual labour work, 7= harvest, use or sell more forest products, 8= get loan from money lender, credit association, bank etc, 9= assistance from others (friends, relatives NGOs), 10= HH members will go to work elsewhere for sending remittance, 11=reduced unnecessary expenditure, 19= any other (specify)		
		Rank 1	Rank 2	Rank 3
Moderate loss	< 50%			
Heavy loss	> 50%			

* Specify how much each response would be likely to contribute (a=0-20%, b=20-80%, c=80-100%)

C. Positive shock
In the last 5 years has your household collected unexpected (large) income from agricultural product than the normal year?

Year	Crop type	Quantification of value increase (in Rs)		How did you respond (cope)? * 1=saving, 2= increased HH consumption, 3= bought livestock, 4= bought land, 5= bought other assets, 6= stopped doing extra casual labour work, 7= reduced/stopped collecting, use or sell forest products, 8= payback loan from money lender, credit association, bank etc, 9= sent away gift to others (friends and relatives), 10= HH members stop sending remittance/ returns home, 11=increase unnecessary expenditure, 19= any other (specify)		
		loss value	normal value	Rank 1	Rank 2	Rank 3

* Specify how much each response contributed (a=0-20%, b=20-80%, c=80-100%)

D. Positive shocks (hypothetical situation)

Assuming in the coming year if household experience a substantial (unexpected) increase in total agricultural production?

Type of gain	Quantification of value Increase (%, unit)	How will you respond (cope)? * 1=saving, 2= increase HH consumption, 3= buy livestock, 4= buy land, 5= buy other assets, 6= stop doing extra casual labour work, 7= reduce/stop collecting, use or sell forest products, 8= payback loan from money lender, credit association, bank etc, 9= send away gift to others (friends and relatives), 10= HH members will stop sending remittance/ returns home, 11=increase unnecessary expenditure, 19= any other (specify)		
		Rank 1	Rank 2	Rank 3
Moderate increase	< 50%			
Large increase	> 50%			

* Specify how much each response would be likely to contribute (a=0-20%, b=20-80%, c=80-100%)

Appendix II

Table AI MLN regression results for coping responses to past situations with an unexpected agricultural income loss

	Coping responses	1 Spend savings		2 Obtain remittance		4 Loan or assistance		5 Sell livestock or land		6 Work more		chi^2 test
		Coef.	*z*	Coef.	*z*	Coef.	*z*	Coef.	*z*	Coef.	*z*	P > chi^2
No.	Explanatory variables											
1	Household size (AEU)	0.172	1.48	0.703	2.56***	-0.0453	0.3	0.0815	0.28	-0.0387	0.15	0.0492
2	No. of adult males in HH (AEU)	-0.322	3.09***	-0.0894	0.43	-0.222	1.64*	-0.0298	0.12	-0.0613	0.37	0.0615
3	Farmland owned (ha)	0.0273	0.21	0.104	0.26	0.0293	0.14	-0.098	0.26	-0.165	0.59	0.973
4	Livestock (TLU/AEU)	-0.0562	1.45	0.0324	0.24	-0.0702	0.96	-0.0790	0.8	0.0485	0.42	0.649
5	Net income from environmental products (USD/aeu)	-0.000142	0.19	0.00078	0.4	-0.000613	0.55	-0.00584	1.57	0.000815	0.33	0.551
6	Income from land rented out	0.00122	0.75	-0.245	1.27	0.00381	1.22	-0.0416	1.12	-0.01478	0.39	0.525
7	Income quartile: 'Less poor' (4)[A]	0.386	1.28	-0.149	0.17	0.857	2.04**	1.933	2.76***	0.448	0.72	0.0851*
8	Net business income (USD/AEU)	0.000585	0.81	0.00164	0.83	-0.000416	0.34	0.000368	0.24	-0.00120	0.69	0.221
9	Pension, support from NGO or government (USD/AEU)	-0.00955	3.57***	0.00459	0.57	-0.0230	3.49***	-0.00945	0.58	-0.00277	0.49	0***
10	Remittance (USD/AEU)	-0.00172	2.7***	0.00242	1.54	-0.00148	1.58	-0.00704	2.37**	-0.00519	2.64***	0***
11	Value of all assets (USD/AEU)	-6.32E-05	1.49	-3.58E-05	0.16	-0.000200	2.71***	-0.000147	1.02	-0.000323	2.01**	0.0695*
12	Cost of power for irrigation (USD/AEU)	-0.0125	1.52	-0.0879	0.93	-0.0621	2.59***	-0.392	2.61***	0.000849	0.03	0.0052***
13	Debt (USD/AEU)	0.000318	1.39	0.000902	1.24	0.000136	0.38	0.000569	0.75	0.000495	1.28	0.268
14	Size of shock [B]	0.259	1.63	0.00503	0.01	0.217	1.17	0.926	1.96**	0.0239	0.09	0.385
	Constant	-0.171	-0.42	-5.504	3.43***	0.791	1.49	-1.419	1.44	0.0974	0.1	
	Number of obs. = 663, Pseudo R^2 = 0.0678											

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Table AII MNL regression results for coping responses to past situations with an unexpected agricultural income gain

No.	Coping response / Explanatory variables	2 Save cash Coef.	*z*	3 Increase consumption Coef.	*z*	4 Pay loan back Coef.	*z*	5 Purchase livestock Coef.	*z*	6 Reduce income activities Coef.	*z*	7 Purchase other goods Coef.	*z*	chi^2 test *P > chi²*
1	Household size (AEU)	0.0795	0.19	0.264	2.5**	-0.084373	0.52	0.0696	0.19	0.0510	0.12	-0.413	1.26	0.0275**
2	No. of adult males in HH (AEU)	-0.598	2.06**	0.0602977	0.56	0.0841	0.61	0.585	1.78*	0.0649	0.25	0.278	1.08	0.0602*
3	Farmland owned (ha)	-0.609	1.03	0.0607	0.46	0.0317	0.19	-0.624	1.78*	-0.229	0.69	0.384	1.02	0.413
4	Livestock (TLU/AEU	0.0201031	0.14	-0.103041	2.14**	0.0499	1.18	0.0955	1.57	0.0918017	1.15	-0.124	0.78	0.242
5	Net income from environmental products (USD/AEU)	0.0049329	2.05**	0.0021	1.15	0.003089	2.48**	-0.005384	0.58	0.0023702	1.32	0.00163	0.72	0.0414**
6	Income from land rented out	0.0079113	0.94	-0.010149	1.86**	-0.000123	0.05	0.0108	1.12	0.0020489	0.37	-0.017	1.46	0.343
7	Income quartile: 'Less poor' (4)[A]	-1.14	1	-0.234	0.86	-0.522	2.03**	-0.336	0.47	0.0269	0.03	0.204	0.32	0.312
8	Net business income (USD/AEU)	0.0012358	0.59	-0.000499	1.91*	0.0005062	0.71	-0.00092	0.64	-0.000347	0.37	0.0010791	1.36	0.178
9	Pension, support from NGO or government (USD/AEU)	0.0180	2.94***	-0.010007	1.64	0.0020771	0.46	0.00599	1.24	0.0111	1.88*	-0.00347	0.39	0.0025**
10	Remittance (USD/AEU)	-0.001038	0.29	0.0006562	0.89	0.0015863	2.17**	-0.003928	1.17	-0.000249	0.13	-0.002951	1.13	0.0921*
11	Value of all assets (USD/AEU)	-4.36E-05	0.24	0.0000828	2.71***	-0.000109	1.74*	0.000216	1.77*	-1.91E-05	0.16	-3.04E-05	0.38	0.0038***
12	Cost of power for irrigation (USD/AEU)	0.057	1.41	-0.010657	0.53	0.0053229	0.39	-0.106	0.69	0.0398031	1.22	0.0032	0.07	0.813
13	Debt (USD/AEU)	-0.000233	0.36	-0.000288	1.52	-0.000352	0.99	0.000167	0.32	-0.00057	1.06	-0.000708	1.31	0.342
14	Size of shock [B]	0.442	1.09	-0.053	0.35	-0.198	1.09	-0.215	0.48	0.531	1.04	1.056	2.68***	0.0631**
	Constant	-1.566	0.91	-1.443	3.89***	0.0684	0.14	-2.87	1.51	-2.34	1.63	-1.34	1.25	
	Number of obs. = 501, Pseudo R^2 = 0.0616													

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Table AIII MNL regression results for coping responses to future unexpected agricultural income loss

No.	Coping responses / Explanatory variables	1 Spend savings Coef.	z	2 Obtain remittance Coef.	z	4 Loan or assistance Coef.	z	5 Sell livestock or land Coef.	z	6 Work more Coef.	z	chi^2 test P > chi^2
1	Household size (AEU)	-0.142834	1.13	0.217	1.01	0.112	0.58	-0.167	0.84	-0.256763	1.77*	0.120
2	No. of adult males in HH (AEU)	0.0142	0.14	0.072	0.47	0.153	0.97	0.174	1.18	0.221994	2.06**	0.329
3	Farmland owned (ha)	0.133	0.81	-0.029303	0.13	-0.270	1.25	-0.259	1.14	0.3559243	2.26**	0.0163**
4	Livestock(TLU/AEU)	0.011	0.32	-0.176949	1.29	0.134771	2.14**	0.0494	0.64	-0.093048	1.31	0.0034***
5	Net income from environmental products (USD/aeu)	-0.001996	2.68**	-0.005789	3.24***	0.0007614	0.56	-0.001502	1.27	-0.003017	2.05**	0.0001***
6	Income from land rented out	0.0005305	0.29	0.0131656	2.41**	-0.049394	1.16	0.0104	2.26**	-0.000806	0.09	0.0074***
7	Income quartile: 'Less poor' (4)[A]	0.0377	0.18	0.9753947	2.63***	-0.389	0.94	0.124	0.34	0.28188	0.78	0.0724*
8	Net business income (USD/AEU)	0.0010611	2.55**	-4.49E-05	0.05	-0.000705	0.73	-0.002319	1.74*	0.0007555	1.27	0.0219**
9	Pension, support from NGO or government (USD/AEU)	-0.002878	0.92	-0.019173	2.56***	0.0032627	0.86	0.0002198	0.07	-0.007559	2.24**	0.0053***
10	Remittance (USD/AEU)	-0.000215	0.93	-0.000741	1.48	-0.000374	0.68	-0.00171	2.01**	-0.000396	1.32	0.211
11	Value of all assets (USD/AEU)	-0.000106	2.91***	-0.000187	2.01**	-5.95E-05	0.63	-0.000277	2.4**	-0.000288	4.29***	0.0003***
12	Cost of power for irrigation (USD/AEU)	-0.004869	0.4	-0.026651	0.87	-0.0239	0.67	-0.008243	0.3	-0.055282	2.03**	0.221
13	Debt (USD/AEU)	-6E-06	0.03	-0.000713	1.35	0.0001342	0.35	0.0003672	1.16	-0.000342	1.04	0.067*
14	Size of shock [B]	-0.236061	1.51	-0.656	2.32**	-0.826	3.01***	-0.057856	0.27	-1.341154	7.66***	0
	Constant	0.7511756	1.57	-0.654	0.78	-1.15	1.52	0.614	0.73	1.98	3.44***	
	Number of obs. = 795, Pseudo R^2 = 0.0747											

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Table AIV MNL regression results for coping responses to future unexpected agricultural income gain

No.	Coping response / Explanatory variables	2 Save cash Coef.	*z*	3 Increase consumption Coef.	*z*	4 Pay loan back Coef.	*z*	5 Purchase livestock Coef.	*z*	6 Reduce income activities Coef.	*z*	7 Purchase other goods Coef.	*z*	chi^2 test *P > chi²*
1	Household size (AEU)	0.312	1.24	0.104	0.9	-0.071201	0.64	-0.033253	0.26	0.155	0.86	-0.301	1.65*	0.214
2	No. of adult males in HH (AEU)	-0.147	0.64	-0.127	1.13	-0.011066	0.11	0.217	1.73*	-0.031443	0.24	0.082	0.57	0.278
3	Farmland owned (ha)	-0.935	2.47	-0.190	1.3	0.0120	0.09	-0.128	0.77	-0.753	2.25**	0.0143	0.06	0.009***
4	Livestock (TLU/AEU)	-0.107	0.86	0.0198	0.6	-0.0116	0.26	-0.046514	1.21	-0.219	2.05**	-0.010676	0.2	0.362
5	Net income from environmental products (USD/aeu)	-0.000524	0.22	0.0017254	2.14**	-0.000627	0.68	-0.000747	0.5	-0.000218	0.13	-0.003473	2.24**	0.0007***
6	Income from land rented out	0.0139	2.25**	-0.011626	2.5**	-0.00375	0.47	0.0008113	0.35	0.0062052	1.36	0.0017984	0.35	0.0005***
7	Income quartile: 'Less poor' (4)[A]	-0.247	0.35	0.102	0.4	0.255	0.93	0.445	1.43	0.320	0.66	-0.292	0.72	0.610
8	Net business income (USD/AEU)	-0.001875	1.11	-0.000452	0.8	-0.0005	0.67	-0.001627	2.3**	-0.002123	1.9*	0.0015093	3.59***	0.0002***
9	Pension, support from NGO or government (USD/AEU)	-0.002173	0.17	0.0052955	1.23	0.0020825	0.39	0.0016789	0.34	0.0065078	1.18	0.0071337	0.99	0.186
10	Remittance (USD/AEU)	-0.000738	0.68	0.0001429	0.6	-0.000383	1.23	-0.001537	2.11**	-0.00063	0.89	-9.55E-05	0.2	0.251
11	Value of all assets (USD/AEU)	0.0001304	1.02	0.000055	1.33	-0.000126	1.92*	0.0000842	1.89*	0.0000731	0.79	-6.63E-05	1.4	0***
12	Cost of power for irrigation (USD/AEU)	0.0061305	0.16	0.0235577	1.61	-0.02448	0.89	-0.068008	2.03**	0.0112	0.35	-0.032035	0.99	0.0049***
13	Debt (USD/AEU)	0.000372	0.6	-6.79E-05	0.31	-0.000427	1.39	-0.000159	0.53	0.0001236	0.24	-0.000233	0.66	0.238
14	Size of shock [B]	2.19	4.51***	-0.041701	0.23	1.021	5.11***	0.781	3.79***	0.827	3.05***	0.421	1.48	0***
	Constant	-3.13	3.28***	-0.204068	0.49	0.562	1.35	-0.602	1.39	-0.955	1.28	0.183	0.26	
	Number of obs. = 787, Pseudo R^2 = 0.0569													

** p<0.1, ** p<0.05, and *** p<0.01*

[A] Dummy variable, takes a value of 1 if the household belongs to income quartile 4 ('Less poor') and 0 otherwise.

[B] Dummy variable, heavy loss (> 50 %) is 1 and moderate loss (< 50 %) is 0.

Paper 4

Simulation of Optimal Decision-Making under the Impacts of Climate Change

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Abstract

Climate change causes transformations to the conditions of existing agricultural practices appointing farmers to continuously evaluate their agricultural strategies towards optimizing revenue. In this light, this paper presents a framework for applying Bayesian updating to study decision-making, reaction patterns and updating of beliefs among farmers in a developing country, when faced with the complexity of adapting agricultural systems to climate change. The approach is applied on an example in which a farmer in Ghana, holding an initial belief, seeks to decide on the most profitable of three agricultural systems (dryland crops, irrigated crops and livestock) by a continuous updating of beliefs relative to realised trajectories of climate (change), using the variables of temperature and precipitation. The climate data is based on combinations of output from three global/regional climate model combinations and two future scenarios (RCP4.5 and RCP8.5) representing moderate and unsubstantial GHG reduction policies respectively.

The results show that the climate scenario (input) holds a significant influence to the development of beliefs, net revenues and thereby optimal farming practice. Also, despite uncertainties in the underlying net revenue functions, the results show that when the beliefs of the farmer (the decision-maker) opposes the direction of the realised climate development, Bayesian updating of beliefs allows for an adjustment of such beliefs, as more information becomes available to the farmer, helping him make the optimal choice between agricultural systems considering the influence of climate change.

Introduction

The UN Intergovernmental Panel on Climate Change (IPCC) states that the climate system is warming and that anthropogenic drivers are *extremely likely* to have been the dominant cause of the observed warming since the mid-20th (IPCC 2013). The evidence of climate change is unequivocal, and it is likely that further warming will increase the "likelihood of severe, pervasive and irreversible impacts for people and ecosystems" (IPCC 2014). Thus, climate change represents a serious global risk, which demands an urgent global response (e.g. Stern 2006). Arguably, climate change will have the greatest effect on the poorest and most vulnerable developing countries and population groups (Das Gupta 2014, IPCC 2014). Many parts of the developing world are thus likely to experience climate-induced declines in agricultural output, poorer health conditions, modifications of rainfall patterns, and more frequent natural disasters e.g. floods, droughts or storms. As a consequence some areas will be rendered more or less habitable or inhabitable, and poverty reduction and economic growth will be severely hindered.

One characteristic of the changing climate is that projections of climate change even for short time horizons are associated with a high degree of uncertainty (e.g. Refsgaard et al. 2013), stemming from different sources such as model uncertainty (e.g. Hawkins and Sutton 2011, Larsen et al. 2013), scenario uncertainty (e.g. Yip et al. 2015), natural variations (e.g. Deser et al. 2012), and incomplete knowledge of the climate system (e.g. Oreskes et al. 1994). This aggregated uncertainty and the best responses here to, are not easily identified through observed time series of past climate and its systemic impacts, nor through more dynamic approaches, including experiments of trial-and-error. Rather, we are likely to learn about the actual realization of climate change only as time passes, and in particular at the detailed level. This is true not only for changes in, e.g. precipitation patterns or the severity of droughts, but also for drivers of these changes (e.g. greenhouses gas emissions), and the uncertainty of these factors. Likewise, the potential impacts of climate change are associated with high uncertainty, e.g. the resulting agricultural yields are conditioned not only on climate but also on the installed adaptive measures, management practices and technologies, etc. Conversely, traditional economic approaches towards characterising such uncertainty rely almost entirely on past experiences, e.g. the real option literature, where you estimate the value gained from additional information before making an irreversible investment (Arrow and Fischer 1974; Simal and Ortega 2011).

Risk and uncertainty are central concepts for decision-making on both mitigation and adaptation to climate change. Where 'risk' generally refers to cases where the probability of outcomes can be ascertained through well-established theories and the availability of suitable data, 'uncertainty' as mentioned above refers to situations where appropriate data may be fragmentary or unavailable (Halsnæs et al. 2007). Climate change scenarios used by e.g. the IPCC (2014) cannot in general be assigned with accurate numerical probabilities. Instead conclusions are expressed in terms like "very likely", which may again be transferred to an approx. numerical value (e.g. "> 90% probability"). Budescu, Broomell and Por (2009) have criticised the IPCC for not explicitly considering the numerical probability of climate change, and they conclude that the consequence of this lack is that different people will interpret the probability terms differently, regardless of the international guidelines. This in turn may skew decisions and introduce significant ambiguity, since risk-based methods are widely used to analyse decision-making in connection with climate change (Vardas and Xepapadeas 2010; Klibanoff, Marinacci and Mukerji 2003). As a result the decision-maker's capabilities and personal bias can play a significant role i.e. in the interpretation of the occurrence that are most likely to happen in the future (or in the decision-makers' expectation of the future) and are often compounded by his/her level of 'risk aversion'.

In the following we use the methodology of Yousefpour et al. (2014, 2015) to simulate an adaptive decision-making, addressing the abovementioned complexity of making 'optimal' decisions for the future under the influence of climate change. This includes the difficult issue of timing, that is, the process of determining *when* a decision-maker (here: the farmer) should shift his focus from one (agricultural) system to another. Basically, the idea is that a decision-maker holds an initial set of subjective beliefs of the likelihood of various climate realizations that for completeness add up to one. As time passes, an adaptive decision maker will observe the development of the climate, enabling him or her to gradually adapt choices. For this aim Yousefpour et al. (2014, 2015) introduces a Bayesian methodology for updating the decision-makers beliefs towards different climate realizations based on observations. The framework makes it possible to simulate the trajectory of learning and reaction patterns among decision-makers in examples where the situation does not develop as expected or predicted. An everyday example of a gradually adaptive decision-making, based on experience could be: should I bring an umbrella when walking to work? To start with, I might always bring my umbrella, but would gradually experience that it is rarely needed thereby instigating an adaptation to how often, or even when, an umbrella should be brought.

The framework for Bayesian updating we have applied matches the process of choosing between agricultural systems as climate change adaptation, and through this point out the advantages of proactive adaptation (*ex ante* – avoid learning by shock [Tschakert and Dietrich 2010]) over reactive adaptation (*ex post* – learning by shock) to climate change. Several authors find that proactive adaptation activities can provide significant welfare gains and resilience to climate change at household level (Boko et al. 2007). Similarly, reactive adaptation can in the long run contribute with proactive initiatives by adding to the pool of knowledge on how to deal with climate change (Lecocq and Shalizi 2007). Fankhauser, Smith and Tol (1999) also highlight that the line between proactive and reactive adaptation can be blurred when working within a dynamic setting. Thus in this paper we will also try to capture the irreversible decisions that must be made to create more permanent adaptation strategies, as opposed to temporary coping strategies and autonomous adaptation initiatives.

To illustrate the methodological aspects of decision-making we have used the example of a representative farmer's choice of agricultural system in Ghana as adaptation to climate change, e.g. simulating reaction patterns among farmers as a response to observations of the 'real' climate developments. As a result the farmer may opt to change his choice of agricultural system, as a response to observations, and he builds confidence in climate projections by experiencing changes over time. This makes it possible to determine which future choices are optimal, when the true climate trajectory is revealed over time.

The example of a representative farmer represents a hypothetical decision-making problem, and indicates how every day (potentially irreversible) decisions can be biased by a wide range of factors. While climate change impacts may involve adjustments from season to season for some crops (autonomous adaptation), some changes will require adjustments to the agricultural production system as such, which may not be easily reversible in the short run. Technically it may be possible, but the costs would be too high for the farmer in the short run, and any changes to agricultural systems can be said to be based on a medium- to long-term strategy, at least implicitly. This may of course result in new pressures on common land for grassing and on water for irrigation, or it may be seen as an on-going process of choosing which land should be allocated to the different systems. Hence in real life farmers may use several agricultural systems on different pieces of land.

Adaptation to Climate Change in African Agriculture

The potential impacts of climate change on African agriculture are expected to be severe and lead to significant losses in the aggregated production without the implementation of effective adaptation (Challinor et al. 2014). Hence the projected warming combined with e.g. reduced and/or highly variable future rainfall patterns is expected to have large effects on select crop types. At the same time the adoption of modern technologies in many parts of Africa, including Ghana, is low, and the local economies highly dependent on agriculture. On the other hand, several studies suggest that suitable adaptation measures may reduce these negative impacts of climate change on agriculture and crop yields (Antwi-Agyei et al. 2012; Antwi-Agyei, Stringer and Dougill 2014; Antwi-Agyei, Dougill and Stringer 2015; Benhin 2008; Boko et al. 2007). For example Boko et al. (2007) argue that proactive adaptation may result in welfare gains and resilience to climate change on the household level, as opposed to Benhin (2008) who indicates that without adaptation the net crop revenues concentrated in South Africa are likely to fall by as much as 90 percent over the course of the 21st century, and that climate change will have the greatest impact on small-scale farmers.

In case studies from north-eastern Ghana, Antwi-Agyei, Dougill and Stringer (2015) identify a poor development of the necessary infrastructure, prevention of market access and missing access to new drought-tolerant species as some of the key barriers towards climate change adaptation in the region. Their studies further show how the barriers can be as simple as lack of information on adaptation options and of understanding the need for implementing adaption initiatives. Hence not all farmers are aware of climate change and the consequences they can have in the long run. Antwi-Agyei, Dougill and Stringer (2015) conclude that it is critically important to address these barriers to be able to successfully implement climate change adaptation in the agricultural sector. In this context Boko et al. (2007) along with Antwi-Agyei, Stringer and Dougill (2014) and Antwi-Agyei, Dougill and Stringer (2015) all propose that proactive approaches enhances the adaptation to climate change. Importantly, they also find that farmers are willing to implement on-farm adaptation strategies and that their decisions highly depend on observations of present climatic conditions. Hence Boko et al. (2007) show that farmers in Africa tend to select crops that are adapted to the current climate in their region, and that they tend to shift towards more heat-tolerant crops, as the weather becomes warmer. Likewise, an increase or decrease in precipitation makes farmers shift towards more water-loving or drought-tolerant species, assuming they are available to the individual farmer.

Evidently, the key to overcoming some of the barriers mentioned may be to find a balance between flexibility (e.g. the opportunity of switching to different types of crops), reducing the vulnerability of the agricultural systems and optimizing the returns obtained by individual farmers. Different crops require different conditions to produce the highest returns. Switching from one agricultural system to another may involve cost and time lags before new crops yield a profit, causing some decisions to be effectively irreversible, and some crops may perform more inconsistently than others with regard to revenues in the face of climate change.

How to address the trade-offs between these different aspects in an evolving climate is the focus of this paper. In the paper we discuss key issues related to adaptation decision-making using a probabilistic framework that simulates how to make an 'optimal' choice of agricultural system which may or may not change dynamically over time, as information about the future climate trajectory is revealed, and compounded by the initial and shifting expectations of the farmer. Combined, this yields a numerical simulation of the decision-makers' learning trajectory, in this example a farmer's, to allow us to investigate explicitly the roles of learning and user preferences in adaptation decision-making, which may be critical in terms of designing effective adaptation strategies, but which are often ignored by integrated decision-support systems.

Methods and Data

To simulate how management decisions may change when new and potentially improved information becomes available we employ the same methodology as Yousefpour et al. (2014, 2015). Yousefpour et al. (2014, 2015) introduces a Bayesian methodology for modelling numerically how the 'beliefs' of local forest managers, i.e. in a certain future climate development (represented by three different climate model projections), are updated as simulated observations of mean temperature, minimum temperature and mean precipitation are drawn from the 'true' climate trajectory (initially unknown to the decision-maker) and becomes available over time. Following, they then discuss best management strategies at three different points in time conditioned by the managers' beliefs at those points in time, whether their behaviour is 'actively-adaptive' or not, as well as local conditions and forest characteristics, e.g. the performance of select tree species as defined by a forest landscape model, the available management options and existing management schemes, ownership types, etc.

In this study we adopt a different approach to better reflect the reality of a Ghanaian farmer's choice of agricultural system under climate change. The farmer's beliefs are here updated based on simulated observations of annual mean temperature and precipitation. Since crops are annual and thus easier to replace we consider short five-year time slices as the baseline for decisions on new management strategies, which we simply define as a choice of 'dryland farming' (i.e. rain fed crops), 'irrigated farming' or 'livestock' as in Kurukulasuriya et al. (2006) For this aim we initially carry out a detailed analysis of state-of-the-art regional climate model projections for Ghana e.g. to properly account also for changes in inter annual variations of temperature and precipitation in our choice of climate realizations, which may have profound impacts on the agricultural performance and hence adaptation decisions on these time scales. Finally we use the net revenue per farm for each type of agricultural system, calculated using the Ricardian method of Kurukulasuriya et al. (2006), as the sole determinant of optimal decisions on adaptation. In line with this model we do not explicitly consider, e.g. crop characteristics as part of our decision-space, and neither local soil types, water resources availability, etc. as these are more or less implicit in the model by Kurukulasuriya et al. (2006).

Updating Beliefs Using Bayesian Analysis

As in Yousefpour et al. (2015) we simulate how the farmer's beliefs concerning three different climate model projections, selected from a larger ensemble (see below), would change in the period from 2015 to 2085 as new annual observations of the actual climate development emerge. Let W_{it} indicate the farmer's belief that a particular climate projection (*i)* from a selection of *(n = 3)* ensemble members will be realized in the year *t*, and that the sum of his beliefs is normalized to one as if they were probabilities (Equation 1):

$$\sum_{i=1}^{n} w_{it} = 1\,, w_{it} \geq 0 \text{ for all } i, t. \qquad (1)$$

Thus, if a farmer truly believes in specific climate projection *j* then his belief towards this realization is given by w_{jt}=1 while w_{it}=0 for $i \neq j$. We assign the farmer's initial beliefs w_{i0} to the year 2015.

We use Bayes' theorem (Bayes and Price 1763) iteratively to update the farmer's belief every year from 2016-2085. Assuming x_t^0 to be an estimate (observation) of the state of the climate (annual mean temperature, annual mean precipitation) randomly drawn from a multivariate normal distribution centred around the 'true' realized climate development (here: as simulated by a climate model), then the updated beliefs (probabilities) at time *t+1* related to the situation at time *t* for each of the *n=3* different climate model projections is given by (Equation 2):

$$w_{i,t+1}(x_t^o) = \Pr\left(\text{model}_i \middle| x_t^o\right) = \frac{\Pr\left(x_t^o \middle| \text{model}_i\right)\Pr(\text{model}_i, t)}{\sum_{i=1}^{n}\Pr\left(x_t^o \middle| \text{model}_i\right)\Pr(\text{model}_i, t)} \tag{2}$$

where the updated belief $w_{i,t+1} = \Pr(model_i|x_t^0)$ is the probability of climate projection *i* representing the true realization of climate change given the observation x_t^0 at time *t*, $\Pr(x_t^0|model_i)$ is the probability that the observation x_t^0 is drawn from the distribution centred around climate projection *i* at time *t*, and $\Pr(model_i, t)$ is the probability of $model_i$ representing the real climate development at time *t*. Using Equation 2 we can update our beliefs in each of the alternative climate projections, provided we know what the real climate development will be. In the present analysis we select each of the three different climate projections in turn to represent the real climate, e.g. a 'perfect' model approach. Realistically, none of the three climate projections however will mimic exactly the real climate and hence one could also have chosen an alternative approach, where e.g. a fourth projection would represent the actual climate.

For simplicity, we assume that the simulated observations of annual mean temperature and annual mean precipitation are drawn from a multivariate normal distribution centred on the real climate realization (Equation 3),

$$\lambda_{x_t^o} \sim N\left(\bar{\lambda}_{x_t^0}(temp, prec), Cov(\lambda^{temp}, \lambda^{prec})\right) \tag{3}$$

where λ^{temp} and λ^{prec} in Equation 3 are calculated from running 30-year time slices of projected annual temperature and precipitation produced by a climate model centred on the consecutive observation points (2020, 2025, …, 2085) used for the management analysis discussed below, and *Cov(…)* is the symmetric and positive definite covariance matrix calculated from the annual mean temperature and precipitation series. Using running time slices rather than estimating the covariance matrix from the full time series as done by Yousefpour et al. (2015) allows for the simulated climate to exhibit natural variations consistent with the climate model projections and adequate for considering five-year periods. Hence in the real climate system decadal or multi-decadal variations occur, e.g. extended periods of more or less precipitation, which may partly or wholly overlap any five-year period, used in this study to represent the observation time used by an African farmer to decide on changing his management practices. As a result his belief update which is based on new observations of the present climate conditions is likely to be influenced by such natural climate variations. Using a 30-year time slice as the basis for estimating the inter annual covariance is consistent with current practices amongst climate and weather modellers, where 20- or 30-year averages are also considered as the base for calculating e.g. climate normal or changes to climate variables in a future climate (assuming approximate stationarity).

The probability distribution of the multivariate normal distribution for annual mean temperature and precipitation is defined by Equation 4 with *k*=2 and the rest of the terms as defined above.

$$\Pr(x_t^0|model_i) = \frac{1}{(2\pi)^{\frac{k}{2}}(Cov(\lambda^{temp},\lambda^{prec}))^{1/2}} \cdot \exp(-1/2\ [(\lambda_{x_t^0} - \bar{\lambda}_{x_t^0})Cov(\lambda^{temp},\lambda^{prec})(\lambda_{x_t^0} - \bar{\lambda}_{x_t^0})]) \quad (4)$$

In our simulations we repeated the belief update from 2015 to 2085, performing random draws at every annual time step, a total of 200 times (or 14000 annual draws all together). Additional repetitions > 200 were not found to change our results significantly. The Monte Carlo procedure was coded in Matlab, and the run time for a single experiment was less than a minute.

Climate Scenarios

To represent different possible climate realizations we use precipitation and (near surface air) temperature output from model combinations in the COordinated Regional climate Downscaling EXperiment (CORDEX) database (Nikulin et al. 2012). In CORDEX, output from a substantial number of regional climate models (RCMs) forced on the boundaries of their model domains by global climate models or earth system models (for simplicity here referred to jointly as GCMs), delivered by numerous climate research institutes, are available across 14 different domains, which cover most regions of the world. To select three members representing different climate realizations, we assessed differences in model performance in terms of absolute and residual values, inter annual variability, year-to-year amplitudes and projected future trajectories from each of the available RCMs over the African model domain, covering the entire continent. For RCM driven by several GCMs, one random RCM output was chosen except for one RCM (CCLM4) to here also study the influence of the GCM. This resulted in data being extracted from the seven model combinations shown in table 1. Climate data for both the available historical period (1951-2005) and the projected future (2006-2100) were used. Annual mean temperature and precipitation anomalies were calculated using a reference period of 1979-2005. Both the (Representative Concentration Pathways) RCP4.5 and RCP8.5 trajectories (IPCC 2013) were considered in order to span a wider range of climate realizations and include scenarios of both intermediate as well as high future greenhouse gas emissions (GHG). The gridded data were extracted on a yearly basis and processed into a spatial mean for Ghana based on grid cells from the CORDEX domain in the latitude-longitude range of 5.7^{o} N to 11.0 ^{o} N and 2.6^{o} W to 0.4^{o} E respectively.

To assess also the sub-annual scales, the climate data were further analysed for changes in monthly values (not shown) as opposed to the annual means. A very limited agreement between the models was seen except for temperature in the RCP8.5 scenario where the temperature increase (as seen in annual values for figures 1 and 2) is generally stronger in the months November-June as opposed to July-October.

In the historical period annual mean temperatures generally increase from approx. 25^{o}C around 1950 to approx. 25.5 ^{o}C around 2005 (figure 1). Here the CRCM and RACMO models however differ with absolute values of approx. 24^{o}C and 23^{o}C increasing to approx. 25^{o}C and 23.5^{o}C, indicating systematic biases of a different order of magnitude than the other models. For the RCP4.5 scenario average values increase steadily reaching approx. 27^{o}C around 2070, followed by a generally lower increase reaching approx. 27.5^{o}C in 2100. The CRCM and RACMO models also exhibit systematic biases for the RCP4.5 scenario, showing lower values reaching approx. 26.5^{o}C and 25^{o}C in 2100 and with CRCM even showing a slight decrease in 2070-2100. For the RCP8.5 scenario, mean annual temperatures of approx. 30^{o}c are seen by 2100 within the range of 29-31^{o}C except for RACMO reaching approx. 27^{o}C. For both RCP scenarios the largest amplitudes of inter annual variations are found for the MPI-CCLM model.

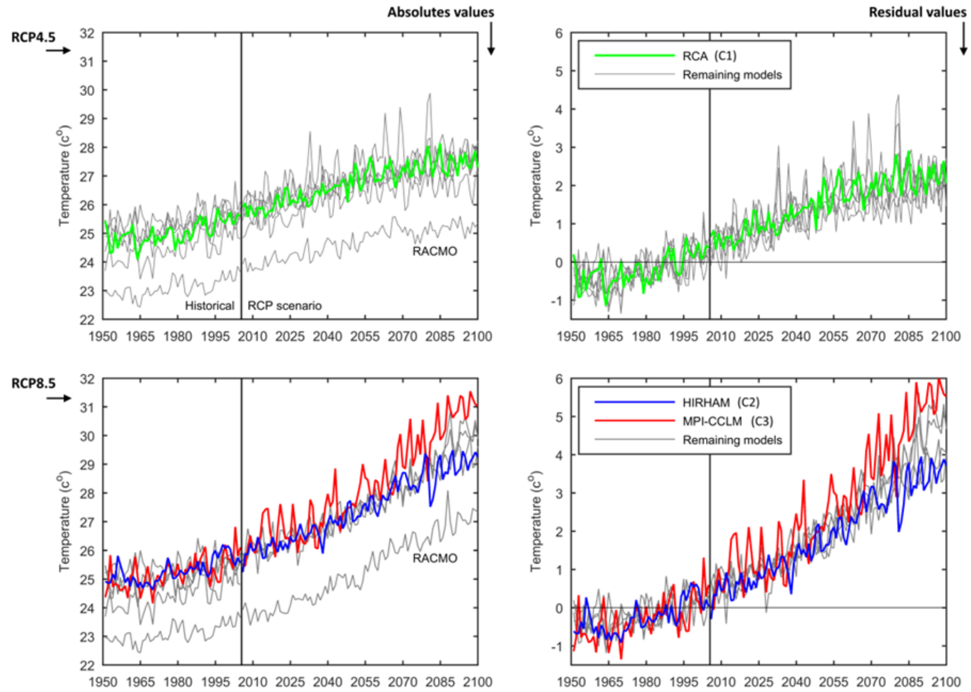

Figure 1 Mean annual temperature output (absolute and residual) over Ghana extracted from the CORDEX database as used to force the decision-making model. Output from the available historical period (1951-2005) and the RCP periods used (RCP4.5 and RCP8.5) (2006-2100). The three scenarios used (C1-C3) are highlighted in colours.

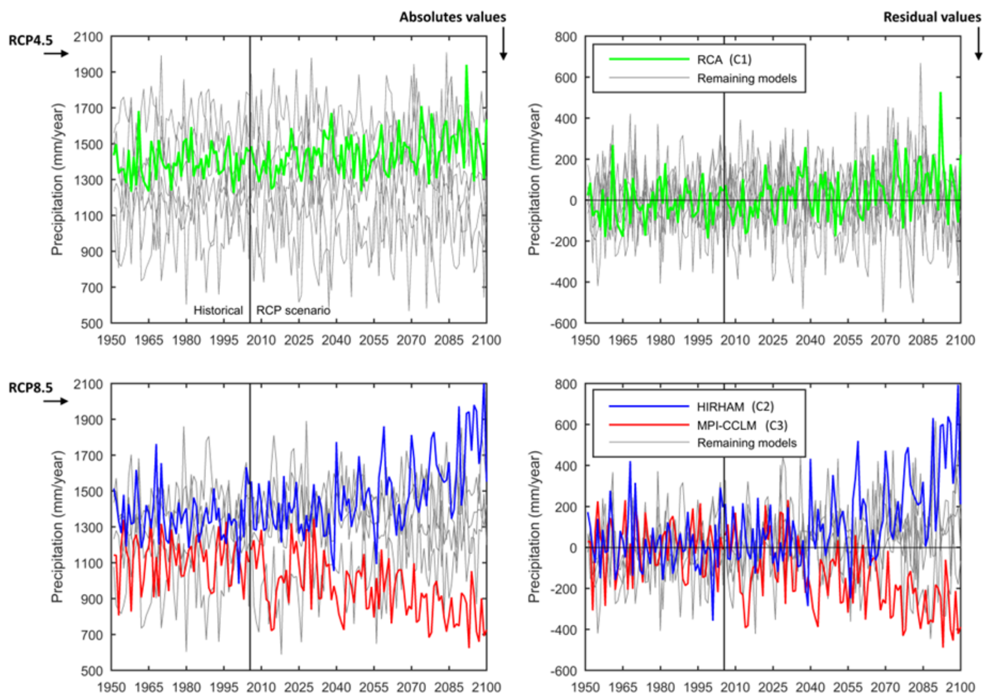

Figure 2 Precipitation output, same as for figure 1, mm precipitation per year.

Table 1 GCM/RCM model combinations assessed for the study and denotation of climate scenarios used in the decision-making model.

No.	GCM/RCM model name	Abbreviated name	Comments	Latest RCM publication
1	MPI-ESM - CCLM4	MPI-CCLM	C3 (RCP8.5)	Baldauf et al. (2011)
2	CNRM-CM5 – CCLM4	CNRM-CCLM		As above
3	MPI-ESM – CRCM5	CRCM	Not available for RCP8.5	Zadra et al. (2008)
4	EC-EARTH – HIRHAM5	HIRHAM	C2 (RCP8.5)	Christensen et al. (2006)
5	EC-EARTH – RACMO22	RACMO		van Meijgaard et al. (2008)
6	EC-EARTH – RCA4	RCA	C1 (RCP4.5)	Berg et al. 2013
7	EC-EARTH – REMO2009	REMO		Jacob et al. (2012)

The precipitation data show a general spread in longer term means between the models. In the 1951-2005 historical period the intermodel spread varies between 990-1630 mm/year and averages 1310 mm/year (figure 2). For the RCP4.5 scenario (2006-2100) corresponding values are coinciding with the historical period (1000-1630 and 1330 mm/year), whereas the RCP8.5 scenario show a small decrease with values of 950-1490 and 1290 mm/year. No data was available for the CRCM model (table 1) for RCP8.5, which proved to be the wettest model for RCP4.5. The RCP8.5 data however does not include the CRCM model (table 1) which is the wettest. Excluding the CRCM model results in the same average statistics for the historical and RCP8.5 analyses respectively. For both RCP scenarios the ensemble mean statistics comprises diverging inter model patterns as some of the models show overall increases and vice versa. This is exemplified e.g. by HIRHAM and MPI-CCLM models exhibiting opposing slopes of 4.4 and -3.1 mm/year in 2006-2100 for the RCP8.5 simulations (figure 2). Also a noticeable inter annual variation is seen exemplified by a minimum-to-maximum difference in the historical period between 420 and 790 mm.

The results of analysing the annual means for temperature and precipitation across the future period of 2006-2100 are found to agree with a recent study by Deque et. al. (2016), based on a larger ensemble of CORDEX RCMs, indicating similarly that the annual mean temperature in Ghana is expected to increase by between 2 and 6°C and that change in rainfall is, on average, still uncertain but in any case modest compared to the inter annual variability.

Lastly, we also analysed the Pearson linear correlation between temperature and precipitation for each of the five-year periods based on 30-year running time slices as discussed above (results not shown). Here the seven models were found to behave quite different, with one model (MPI-CCLM) showing a strong and increasingly negative correlation towards the end of the century, whereas other models showed positive correlations or no trend at all. Based on the combined results we finally selected three climate projections to be used for the further analyses, reflecting the full span of possible climatic outcomes. As low emission and low impact scenario we selected the RCA model, downscaling the RCP4.5 scenario (hereafter entitled C1), to constitute a 'baseline' climate of minimal change. The second scenario (HIRHAM, RCP8.5 – entitled C2) was chosen due to being wetter than most, representing a temperature increase in the lower range of the models included here, and exhibiting a positive temperature-precipitation. Conversely, the third scenario (MPI-CCLM, RCP8.5 – entitled C3) was selected for being the driest, having the highest temperature increase by the end of the century and a strong negative temperature and precipitation correlation.

Agricultural Systems

We assume for simplicity that the farmer's principal objective is to maximise the net revenue of his agricultural activities. For this aim we adopt the economic model developed by Kurukulasuriya et al. (2006) and apply this to Ghana. In this cross-sectional approach the relationships between climate and net revenues from three different agricultural systems: dry crops, irrigated crops and livestock are studied using a standard Ricardian model formulation for each agricultural system. Based on an ordinary least squares regression and using the results of e.g. more than 9,000 farm surveys conducted in 11 different countries in Africa (including information on water flows, local soil types and a variety of economic variables), the marginal climate impacts on net farm revenues per farm (in USD) as estimated by Kurukulasuriya et al. (2006) are reproduced in table 2.

Table 2 Marginal climate impacts on net revenue per farm (US Dollars/USD) based on data presented by Kurukulasuriya et al. (2006). Ordinary Least Square (OLS) numbers in parentheses are the maximum and minimum coefficients (95% confidence intervals). *** p<0.05, and *** p<0.01.*

Marginal impact OLS	**Dryland crop**	**Irrigated crop**	**Livestock**
Temperature	-239*** (-335, -142)	3005 (-2040, 8048)	-379 (-775, 17)
Precipitation	15*** (5.1, 25)	301.3 (-896.6, 1499.3)	19.9** (0.3, 39.5)

The marginal effect of changes in precipitation specified by the coefficients in table 2 corresponds to an increase in the annual mean precipitation of 1 mm (calculated from monthly means). Similarly, the marginal effect of changes in temperature corresponds to an increase in the annual mean temperature of 1^{o}C. The baselines for these estimates were set by time series of climate observations spanning 1988-2003 (temperature) and 1977-2000 (precipitation). The numbers in parenthesis indicate the 95% confidence intervals and will in the following be referred to as minimum respectively the maximum coefficients. For more details about the model a detailed description is provided in Kurukulasuriya et al. (2006).

The main advantage of the regression type model by Kurukulasuriya et al. (2006) is that the net revenues revealed by their analyses in a simple way reflects the benefits and costs of autonomous adaptation and coping strategies, such as the choice of sowing method and timing. This includes a variety of contributions and the introduction of substitute actions, which farmers have incorporated in order to adapt to the current climate viabilities. As a result it is readily possible within the framework to simulate an irreversible decision, as autonomous adaptation is already included. Labour costs have not been included, since the shadow price of wages that farmers apply to their own time cannot easily be measured.

Conversely, it is also evident that the Ricardian model also has its obvious deficiencies. Given that the empirical data spans 11 countries across the entire African continent the coefficients in table 2 are found to vary considerably, which is perhaps most evident in the case of irrigated farming. Similarly, the results of modelling net farm revenues are also going to be associated with large spreads depending on whether the minimum coefficient (which is negative) or, say, the mean coefficient (which is positive) is used. If one considers only the mean coefficients then it is furthermore clear that the model is strongly biased towards irrigated farming, which Kurukulasuriya et al. (2006) attributes to an overrepresentation of data on irrigated farming from Egypt; whereas in Ghana existing crops are mainly rain fed.

Since, in this study, we will be mainly interested in demonstrating how the farmers' beliefs can have an impact on management and not to carry out a quantitative impact assessment, we have adopted the model by Kurukulasuriya et al. as it is, however, we will explore the span of possible outcomes by considering not only the mean coefficients but also their minimum and maximum values. Conversely, for more quantitative and local studies the authors will endorse more realistic modelling approaches.

In the following sections we show the results of simulating optimal decision-making using the described Bayesian methodology while evaluating the mean annual net revenues of his agricultural activities every five years starting in 2020 and ending in 2085. The latter is discussed in the context of choosing between the three types of agricultural system. For this aim we have made the following assumptions: The farmer makes rational decisions; the farmer is not risk adverse; the farmer bases his choice of agricultural system on net revenue; the farmer has access to information about agricultural systems on which he can base his decisions in each step of the framework; the farmer can only use one agricultural system at a time.

Results

Presented here are the results from the Bayesian updating framework. The development of the farmer's updated belief developing towards the realised climate trajectory over time is shown in figure 3 as described in equations 1-4 and in Yousefpour et al. (2015). The updated belief is shown for four combinations of initial belief (either equally distributed or with an 80%/10%/10% belief towards a specific realised climate) and the three climate scenarios. The figure shows that all beliefs converge towards the realised climate, albeit over a much varying duration (from a few years to approx. the 2015-2080 period) and with diverging pathways. The convergence period (after which the belief is certain on the realised climate) is primarily a function of the realised climate with shorter convergence times from C1 through to C3. The convergence periods are highly correlated with the (combined) climate signal seen in the temperature and precipitation data (figures 1 and 2 respectively). Especially the lack in precipitation signal in C1 is likely to temporally restrain the certainty in climate scenario belief whereas the combined strong decrease in precipitation and strong increase in temperature in C3 leads to a swift convergence here. A minor influence from the initial belief is seen with convergence times up to 5-10 years faster when the initial belief (80%) is directed towards the specific scenario.

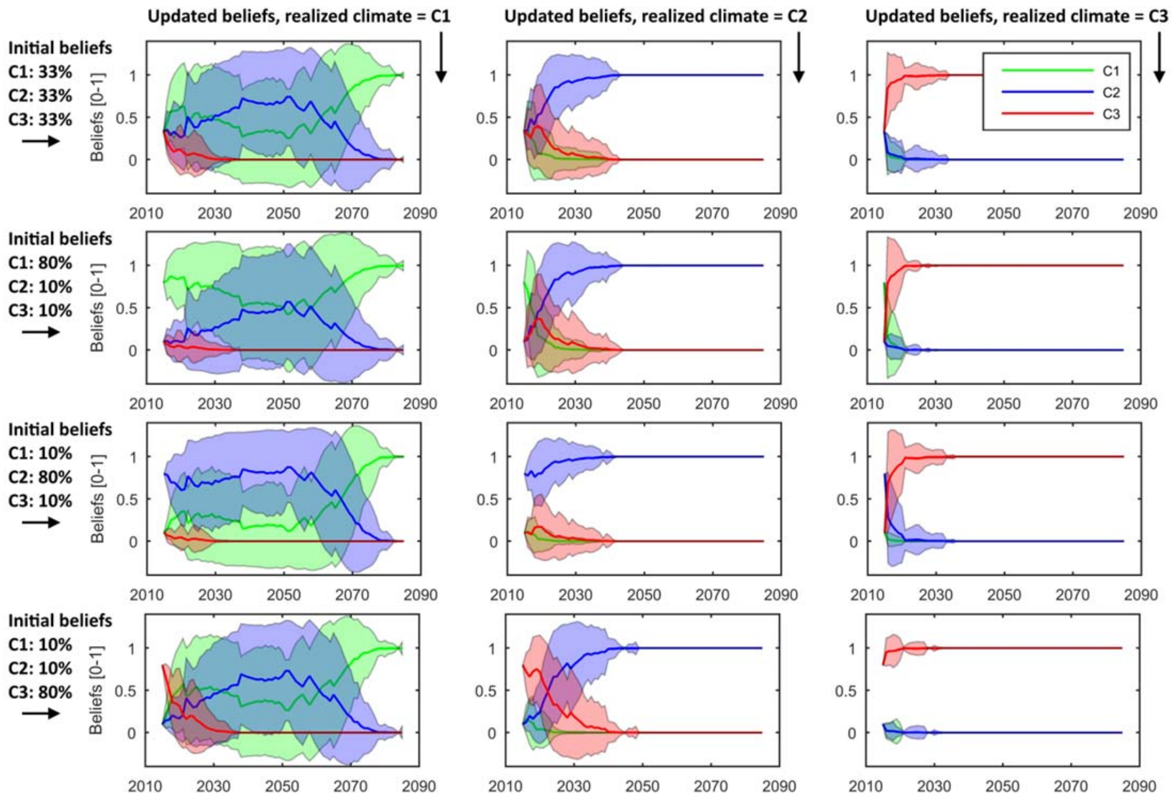

Figure 3 Update of belief during the study period dependent on initial belief and realized climate.

The resulting net revenue based on each of the climate scenarios, C1-C3, and agricultural systems, dryland, irrigated and livestock, is seen in figure 4. From the figure, three main points are evident: I) between each agricultural system, high general variations in net revenues are seen with values in both the profitable and non-profitable (negative) range. Specifically, dryland crops in C3 (dry and warm) and livestock in all scenarios (C1-C3) turns non-profitable for results using mean coefficients. Assessing the entire net revenue span using minimum and maximum coefficients significantly increases the possible net revenue span for each agricultural system especially for irrigated agriculture (notice the varying y-axis limits in figure 4) which is also evident when assessing the coefficients in table 2. II) The climate scenario, C1-C3, has a distinct effect on the resulting net revenue trajectory e.g. with an incisive negative development for dryland and livestock systems under C3. III) Finally, climate variability affects the net revenue on shorter time spans also with positive-to-negative year-to-year net revenue variations.

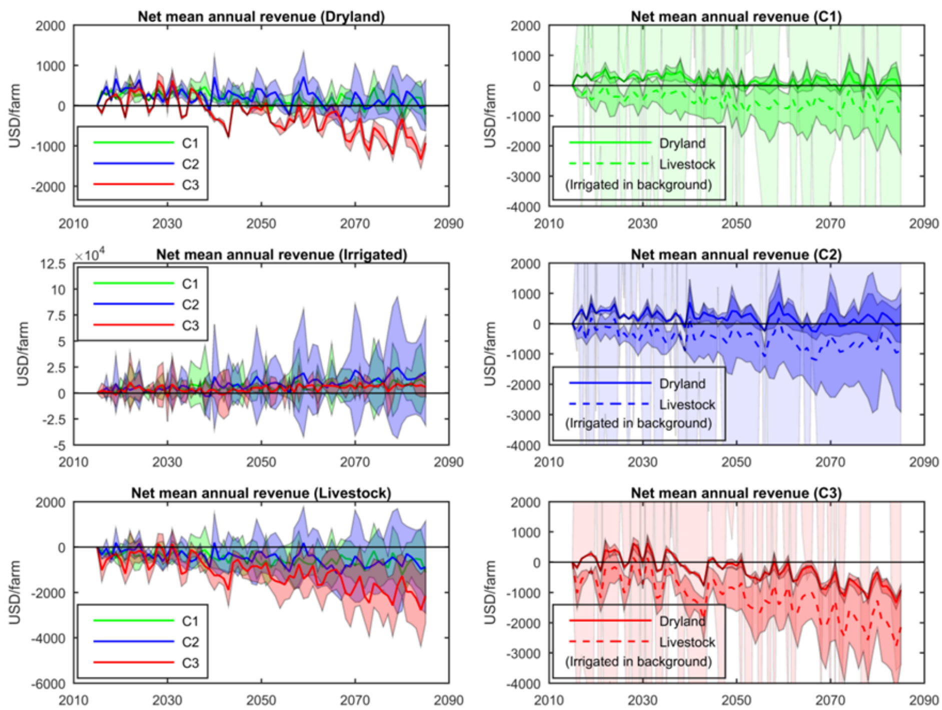

Figure 4 Calculated net revenues during the study period dependent on agricultural system practice and realized climate. All results are plotted as minimum and maximum coefficients (95% confidence: coloured area – see table 2) around the mean net revenue functions (Kurukulasuriya et al. (2006). For easier comparison, results are sorted for both agricultural system (left column) and realized climate (right column). For the realized climate, the y-axis limits are specified to enable comparisons between dryland and livestock systems as the irrigated practice generates significantly higher net revenues.

The resulting net revenues (USD/farm) and choice of agricultural systems (1-3), both over time (2020-2085), based on the maximization of the former, is shown in figure 5 using mean and minimum coefficients for the combinations of the four distributions of initial beliefs and the three realised climates analysed. From figure 5 it is seen that employing irrigated agriculture is the optimal agricultural system regardless of the realised climate scenario when using mean coefficients. The net revenue function following the development of the climate trajectory, for C1 being the realised climate scenario, shows large variation in the net revenue function when the decision maker have different initial beliefs. The distance between the curves also represent the range of net revenues that the decision makers take decision upon, because of their large variation in initial belief of the future climate development. When using minimum coefficients, dryland agriculture is preferred over the other agricultural systems in 2025 and from 2035 and onwards for C1 and C2, whereas for C3 irrigated agriculture still maximizes net revenue (converged from 2040 and onwards). For all combinations of realised climate and coefficients, the influence of initial belief is seen to diminish or completely disappear within, most often, the first 5-10 simulation years. Climate scenario C1, using mean coefficients, is an exception. This is caused by the corresponding substantial shifts in belief for C1 throughout the analysis period as evident in figure 3.

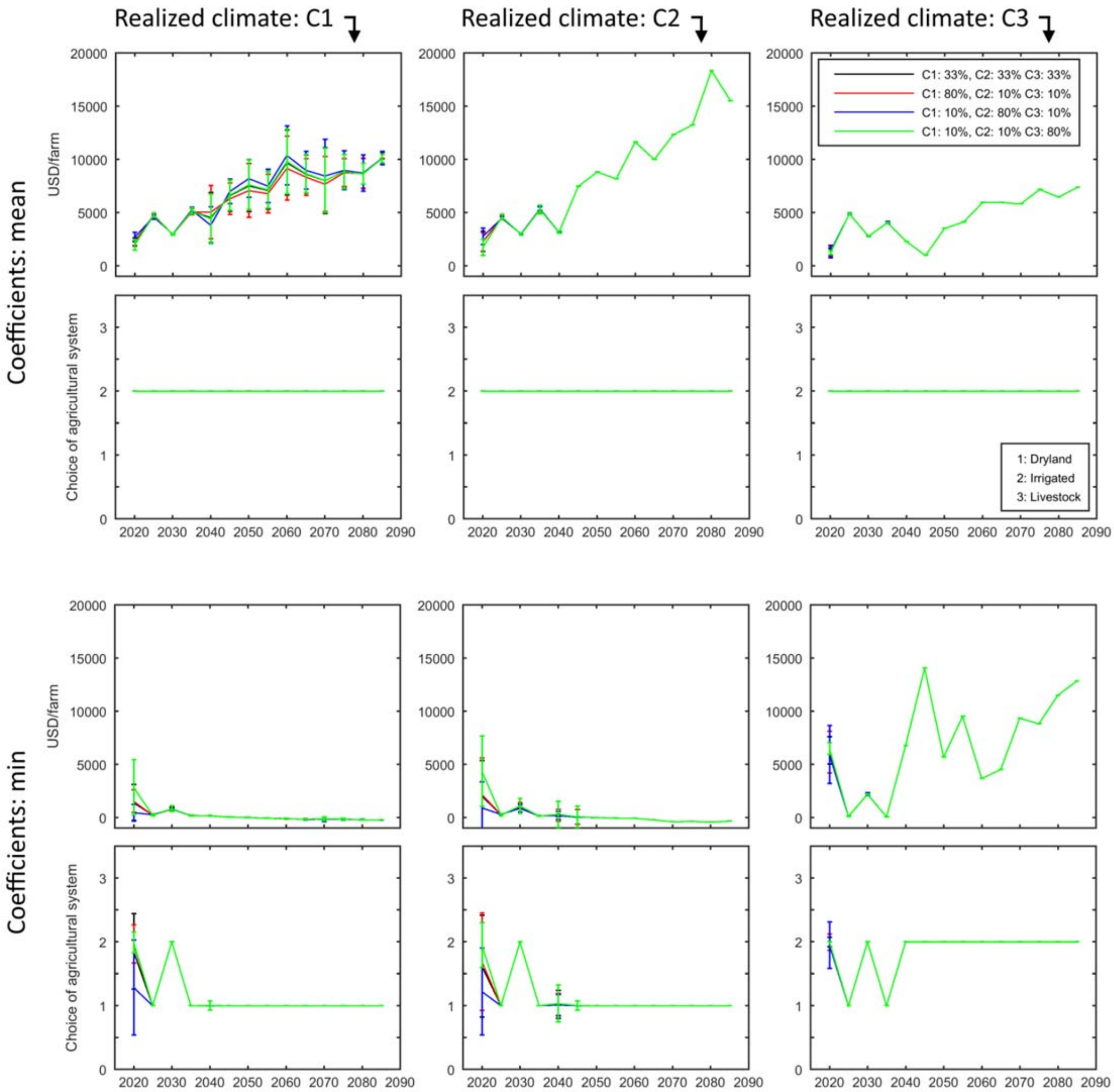

Figure 5 Choice of agricultural system (1-3) based on net revenue maximization (USD/farm) dependent on the realized climate in the three climate scenarios (C1-C3; temperature and precipitation) and the farmer's initial belief. Results are presented dependent on the use of mean or minimum (95% confidence) net revenue coefficients (table 2) as discussed above (as in Kurukulasuriyaet al. (2006)).

Concluding Discussion

This study presents a novel approach to simulate the consequence of decision making under the impact of climate changes, simulating how a decision maker can change behaviour and the consequence of the decisions as new knowledge is revealed over time. The paper also adds to the discussion on how Bayesian updating can contribute to the development of adaptation to climate change, and how the decision-maker can handle the uncertainty of climate change. Therefore, the discussion will focus on the Bayesian updating framework developed here, its relevance and opportunities for improvement. The results regarding *which* agricultural system should be chosen *when* and the possible net revenue will only be briefly touched upon, as the data and net revenue functions are judged too general; cf. the above section on Agricultural Systems.

The approach helps to bridge the development within climate change and the management decisions facing farmers. The latter is often based on a combination of variables, e.g. sociological, economic and ecological. This paper solely considers the farmer's observation of the climate variables precipitation and temperature, updating his belief of the true climate development, followed by an observation of net revenue from the agriculture system based on his belief in the climate, and a decision based on these observations. Despite this limitation, the approach presented here is useful in that it frames the different options available to farmers facing climate change and the consequence of having a misjudged initial belief.

The main finding of this paper is that with the method presented, it is possible to simulate future choices of the farmer, to contradict original beliefs and to highlight the consequences it can have to make a wrong choice. A key finding is that irrigated crops, independently of the realised climate development, is a main preferred choice of agricultural system due to the, upward-sloping curve for net revenue (US dollars per farm/year) regardless of climate scenario (figure 3). The choice of irrigated crops may, however, be too optimistic and unrealistic; as the implementation of irrigated crops will require making considerable investments (depending on the way irrigation is established and carried out). Irrigated crops may be unrealistic for many farmers, as this agricultural system entails more intensive management, high costs for implementation and the system is therefore not necessarily available to the majority of farmers. Further, the mean coefficients used (table 2) are likely to be affected by, and therefore biased towards, countries where irrigation water available and therefore implemented into the agricultural system, here mainly Egypt Kurukulasuriya et al. (2006). Therefore, the results based on using the minimum coefficients (95% confidence), where also the dryland agricultural system is preferred for two climate scenarios, is likely to be more realistic for this Ghanaian example. The right column in figure 4 shows how the agricultural system becomes competitive with one another and the development through the three climate scenarios and time. By applying the minimum coefficients it has been possible to show how the decision-maker can change behaviour over time, as new information is revealed, contradicting his original beliefs. This proves that it is possible to simulate a change in a reaction patterns among farmers in examples where the climate does not develop as predicted and according to the farmers belief.

The lack of opportunities to implementing irrigated farming, as highlighted above, also has another implication regarding the remaining two agricultural systems. Dryland crops are cultivated on the farmer's privately owned land, whereas it is normal in many locations to use common or public land for livestock grazing (Kurukulasuriya et al. 2006; Kassahun and Jacobsen 2015). Consequently, there is no linear relationship between a farmer's income from livestock and the amount of land he owns or has the right to cultivate. The choice between livestock and dryland crops is thus more a matter of *where* to make an effort in terms of required investments (e.g. seeds, animals) and labour. Also, livestock covers a huge range of animals, and it should be taken into consideration that small livestock such as goats are more heat tolerant than cattle. This has to some extent been incorporated into the net revenue for livestock, as the data from Kurukulasuriya et al. (2006) include a variety of contributions and alternative actions, which farmers have introduced in order to adapt to current climate viabilities. The discussion concerning *where* to make the effort also leads to a discussion of the cost of labour, as the cost of household labour has not been included in the functions for the net revenue of the different agricultural systems. The results of Kurukulasuriya et al. (2006) indicate that growing crops is more management intensive than keeping livestock. Kurukulasuriya et al. (2006) base this assumption on the fact that a large household earns higher revenue from crops and lower revenue from livestock than smaller households. The function applied in figure 4 based on Kurukulasuriya et al. (2006) clearly shows that the net revenue generated from livestock are more sensitive to climate change variabilities, than dryland crops exemplified though the large variabilities in the net revenue functions for irrigated crops compare to dryland crops. This then indicates that the farmer is likely to be more willing to update his beliefs if changes concern precipitation rather than temperature, as precipitation has a greater influence on growth. The decision-maker may erroneously update his beliefs on precipitation, as there can be huge fluctuations in precipitation. And further; the decision-makers (should) therefore require a solid knowledge base for updating his beliefs in a realistic way. This could be the explanation on why we see the frequent change among agriculture systems in figure 5, among for calculations on minimum coefficients in the early years until year 2040. The increasing precipitation patterns for C2 from approx. 2040 and onwards causes the farmer to choose dryland crops from this point in time. For the C3 scenario, the decrease in precipitation causes the opposite towards a choice for irrigated crops. Some effect may further be seen for the stronger temperature increase for C3 over C2 (figure 1).

With regard to farmers' ability to react in a proactive way in order to adapt to climate changes, we have considered it relevant to compare the three agricultural systems within this framework, as a change in agricultural system is at some level an irreversible decision towards being resilient to climate change for the current period (5 years), compared to more untenable coping strategies such as reduced consumption, cash savings or increase in debt. However, we should not forget that the setting is highly dynamic, and as highlighted above, the line between proactive and reactive behaviour can be blurred, meaning that what is optimal today may not be optimal next year. One should also pay attention to the findings of Antwi-Agyei, Dougill and Stringer (2015) concerning barriers to climate change adaptation: It can be difficult for the individual farmer to sell his crops if there is no market; this is a question of supply and demand and having access to a market – a barrier which not even this framework can overcome.

Furthermore, it may be relevant to mention how most farmers will in fact choose to combine the three suggested agricultural systems. Kurukulasuriya et al. (2006) also mentioned this in their description of the data, assuming that the farmer chooses input and output that optimise the net revenue of these three main agricultural systems and minimise the risk, something the current framework was not able to handle.

The approach presented here helps in bridging the development within climate change and the management decisions farmers are facing. The latter in integrated decision support systems is often based on a combination of variables, e.g. sociological, economic and ecological. This paper focuses on the farmer's observation of the climate variables precipitation and temperature, updating his belief of the true climate development, followed by an observation of net revenue from the agriculture system based on a belief in the climate, and a decision based on these observations. This may somewhat prove to be a limitation of the approach although facilitating the different options available to farmers facing climate change.

In the approach presented here, we aim at applying a more thorough analysis and implementation of the climate data component of this type of study. This, not only by applying the most recent set of regional climate model simulations available but also by integrating these in a fashion where not only the extreme end-period outcomes are included (e.g. high temperature increases by 2100), but also by analysing and including much diverging trajectories of both temperature and precipitation and the associated correlations and variabilities. We thereby enable the assessment of a broader range of the possible span of resulting outcomes in net revenues and associated agricultural decision-making.

The Bayesian updating framework is a first step in developing a theoretical approach to updating beliefs on climate change, making proactive adaptation possible, whether being proactive or reactive. Most importantly however, we recognise the need to move from the current farm-based level of advancement to working in a village or country setting, when the issue is scarcity of resources, e.g. water, as it will not be possible for all farmers to irrigate their crops under the influence of climate change, even if the results of the Bayesian framework suggest that this agricultural system is preferable. Of other settings where this approach could be relevant is in relation to the implementation of policies, decision support for a region or support from donors and NGO's, as this is often very time consuming to implement and can have similarities with irreversible decisions.

Future research on this matter should focus on the possibility of merging individual decision-making with available resources, based on more empirical knowledge of farmer's choice of climate change adaptation or coping in the case of substantial unexpected shocks. A more specific analysis on sustainability aspects and consequences of decisions under a given climate change scenario should therefore be possible also highlighting resilience. In a wider perspective it would be interesting to see how a Bayesian framework could contribute to revealing and identifying opportunities for adaptation and mitigation of climate changes and – if possible – how it may contribute to optimising farmers' resilience to climate change and increased sustainable development.

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