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From CBA to decision trees and cognitive maps: Supplementing costs and benefits to acknowledge uncertainties and complexity in decision making

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To my parents Ioana and Marin,

to my brother Paul,

to my friend, companion and love Denis,

and to our loving dog,

Bonnie

Abstract

Decision making has always been defied by uncertainty, but humans developed strategies to overcome this difficulty. Climate change, however, has brought new challenges: on the one hand, many of these strategies have become inappropriate to face the changes of the climate system and its social impacts; on the other hand, climate change is a pervasive problem which needs an adequate and extensive response. This thesis takes the cost and benefit framework as a starting point to show *if* and *how* revealing uncertainties and complexities may improve decision-making and project appraisal. Overall, the work undertaken here demonstrates that improving decision-making based on costs and benefits is both necessary and feasible. The cost-benefit model may benefit from being used in synchronicity with (semi-) qualitative and illustrative methodologies that are better suited to reveal and communicate complexities underlying decision-making. Communicating on complexities and uncertainties through their illustration, for example, in the form of decision trees or mental models may enable to understand and acknowledge model assumptions. It may also be more desirable in order to avoid locking-in present and future societies in both built and social infrastructures founded on mental constructs that have been inherited from the past. In order to achieve this, economic assessments need also to be supplemented by multidisciplinary and participative approaches that expose knowledge which would otherwise remain hidden, while valuing plurality and democratic accountability. Using system-thinking and democratic participation with(in) more traditional approaches may enable to identify *root causes* of vulnerabilities and a more diverse range of interventions and to visualise and highlight the inter-linkages between systems and their complexity. This work is anticipated to be a starting point for more sophisticated applications of decision trees as well as more integrative and associative appraisal approaches using multiple methodologies. In addition, future research can build on different insights provided by neuroscientists and psychologists. Sound decision-making may not come from methodological abstractions alone, but from humans' own cognitive and physiological capacity to develop and implement them.

Lay Summary

Decision making has always been difficult due to uncertainty about the future, but humans invented strategies to overcome these difficulties. Climate change, however, has brought new challenges: on the one hand, many of these strategies have become inappropriate to face impacts of climate change; on the other hand, climate change is extensive which needs a response from everyone, everywhere, at every moment in time. This thesis takes the cost and benefit framework as a starting point to show *if* and *how* divulging uncertainties and complexities may improve decision-making and project evaluations that are done prior to investments. Overall, the work undertaken here demonstrates that improving decision-making based on costs and benefits is both necessary and feasible. The cost-benefit model may benefit from being used together with (semi-) qualitative and illustrative methodologies that are better suited to communicate on complexities underlying decision-making and that enable to understand and acknowledge model assumptions. Illustrating complexities may result insightful and complementary. Using the benefit-cost model together with other more appropriate evaluation methods may also be more desirable in order to avoid reproducing from the past, what may not be suited for the future. In order to achieve this, economic assessments need also include the participation of actors from different backgrounds to expose knowledge that would otherwise remain hidden, while valuing democratic participation. Including interactions across various research domains and participants may enable to visualise and highlight the inter-linkages between domains and their complexity, instead of inhibiting what is the very nature of interactions of societies with their environment. This may enable to identify the *root causes* of vulnerabilities and a more complete range of interventions. This work is anticipated to be a starting point for more sophisticated applications, more participative and interlinked evaluation methods that use several methodologies. In addition, future research can build on different insights provided by neuroscientists and psychologists. Sound decision-making may not come from methodologies alone, but from humans' physical capacity to develop and implement them.

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While writing these words I can't believe I am almost done after six (almost 7!) years of hard work and dedication - except the past two years. I write this with both a mixture of anticipated relief and the curiosity about what will come next. However, I shall not be afraid of uncertain futures!

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Alina Tepes

“May your hands always be busy
May your feet always be swift
May you have a strong foundation
When the winds of changes shift
May your heart always be joyful
May your song always be sung
And may you stay forever young”

— Bob Dylan, *Forever Young*

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Chapter 1

Introduction

This thesis builds on the cost and benefit framework of climate adaptation as a widely used decision tool and attempts to suggest ways to expand the information base that may improve policy making in the realm of global climate and environmental change. In this introductory section, a brief overview is provided of policy decision-making generally and the use of the cost-benefit analysis (CBA) as well as its fundaments (Section 1.1.1). When introducing the notion of uncertainty, climate change is taken as an example to illustrate how uncertainties challenge traditional decision-making (Section 1.1.2). Following this, the introduction provides some brief insight in the different terminologies that have arisen in the environmental literature about adaptation (Section 1.1.3), sustainability (Section 1.1.4), resilience (Section 1.1.5) and the different tensions that separate these research communities on ideological grounds of moral and epistemological belief systems (Sections 1.1.3 to 1.1.5). This sets the stage to the summary of more specific research gaps (Section 1.2), research questions (Section 1.3) and the main hypothesis posed in this thesis (Section 1.4) before announcing its structure (Section 1.5).

1.1 Background

1.1.1 Cost benefit analysis and policy evaluation

Nowadays, investment decisions heavily rely on budget limitations and these are widely institutionalised and dictated at international, regional and national levels (Schick, 2003). Comparing costs and benefits of alternative investment opportunities is therefore useful in order to effectively allocate resources (Pearce, 1983). This comes in addition to other strategic and political considerations as well as preferences and values that are inherent to upstream reflections which precede decisions (Kalt & Zupan, 1984). Within this context, various economic appraisal methodologies have been developed such as the cost-comparison and the cost-effectiveness approaches. In particular, the CBA has been the most widely applied to project evaluation (HMT, 2018; Turner et al., 2002). For several decades it has become a prerequisite in investment practice in order to validate the viability of investment possibilities and decisions, in both private and public policy arenas (Daily et al., 2009). In several countries it is prescribed by law for example for dam-building projects (Hinkel et al., 2015).

CBA seeks to evaluate different investment possibilities and their cost-efficiencies on the common basis of monetary values. It compares different available policy options by quantifying and ranking their outcomes, regarding positive impacts of an intervention as benefits and negative impacts as costs. Monetary values of individual costs and benefits are then summed up to obtain the total sum of annual costs and benefits which then serve to calculate the net benefit or net cost of a given investment over a project's lifetime, called the net present value (NPV). Interventions that pass the cost-benefit test, that is $NPV > 0$ (net benefits − net costs > 0), are said to be desirable, because they are considered to generate enough benefits so as to cover all costs and still have an additional gain. Alternative interventions are then ranked in decreasing order of $NPVs$ and the highest $NPVs$ are considered to be the most cost-efficient investments as they bring about the highest possible wealth (Wegner & Pascual, 2011). CBAs provide additional metrics to be analysed such as the Benefit-to-Cost Ratio (BCR). A $BCR > 1$ indicates a project has a positive NPV but this indicator has the advantage of allowing comparisons of different sizes (for example, market sizes).

The CBA methodology has its roots in utilitarian theory of neoclassical economics (Wegner & Pascual, 2011). Its attractiveness for sound decision-making is mainly derived from the common and objective basis it provides to appraise and compare projects on same monetary scales and to address efficient allocation requirements of scarce resource. It also receives support on the basis of its coherency with global market economies, which is considered beneficial both to the private and public sector (Wegner & Pascual, 2011). The CBA is also regarded as enabling transparent decision processes and a framework that can convey complex realities in a simple and familiar manner, thus facilitating decision-making. Since it was first developed, this model has been subject to several critiques (Wegner & Pascual, 2011) which have also served to augment efforts of improvement (Barbier & Markandya, 2013; Chiabai, Galarraga, Markandya,

& Pascual, 2013). For example, a main limitation of this model, some scholars argued, is that values accounted for as costs and benefits may be different than utilitarian and not necessarily individualistic nor commensurable in monetary terms (Wegner & Pascual, 2011). According to Gómez-Baggethun, de Groot, Lomas, and Montes (2009) the evolution of economic theory eventually led during the "marginal revolution" of neoclassical welfare theory to the eviction of nature and environmental resources from the economic production function. At the opposite, other scholars advanced that for example environmental economics have largely contributed to address the theoretical weaknesses of the CBA with the purpose of communicating on the value of nature and environmental resources for human welfare (Turner et al., 2002). For the advocates of this school of thought, the internalisation of the environment in utilitarian economic theory has the advantage of addressing the neglect of nature's role in market-based policy making (Costanza et al., 1997) and is better than nothing given the extent and pervasiveness of the utilitarian approach in market economies (Wegner & Pascual, 2011).

Though inherent complexities to the application of the traditional CBA have long been debated, such as the choice of the discount factor (Chiabai et al., 2013; Markanday et al., 2019), some other intricacies especially deep uncertainties remain challenging (Cavallo & Ireland, 2014; Marchau, Walker, Bloemen, & Popper, 2019; Weinstein, Eugene Turner, & Ibáñez, 2013). This is so especially when frameworks and models require to be accessible and user-friendly for their non-expert audience (Dittrich, Butler, Ball, Wreford, & Moran, 2019; Lempert, 2002). Alternative tools such as robust decision-making (Lempert, 2002; Marchau et al., 2019) and real options (Scandizzo, 2012; Trigeorgis, 1995) were developed to provide different frameworks for decisions under uncertainty. However, as compared to traditional CBAs, these are more time consuming, computational and more expensive methodologies which are less familiar to practitioners and more difficult to interpret (Dittrich et al., 2019).

1.1.2 Uncertainties

1.1.2.1 Decision-making under uncertainty

Uncertainties are ubiquitous in everyday life and unavoidable. On a daily basis we are repeatedly required to make decisions. We have to decide about what we eat, what activities we undertake, we have to decide about job offers and applications, about where we live, what we eat, whether we invest in a house or if we prefer renting but also about who or when we marry. There are several definitions of uncertainties in the literature. Generally speaking, uncertainties can be defined as *"limited knowledge"* about the future, present and the past (Walker, 2013 cited in Marchau et al. (2019), page 2). Uncertainties can also be categorised according to different dimensions such as uncertainty levels, sources and nature (Refsgaard et al., 2013). In their opinion article, Taebi and Kermisch (2020) argue that in risk governance, normative uncertainties need to be addressed along with scientific and technical uncertainties. According to these authors, normative uncertainties arise when there is not one unequivocal right or wrong answer to an ethical question regarding for example risk, values, equity, voluntariness, irreversibility or catastrophic potentials (Asselt and Renn, 2011 in Taebi and Kermisch (2020)). Another definition is related to a large number of possible outcomes which cannot be known and to which, sometimes, no likelihood measured by probabilities that a certain event occurs can be associated (HMT 2007 in Watkiss, Hunt, Blyth, and Dyszynski (2015)). In 1921, Frank H. Knight distinguished risk from uncertainty, the first being the quantifiable uncertainty and the second being *"incalculable and uncontrollable"* (Marchau et al. (2019), page 6). The *incalculable and uncontrollable* character of uncertainty could be explained by the fact that human beings may be unable to imagine, visualise and predict the infinity of possible events that they may have to face. Illustrative for such surprises that we do not see coming include the 2008 world economic crisis and the impacts from the global epidemic outbreak in 2020. Forrester (1971) deems *"Evolutionary processes have not given us the mental skill needed to properly interpret the dynamic behavio[u]r of the systems of which we have now become a part."* because our *"Social systems belong to the class called multi-loop non-linear feedback systems. In the long history of evolution, it has not been necessary for man to understand these systems until very recent historical times."* (Forrester (1971), page 3).

Even if information was complete, G. Morgan, Henrion, and Small (1990) argue, uncertainties may arise *"because of simplifications and approximations introduced to make analy[s]ing the information cognitively or computationally more tractable. As well as being uncertain about what is the case in the external world, we may be uncertain about what we like, that is about our preferences, and uncertain about what to do about it, that is, about our decisions. Very possibly, we may even be uncertain about our degree of uncertainty. The variety of types and sources of uncertainty, along with the lack of agreed terminology, can generate considerable confusion"* (G. Morgan et al. (1990), page 47).

To tackle this confusion, human beings have learnt how to live with uncertainties and developed heuristics, strategies, technologies and institutions to make decisions in their presence. G. Morgan et al. (1990) wrote that *"Historically, the most common approach to uncertainty in policy analysis has been to ignore it."* (G. Morgan et al. (1990), page 43). According to Marchau et al. (2019) ignoring (deep) uncertainties is *"attractive"* (Marchau et al. (2019), page 4), because even under the best circumstances decision-making is made difficult enough by budget constraints, conflicting stakes and political turmoil. These authors recognise that common strategies and heuristics developed to deal with uncertainty do not always yield good outcomes because when our *"cognitive processes for dealing with uncertainty introduce error or bias into our judgements we are often unable to detect the facts"* (G. Morgan et al. (1990), page 1).

The purpose of policy analysis is to evaluate, order and structure incomplete knowledge to enable decisions with as complete an understanding as possible (Morgan (1978) in G. Morgan et al. (1990)). Policy analysis is an analytical undertaking that intervenes in support of decision-makers in the private or public domain that need to make a decision or find answers to a given problem. According to G. Morgan et al. (1990) the lack of agreement on or the difficulty to choose among alternative paradigms and the prevalence of messy wicked problems make the selection of a criterion of what is *best* especially difficult. These authors provide three fundamental arguments about why uncertainties should not be ignored:

- ***Elicitation of uncertainties:*** *A central purpose of policy research and policy analysis is to help identify the important factors and the sources of disagreement in a problem, and to help anticipate the unexpected. An explicit treatment of uncertainty forces us to think more carefully about such matters, helps us identify which factors are most and least important, and helps us plan for contingencies or hedge our bets.*
- ***Multiple world views and uncertainty of judgement:*** *Increasingly we must rely on experts when we make decisions. It is often hard to be sure we understand exactly what they are telling us. It is harder still to know what to do when different experts appear to be telling us different things. If we insist they tell us about the uncertainty of their judgments, we will be clearer about how much they think they know and whether they really disagree.*
- ***Dynamics:*** *Rarely is any problem solved once and for all. Problems have a way of resurfacing. The details may change but the basic problems keep coming back again and again. Sometimes we would like to be able to use, or adapt, policy analyses that have been done in the past to help with the problems of the moment. This is much easier to do when the uncertainties of the past work have been carefully described, because then we can have greater confidence that we are using the earlier work in an appropriate way.*

Other authors report the importance of acknowledging uncertainties and complexity in decision-making in order to make decisions more rigorous, robust and *"democratically accountable"* (Stirling (2010), page 1). Scholars also developed methodologies to support decisions under deep uncertainties that cannot be reduced, and that are characterised by the fact that they cannot even be identified (Marchau et al., 2019).

1.1.2.2 Uncertainties and climate change

The climate change research offers an illustration for policy making and research in dealing with uncertainty. Hallegatte, Shah, Lempert, Brown, and Gill (2012) affirm that *"climate change is a fantastic example of "very deep" uncertainty – with plenty of competing viewpoints and values, no clear probabilities within any of them, and highly interrelated decision series over time"* (Hallegatte et al. (2012), page 4). For these authors deep uncertainties are characterised by the extent of at least one of the subsequent elements, partly overlapping with Morgan and Henrion's criteria above and which prominence confer their *"deep"* character:

- *Knightian uncertainty: multiple possible future worlds without known relative probabilities; (Knightian uncertainty being aleatory or epistemic that cannot be reliably quantified).*
- *Multiple, divergent but equally-valid world-views, including values used to define criteria of success; and*
- *Decisions which adapt over time and cannot be considered independently.*

The challenges of climate change are related to its magnitude and the partial knowledge that exists about physical processes underlying this transformation but also to the possible impacts and risks to societies (Marchau et al., 2019). Similar to Forrester (1971) expression about the social systems, the Earth system is also a multi-loop non-linear feedback system that is not entirely understood and which makes projections and anticipatory responses difficult. Linear, but also non-linear changes can possibly be expected. Gradual changes are for example temperature increase, sea level rise, melting of glaciers, increase in length of the growing seasons, increase in precipitations and extreme events such as cyclones or drought periods and heat waves. S. Dessai and van de Sluijs (2007) also provide examples of abrupt changes: these are the possible strong reduction or even shut down of the so-called thermohaline circulation in the oceans which could lead to a cooling of North and North-West Europe, melting permafrost and massive emissions of the greenhouse gas (GHG) methane. Ultimately, this may cascade down to the disintegration of the West Antarctic Ice Sheet or to strongly increased melting of the Greenland Ice Sheet and several meters of sea level rise in the long term (S. Dessai & van de Sluijs, 2007). Such climatic regime shifts result from achieving what has become known as tipping points, which are unknown critical values of tipping elements at which the system is qualitatively changed. Tipping points are known to trigger the system – under certain circumstances to another qualitatively different state by small perturbations (Lenton, 2011). Various tipping points can also be reached concomitantly which cause domino effects across systems (Lemoine & Traeger, 2016). Such events have traditionally been viewed as high-impact low-probability events which were neglected because the probability of occurrence is low enough to consider it would unlikely happen. For example, the Intergovernmental Panel on Climate Change (IPCC) climate scenarios have been based on central distributions, ruling out *"the medium confidence that global mean sea level rise will not exceed the likely range by several tenths of a meter of sea level rise during the 21st Century"* (Hinkel et al. (2015), page 188). Recent research provides evidence about increasing likelihoods of tipping points which increase the probability of other being triggered – climatic or non-climatic – concomitantly causing domino effects (Lemoine & Traeger, 2016) and about the importance of fat tails, extreme outcomes and corresponding impacts in economic analysis (Hinkel et al., 2015; Lemoine & Traeger, 2016; Pindyck, 2010). In fact, at a given probability – be it low – there is at least a possibility of those extreme outcomes to occur and it is necessary to know what exact risk the society is willing to take (Hinkel et al., 2015).

Climate change has probably also been the most recent impetus for putting uncertainty on top of research agendas. This occurred through the attempt by scientists to divulgate alternative decision tools that put more emphasis on robust decisions in front of the possible realisation of multiple scenarios rather than on decisions based on predictions. According to Watkiss et al. (2015) there has been a need to complement traditional economic appraisal methods such as CBA to better account for and embrace deep uncertainty. This may be achieved with frameworks that allow to anticipate rather than to predict uncertainty (Marchau et al., 2019). For instance, methods proposed include robust decision-making (Hallegatte, 2009; Lempert, 2002), the real options (Scandizzo, 2012) and stochastic modelling (Abadie, Chiabai, & Neumann, 2019; Galarraga, Sainz De Murieta, Markandya, & Abadie, 2018), iterative risk management (Watkiss et al., 2015) but also dynamic adaptive policy pathways which allow for monitoring and adjustments as new information arises (Haasnoot, Kwakkel, Walker, & ter Maat, 2013). The growing literature on these methods occurred parallel to an evolution from *science-first* towards *policy-first* approaches that mainstream climate change into the project cycle thus putting more emphasis on the decision problem and being more user-bound (Ranger, 2013). This development has also brought to light the relevance of deliberative decision-making methodologies which enable multiple world visions to be expressed thus expanding the range of possible scenarios considered and facilitating the acceptance of decision implementations through democratic participation (Wegner & Pascual, 2011). This represented a breakthrough, in that traditional approaches that tend to grant overconfidence in consensus and underexpose scientific dissent, moved to promoting deliberative models in which the diversity of voices, ambiguity and ignorance are acknowledged (Sluijs, Est, & Riphagen, 2010; Stirling, 2010). These evolutions were likely also conditioned by the different demands for policy guidance. Thus, S. Dessai and Hulme (2004) argued that the interest in understanding risk and likelihood of climate scenarios grew as a priority due to the role of climate predictions in guiding adaptation and mitigation policies. A move to embracing uncertainty may have been enabled by the increasingly used concept of resilience, which is according to Carl Folke et al. (2010) about coping with uncertainty in all ways.

1.1.3 Adaptation

Throughout history the irregularities of climates and the insecurities it has engendered have played a major role in motivating social and technological innovation (Young, Walker, Dixon, & Walker, 1989). To that extent, uncertainties may have also been a trigger to adaptation. Adaptations are therefore not new but "its analysis in the climate change domain emerged with the growing awareness of climate change itself" (Smit and Wandel (2006), page 284).

Physiologists for example have studied how animals react to and cope with environmental challenges. Young et al. (1989) defined physiological adaptation as a modification in the animal's behavioural or metabolic responses, resulting from an event that improves the ability of the animal to cope with a subsequent challenge. Smit and Wandel (2006) report that many definitions of adaptation have been proposed in natural sciences but that they broadly all refer to *"the development of genetic or behavioural characteristics that enable organisms or systems to cope with environmental change in order to survive and reproduce"* (Smit and Wandel (2006), page 283).

In human-related systems of global change, adaptation has been used to define actions, processes or outcomes in response to changing conditions of those systems or their environment and that enable humans, households, societies, countries or regions to cope, readjust and live with new challenges or opportunities (Smit & Wandel, 2006). In the context of climate change, according to R. A. Pielke (1998), *"Adaptation refers to adjustments in individual, group, and institutional behavio[u]r in order to reduce society's vulnerabilities to climate"* (R. A. Pielke (1998), page 159). However, according to R. Pielke, Prins, Rayner, and Sarewitz (2007) definitions have not been straightforward and different interpretations of what climate change and adaptation refer to resulted in confusing decision-makers and ultimately limiting implementation. R. A. Pielke (1998) argued that different approaches to adaptation arose as a result of different visions of the core institutions that guide climate policy, that is, the United Framework Convention on Climate Change (UNFCCC) and the IPCC. Similarly, Smit and Wandel

(2006) provided a detailed analysis about how the different articles of the Convention proposed complementary entry points to adaptation. As an example, the authors show that a first group of studies heavily relied on climate and socio-economic scenarios to forecast possible futures which was adapted to the then concomitant predict-and-optimise decision-making tools. Scholars from this line of thought sought to address Article 2 of the UNFCCC by developing top-down approaches using climate projections as an input to integrated assessments and global general equilibrium models which were then applied for drawing decisions at local levels. In these models, the role of adaptation was marginal to the extent that it served to explain the degree to which it could moderate or cancel out negative climate impacts or increase potential positive effects, to avoid the climate threat (Smit & Wandel, 2006). In contrast, other scientists moved from questions about *which* adaptation and *for whom*, to *how* it should be implemented, in *which* way and *by whom*. Academics from this line of thought took more pragmatic bottom-up approaches that helped identifying how to plan and design adaptation (Wilby, Robert & Dessai, 2010). Vulnerabilities, adaptive capacities and exposures are usually not assumed by the researcher in these studies. Rather they are empirically elicited from communities which knowledge and need is recognised. Thus these are made central actors of decision-making processes (Smit & Wandel, 2006).

In contrast to adaptation at equilibrium states, adaptation is recognised to most likely consist of transition processes and constant adjustments (Holling, 1973; Tol, Fankhauser, & Smith, 1998). In this context, it has evolved to refer to adaptive pathways and adaptive policy making (Haasnoot et al., 2013) based on iterative risk management (Watkiss et al., 2015) as well as to a combination of those (Haasnoot et al., 2013). Adaptive pathways explore possible interventions depending on an unfolding unforeseeable context. Adaptive policy making, instead, emphasises the monitoring and learning process of adaptation that leads to new action. These approaches are deeply rooted in different aspects of adaptation: the recognition of deep uncertainties in climate projections and the required flexibility to adapt to the unknown (Hallegatte, 2009), as well as the shift away from impact assessments towards policy-oriented studies (Downing, 2012; Watkiss, 2015).

However, O'Brien et al. (2004) argue that in the climate change community, adaptation has been usually regarded as a response to vulnerability as only conditioned by climate hazards, where in reality multiple stressors of global change are interacting. As described earlier, the definition of adaptation due to the very nature of the IPCC and the UNFCCC is constrained within the climate objectives of these institutions, which conditions the formulation of definitions and objectives (Adger, 2006). Following Cutter (2018), such a definition provides little space for broadening up interpretations. It is at risk of missing important information, especially in contexts in which climate is only one among multiple stressors that make livelihoods difficult (R. Pielke et al., 2007). Even if adaptation research has evolved to include other hazards and vulnerabilities not directly related to climate change such as equity, justice, governance and decision-making processes, there has been a growing awareness that restricted goals and values of adaptation also constitute its own barriers (R. Pielke et al., 2007). For example, in the context of environmental change, climate hazards have only timidly and lately been integrated with biodiversity or land degradation pressures although they were tightly linked topics developed under the same UN Earth Summit in 1992 (Sanz et al., 2017). Scholars that investigated major variables limiting adaptation found that these depend on societal factors like ethics, goals, values, relation to risk, knowledge and culture which are not immutable and can be overcome (Adger et al., 2009). Donald R. Nelson (2011) defends for example that adaptation has been brought up as a conservative process which does not allow to think *"outside of the confines of maintaining the status quo"* (Nelson (2011), page 116). According to the author, the concept has not been defined and developed in the context of a *pluralistic world* which hampers different worldviews to be expressed and to meet, enshrining the social inertia that disables humans to act. In addition, Nelson (2011) sustains that the overemphasis on the economic and market-based aspects of climate change and adaptation has long concealed non quantifiable losses and values which can undermine broader adaptation. Thus, adaptation decisions may fail to reach their objectives and increase vulnerability which has often been referred to as *maladaptation* (Barnett & O'Neill, 2010). Overspecialised adaptation for example in the climate hazard, the omission of the consequences of adaptation *downstream* with a lack of diversity in adaptation responses can drastically undermine adaptation at larger scales (Walker et al., 2006).

1.1.4 Sustainability

The concept of *sustainable development* emerged in the 1980's as a concept that sought to bridge the gap between increasingly visible ecological consequences of human activities and socio-economic concerns (Robinson, 2004). It has been popularised by the Brundtland Report *Our Common Future* in 1987 in which it is defined as development that *"ensure[s] [that] it meets the needs of the present without compromising the ability of future generations to meet their own needs"* (UN (1987), point 27). Ideas about sustainable development have since fed the environmental literature that questioned *if* and *how* to protect the environment.

While the concept has been useful to focus and attract to policy arenas concerns and inter-linkages among the environment, social and economic conditions, sustainable development has also been largely criticised on the grounds of different ideologies and values (Brown, 2011; Robinson, 2004). For some, sustainable development would bridge the gap between poverty and environmental issues, thus reforming the growth paradigm (Robinson, 2004). For others, sustainable development would promote *"green fakery"*, *"delusions"* and *"cosmetic environmentalism"* which called to a radical impulse from the development paradigm towards changes in behaviour, priorities and moral values to encourage sustainability (Robinson (2004), pages 374 and 375). This contested domain stems from the vague terms of sustainable development (similar to adaptation and resilience) that allow for multiple interpretations on various ideological grounds, spreading from promoting the status quo to more fundamental transformation (Brown, 2011; Robinson, 2004).

There have been similar disagreements in the climate change literature, where the notion of *"sustainable adaptation"* promoting synergies between climate adaptation and sustainable development was perceived as a paradox (Brown, 2011). As argued by Katrina Brown (2011) vulnerabilities to climate have most often been associated to poverty which led to mainstreaming climate adaptation activities within current development practice. However, the author wrote, this has been done (i) without questioning whether business-as-usual development practices could undermine adaptation (ii) without considering that adaptation practices may indeed be unsustainable or that sustainable development may attenuate climate responses and (iii) neglecting unknowns in the linkages between poverty alleviation and climate adaptation which make synergetic action difficult.

As developed in earlier paragraphs, adaptation to climate change appears to have evolved mostly disconnected from other environmental and socio-economic hazards, while in reality biophysical systems of which humans are an integral part are highly coupled. According to Folke et al. (2002) the implicit assumptions that human and natural system function independently has been a major error in policy making as regarding natural resource management. In such uncoupled systems, linkages are neglected which are core hubs through which vulnerability, adaptation and sustainability mechanisms are propagated. The lacking systemic approach focusing on the root causes of unsustainability may create undesired outcomes from adaptation for sustainability or from sustainability to adaptation (Brown, 2011).

Major sustainable development initiatives under the umbrella of the United Nations within which the *Rio Conventions* were developed may have helped in advancing towards the Millenium and Sustainable Development Goals (MDGs[1] and SDGs[2]). With hindsight however, there has also been growing recognition that the policies implemented to reduce persistent sustainability issues have failed and may even increase them (Weinstein et al., 2013). Sustainable development practices that society is increasingly promoting is essential, but, as Sterman states in Weinstein et al. (2013), *"[M]ost efforts in the name of sustainability are directed at symptoms of unsustainability rather than causes"* highlighting a *"widespread failure of system thinking"* (Weinstein et al. (2013), page 4). Although resilience has more recently emerged as a concept that integrates system dynamics, comparable debates to those in the sustainability and adaptation communities surfaced, based on unmeasurable moral, political and epistemological beliefs of scholars within the different research communities (Olsson, Jerneck, Thoren, Persson, & O'Byrne, 2015).

1.1.5 Resilience

With the increased recognition that humans are a main driving force of ecosystem dynamics, resilience entered the research and policy forum as a new concept that refers to the complex interactions between systems and their own sub-elements (Gallopín, 2006). Promoted by international disaster risk reduction frameworks, the concept of

1. https://www.un.org/millenniumgoals/
2. https://sdgs.un.org/es/goals

resilience has gained momentum in several sectors (Cutter, 2018) and sustainability debates (Gallopín, 2006). In this context it has also become normative, in that it has increasingly been used in policy making as a criterion to stimulate fund allocation and project implementation (Olsson et al., 2015).

Resilience is usually referred to as the ability of a system to absorb perturbations and maintain or recover its functions after a shock. The concept was introduced by (Holling, 1973) in ecological science before being extended to various domains such as psychology and engineering. One of the most influential studies since, defines resilience as *"the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks"* (Walker et al. (2006), page 3). There are in reality a multitude of definitions of resilience. However, the lack of a transdisciplinary definition has often been viewed as being a major weakness for implementing resilience because it requires standardisation in view of measurements and comparison (Gallopín, 2006; Juan-García et al., 2017).

For some, the resilience concept broadens the idea of adaptation, to account for system dynamics, interaction and feedback (Nelson, 2011), unexpected conditions of low probability/high impact events (Butler et al., 2014) and overcome (deep) uncertainties (Juan-García et al., 2017). For others, resilience is part of adaptation processes (Gallopín, 2006). Beyond embracing different definitions, the different resilience perspectives have emerged in the context of research and policy traditions that have been contingent on and shaped by specific epistemological beliefs (F. Miller et al., 2010; Olsson et al., 2015). Some scholars develop the argument that resilience theory, as deployed by the natural scientists, is implicitly based on a conservative understanding of a structured society, in which social change is slow because shared values, order and stability are the *good norm* (Olsson et al., 2015). At the opposite, social scientists draw upon conflict theories in sociology viewing the social order as a result of tensions between different interests, inequality, power and agency and the reversal of the established social order (Olsson et al., 2015). This motivates the debate around transformation as a means for resilience. In fact, one of the main contradictions is the boundary of transformation which Walker et al. (2006) had already referred to as the same *"basin of attraction"* vs. *"new landscapes"* (Walker et al. (2006), page 2). Changes can occur within a system near a unique equilibrium with altered functionalities – the natural science perspective. Changes can also occur outside of a system implying shifts among various equilibria and deep transformations of the social and legal systems – the social science perspective (Olsson et al., 2015). For example, engineering resilience refers to the property of returning to equilibrium after a shock while ecological resilience conceptualises resilience as an aptitude to navigate between a multitude of equilibria within "basins of attraction" (Holling (1973), page 20). This is because engineered systems aim at providing a specific function through the consolidation of various elements that work together. In the wastewater sector for example, resilience translates into water utilities' duty of maintaining service to its customers. In ecological resilience instead, a system can move from an equilibrium to another without disturbing its functions, or forcing dependent elements to adapt to transformational driving forces.

To date, the choice of *"muddling through"* as a strategy for decision-making (Neumann, Rieckermann, Hug, & Gujer, 2015) has been conditioned, according to Folke (2006), by the single equilibrium view in mainstream ecology and resource management. According to Watkiss (2015) this was also due to the predominance of the *predict-and-optimise* approach in decision-making discussed earlier. Holling (1973) argued that equilibrium states do not necessarily translate to resilient ones, and that resilience may also be the result of instability. F. Miller et al. (2010) defend that analysts of vulnerability and those of resilience theory have kept synergies *"artificially separate by conceptual constructs, scientific traditions, and lack of interaction between the two academic communities involved"* (F. Miller et al. (2010), page 1). Ultimately, resilience is not an objective per se, but serves to uphold performance of a system by fine-tuning its properties, for example robustness and flexibility (Butler et al., 2014). Broadly, it could be interpreted as a set of symbiotic properties, that together, support performance of a system even under stress and perturbation. In the wastewater sector for example, resilience is also thought to be a useful concept for the paradigm shift from the *"fail safe"* to the *"safe to fail"* culture (Butler et al., 2014).

Such discrepancies in world perceptions and the persistence of epistemological beliefs make dialogue difficult where it should contribute to enhance it (Olsson et al., 2015). If global challenges are given a chance to be overcome, F. Miller et al. (2010) argue, methodologies need *"to be better at identifying convergence, seeking collaboration to advance integrated social-ecological knowledge, and building on the strengths from different fields"* (F. Miller et al. (2010), page 1).

1.2 Summary of research gaps

1.2.1 Research gap 1: beyond costs and benefits

Although adaptation is a human behaviour inherited from evolution, the transition of adaptation to climate change from a passive towards an active approach as one more concept to guide policy (Schipper, 2004) brought with it additional challenges: one of the reasons is firstly, because there are already underlying multiple pressures that render human organisations more vulnerable. For example, agricultural systems are under pressure of strong demographic growth that drives higher food demand and land (FAO, 2016), as well as environmental degradation ((EEA, 2015). Secondly, because climate change is prospected to be unprecedented and non-stationary (Milly et al., 2008) which links to deep uncertainties that are difficult to deal with in decision-making. Thirdly, there are several problems with estimating adaptation costs and benefits (Wreford & Renwick, 2012). Examples include the definition of adaptation which is not always straightforward (McGray, Hammill, Bradley, Schipper, & Parry, 2007) and the impossibility to predict probabilities of future climate impacts that would allow planning (S. X. R. Dessai, 2005). Estimating costs of adaptation also involves the application of economic tools on poorly understood systems of biophysical change (Almagro et al., 2016) that have their own strengths and limitations.

Despite the wide recognition of these shortcomings, costs and benefits remain widely considered to be of value and a prerequisite in investment decisions in the environmental realm. Naturally, questions arise about how to find conciliation between the requirements of existent decision-making environments and tools on the one hand and the complexity of environmental change on the other hand. Such a conciliation would facilitate decision-making. More precisely, the question arises as to whether the cost and benefit information base for adaptation can be extended to inform decision-making.

1.2.2 Research gap 2: improving the information base to reduce uncertainties

The cost-benefit model remains an attractive and widely employed economic tool in investment decision-making. However, in face of deep uncertainties and the increasing recognition of complexity, there has also been a growing interest in alternative evaluation tools that enable to better model the reality of uncertain investment contexts and account for plurality (T. R. Miller et al., 2008; Wegner & Pascual, 2011). This is also the case for investment appraisals in developing country contexts where more acute data scarcity renders its application difficult (van Pelt, 1993). Here, the question arises about whether improving the economic knowledge base enables to reduce uncertainties and ground the legitimacy related to the application of the CBA for the purpose of adaptation investments in developing countries.

1.2.3 Research gap 3: revealing complexity in CBAs and introducing flexibility

When undertaking traditional CBA, policy analysts are required to predict the future evolution of parameters such as climate impacts or prices. For this reason, when a decision is taken upon CBA-based recommendations, the decision usually assumes it will not change over the project's lifetime. However, deep uncertainties and the limits to predictability have more recently come to challenge traditional decision-making tools (Marchau et al., 2019). Regardless of the possibilities available to reduce the information gap, and despite its strengths, the traditional deterministic cost-benefit model may be difficult to reconcile with real world investment situations in which uncertainty and unexpected events that are impossible to predict play a crucial role. According to Hull (2009) and Nordhaus (2011), the calculation of the NPV which is based and depends on the prediction of future costs, benefits and possible climate or socio-economic impacts cannot hold anymore in such circumstances because it is either biased towards under- or over-investments. In reality, before an investment is realised, a decision-maker usually has the opportunity or the *"option"* to invest or not, or to invest now or later – with associated risks to each decision – depending on market circumstances and expected new information (Hull, 2009). The question is therefore whether revealing complexities and uncertainties in decision contexts for example through decision-tree illustrations can improve the cost-benefit model and the information base for decision-making.

1.2.4 Research gap 4: plurality as an opportunity for uncovering complexity

After adaptation, resilience has become a regulatory concept influencing investment decisions. On the one hand, as described earlier, the resilience concept implicitly refers to the complex interactions between systems and their own sub-elements (Gallopín, 2006). To that extent, it provides the opportunity to acknowledge complexity. On the other hand, resilience research and practice has encountered difficulties of implementation due to a lack of common understanding of resilience across disciplines. This was often imputed to the absence of a common definition of resilience which has been similar in the field of adaptation. The questions that arise here are firstly, how resilience can be used as a concept to reveal complexity in socio-economic systems. Secondly, whether a unique definition is necessary and whether using the multiple interpretations and understandings of resilience cannot be an opportunity to elicit the complexity of systems in a more integrative and holistic way.

1.3 Summary of research questions, materials and methods

In view to inform policy making in the domain of climate and environmental change more broadly, this thesis explores several research questions as follows:

1. How can cost and benefit-based decision-making tools on the one hand and the complexity of environmental change on the other hand can be conciliated to enhance decision-making?
   (a) More precisely, this thesis explores if and how the cost benefit information can be expanded on the basis of a broader view of adaptation, drawing upon similar research in the biodiversity and soil degradation research domain that have common grounds, yet are rarely considered jointly.
   (b) This thesis also investigates whether expanding the cost and benefit information base as a legitimate strategy to reduce uncertainties enables to justify the use of the CBA applied to climate adaptation and especially, if it can be used to draw policy recommendations.
2. Is the improvement of the data/information base enough to make the cost-benefit model more legitimate? Are decision trees useful in embracing complexity instead of inhibiting it while also being better accepted?
   (a) To extend the previous analysis, it is further investigated whether the cost-benefit model can be extended to incorporate more complexity and uncertainty in decision-making, especially those related to the climate impacts and the price fluctuations.
   (b) Throughout the previous chapters a core question has emerged. If the cost-benefit analysis is not an appropriate model for contexts of deep uncertainty, how then enhance and complement the capacity to generate information as a support for decision-makers?

To answer question 1 (a), Chapter 2 of this thesis (Tepes, Galarraga, Markandya, & Sánchez, 2021) provides a literature-based economic inventory of sustainable land management (SLM) techniques at the farm level. It does so by making the case for SLM measures as adaptation strategies for the agricultural sector, while bridging land and soil degradation to the climate change literature. The choice of the farm level analysis is relevant to provide cost and benefit estimates as experienced by farmers in the real world, thus avoiding abstract and biased conceptualisations of adaptation action. This chapter has been developed as part of the EU FP7 ECONADAPT Project under the Working Package 3 on costs and benefits of adaptation.

To answer question 1 (b), Chapter 3 develops a CBA for adaptation investment decisions in a developing country context. Specifically, a cost-benefit model for climate adaptation investment is undertaken in clove plantations of Zanzibar (United Republic of Tanzania). Clove plantations are characterised by uncertainties due to the nature of the agroforestry systems in which clove trees grow and the climate change impacts for the region that remain unclear. To do this, insights into the Zanzibar country and clove sector contexts are provided, as well as the conceptual and methodological framework used for the consideration of uncertainties in the assessment of adaptation options. This chapter was developed as part of the EU FP7 ECONADAPT project Working Package 9 on International Development. The material for this study was collected in close collaboration with the Department of Forestry of the Ministry of Agriculture, Forestry and Natural Resources of Zanzibar during two field missions carried out in January and June 2016. It is a product from local stakeholder workshops organised for the development of the UK-funded Climate Change Action Plan of the Revolutionary Government of Zanzibar in the context of the Zanzibar Climate Change Strategy. This included 20 semi-structured interviews with main actors of the clove sector and clove farmers on the archipelago.

To elaborate on questions 2 (a), Chapter 4 extends the CBA to decision trees in order to reveal complexity and test whether such a support tool can complement cost assessment through more transparent illustration of model assumptions or otherwise hidden information. This is an illustrative tool that aims at divulgating information and making it more accessible to non-expert communities.

To investigate question 2 (b), Chapter 5 (Tepes & Neumann, 2020) moves from the adaptation concept from a purely climate perspective to investigate a more integrative resilience view applied to the wastewater sector, in which multiple stressors and adaptations are allowed for. If many argue that resilience implementation – as adaptation action before – is hampered because a common definition is missing across domains, a more holistic approach is presented here: this chapter captures multiple perspectives of resilience by eliciting and comparing cognitive maps of diverse agents both from within as well as external to a wastewater utility. Fuzzy Cognitive Mapping (FCM) is used as a practical tool to elicit subjective views on resilience mechanisms and illustrate the methodology in co-production with professionals from the wastewater sector in the Belfast area (Northern Ireland). This study has been developed as part of the EU H2020 ALICE RISE Project during a 10-months secondment at Northern Ireland Water (NI Water) in Belfast (Northern Ireland).

1.4 Main hypotheses

The research undertaken within this thesis is founded on three overarching hypotheses:

1. Uncertainties, as an aspect of complexity, represent a challenge for traditional project appraisal tools which may be a limitation to climate adaptation, sustainability and resilience implementation.
2. Human-environment systems and dynamics require system- and holistic thinking that acknowledge and embrace complexity.
3. Resilience and adaptation are about managing change. Although the scope for climate adaptation can be opened-up, in this thesis it is assumed that the concept of resilience as it emerged in different research and policy contexts, widens the system boundaries of adaptation and provides a more pluralistic approach into environmental and response change.

1.5 Thesis structure

Against this vast and intricate background in adaptation, sustainability and resilience research and practice, this thesis provides insight into three different available tools for decision-support and investigates if and how policy decisions may be better informed in the realm of environmental change under uncertainties. These methodologies include the CBA, decision-tree analysis and cognitive mapping. As illustrated in 1.1, this thesis is divided in four core chapters that encompass visions mostly related to climate change economics (Chapter 2 and Chapter 3), approaches that attempt to illustrate uncertainty and complexity to support decision-making (Chapter 4) and more pluralistic and integrated views of adaptation (Chapter 2) and resilience (Chapter 5).

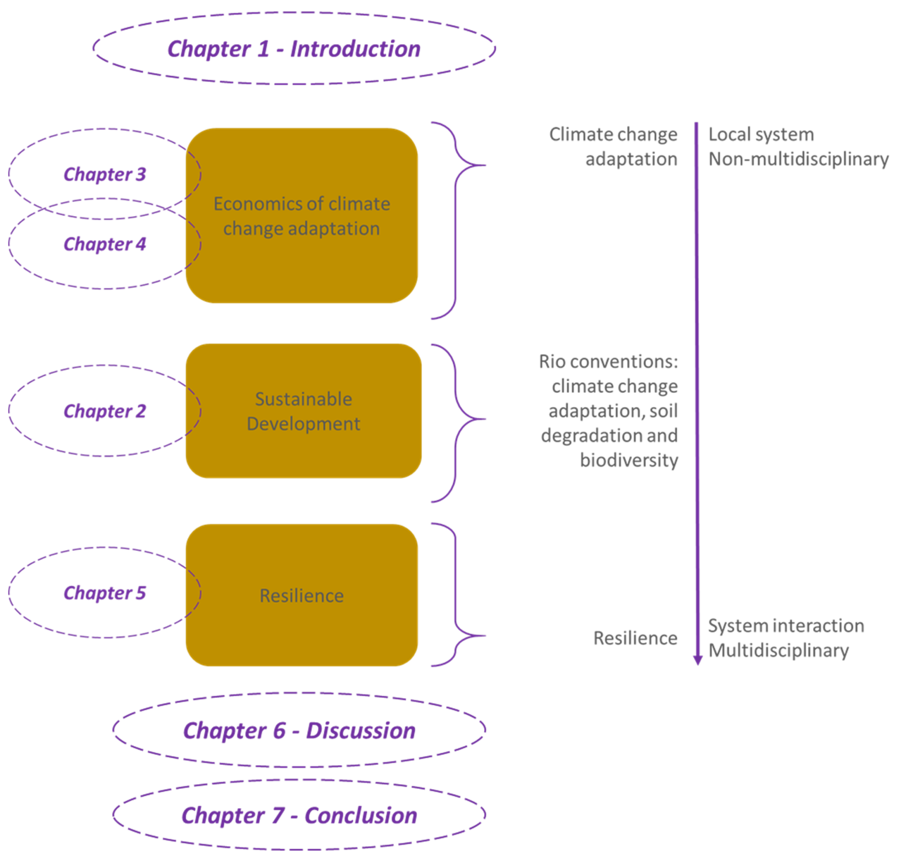

Figure 1.1: Framework and scope of thesis chapters

After the termination of this introduction, Chapter 2 explores costs and benefits of adaptation in the agricultural sector looking at adaptation activities that are common to the three Rio Conventions in the domain of land degradation, biodiversity and climate change. Chapter 3 presents a cost-benefit model for climate change adaptation in Zanzibar's clove plantations investigating what adaptation measures are economically sound, based on projected climate impacts in the region. As an extension, Chapter 4 explores how the cost-benefit model can be supported and combined to backward looking decision diagrams to include and most importantly illustrate and visualise uncertainty and flexibility to support decision-making processes. Finally, Chapter 5, enlarges the climate adaptation perspective by exploring multiple perspectives and mechanisms of resilience and vulnerability applied to the wastewater sector. Chapter 6 discusses key points and enlarges perspectives of decision-making under uncertainty. Chapter 7 concludes and suggests pathways for future research.

Chapter 2

Costs and benefits of soil protection and sustainable land management practices in selected European countries: towards multidisciplinary insights

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2.1 Introduction

Soil degradation means physical and chemical perturbations of soils which alter the fine-tuned balance of their biodiversity and ecosystem functioning (Bardgett & Van Der Putten, 2014). Soil degradation has been shown to decrease soil fertility and agricultural productivity. This has cascading effects in reducing crop quantity and nutrient values, and in the deterioration of other ecosystem services including food security, human health and wellbeing (Blum, Zechmeister-Boltenstern, & Keiblinger, 2019; Brevik & Burgess, 2014; European Commission, 2020a, 2020b; Lal, 2009; Mills et al., 2019; Montanarella et al., 2015; Penuelas, Janssens, Ciais, Obersteiner, & Sardans, 2020; Rojas, Achouri, Maroulis, & Caon, 2016; Veerman et al., 2020; Wall, Nielsen, & Six, 2015; Zhu et al., 2019). Such impacts are reported to affect human fertility (Hauser et al., 2015), the gut microbiome (Blum et al., 2019), endocrine and auto-immune disorders (Di Nisio & Foresta, 2019; Gore et al., 2015) and cognitive development (Gilbert, O'Shaughnessy, & Axelstad, 2020; Riché, 2021).

Although soil degradation is *"not well monitored, and often hidden"* (European Environment Agency (EEA), 2019), information available for Europe suggests that healthy, fertile soils continue to be lost. Drivers of soil degradation are not forecast to change favourably in the future, so these trends are likely to continue unless there are appropriate interventions (European Environment Agency (EEA), 2019). In addition, there are reports of weak remediation strategies for protecting soil resources in the European Union. This is due both to a lack of binding regulations (European Environment Agency (EEA), 2019; Paleari, 2017) and the absence of strong coordination of soil protection policies among Member States (Ronchi, Salata, Stefano Arcidiacono, Piroli, & Luca, 2019).

Soil degradation is a natural process that stems from and results in soil erosion through wind and water, loss of soil organic carbon, nutrient imbalance, acidification and salinisation (Lal, 2015; Paleari, 2017). However, there are also substantial human drivers of soil degradation. Modern agriculture appears to have made soils more vulnerable through a number of practices: deforestation (Perugini et al., 2017; Pinheiro Junior, Pereira, de Souza O Filho, & Beutler, 2019; Salvati, Sabbi, Smiraglia, & Zitti, 2014), excessive ploughing (Sándor et al., 2020; Sutinen, Gustavsson, Hänninen, Middleton, & Räisänen, 2019), annual monocultures (Crews, Carton, & Olsson, 2018), inappropriate fertilisation and nutrient imbalance (EUROSTAT, 2020; Guo, Han, Li, Xu, & Wang, 2019; OECD, 2020; Savci, 2012; Sun, Zhang, Guo, Wang, & Chu, 2015), inappropriate use of heavy machinery (Bennett, Roberton, Jensen, Antille, & Hall, 2017; Pijl et al., 2019; Shah et al., 2017), inadequate irrigation technologies (Kharche, Dongare, Patil, & Katkar, 2017; Osman, 2018), intensified production (Montanarella, 2007) and other land use intensification interventions (Paul, Techen, Robinson, & Helming, 2019; Tsiafouli et al., 2014). This is a matter of concern given the shift that might be required towards plant-based diets (Willett et al., 2019) for an increasing global population and combined climate change effects (IPCC, 2019). Together, these factors intensify the pressures on non-renewable soils (Amundson et al., 2015; Montanarella et al., 2016; Smyth & Dumanski, 1993).

Because it is human driven, agricultural practice may also provide an opportunity to avoid and reverse soil degradation and minimise its effects on food security and its feedbacks into climate change (IPCC, 2019). Soil protection practices such as reduced- or no tillage, mulching and soil covers, de-compaction, vegetated buffer strips and crop rotations have been widely used for this purpose. In Europe, these measures re-gained popularity with the approval of the Thematic Strategy for Soil Protection in 2006, which formally recognised the significance of soil degradation for European economies. Also referred to as sustainable soil management, conservation agriculture, smart agriculture, nature- or ecosystem-based solutions, such practices have been the focus of several initiatives, for instance the *Global Soil Partnership* (Montanarella et al., 2016) and the *EU mission on soil health and food* in preparation for *Horizon Europe* research and innovation programmes starting in 2021 (Veerman et al., 2020). Under the heading of SLM, they have also been widely promoted as a fundamental response to common objectives of the Rio Conventions (Akhtar-Schuster, Thomas, Stringer, Chasek, & Seely, 2011), and as a catalyst for meeting several SDGs (Keesstra et al., 2016; Sanz et al., 2017).

Soil protection practices are generally considered as desirable actions and an appropriate approach to prevent, reduce and reverse soil and land degradation (Sanz et al., 2017). These practices and policies aim to maintain the long-term productivity of ecosystems through integrated management of soils, water, vegetation and biodiversity within their specific biophysical and socio-economic contexts (Smyth & Dumanski, 1993). By doing this, such systems are sometimes reported to address climate change adaptation objectives for the agricultural sector, assuming that by increasing the quality of soils or by limiting their depletion they will make soil systems less vulnerable and more resilient to external shocks than they would be with no action (Sanz et al., 2017; Watkiss et al., 2015). Soils are also seen as large carbon reservoirs that are able to buffer carbon emissions from land use (Almagro et al., 2016; IPCC, 2019). Some authors report that soil protection measures may limit climate impacts on water security (Eekhout & de Vente, 2019) and set grounds for future resilience (Hallegatte, 2009; Ranger & Garbett-Shiels, 2011). In addition, the inherent flexibility of soil protection practices, for example by varying crops or planting times, is also considered to make such measures robust and desirable for future uncertain conditions (Adger & Vincent, 2005). However, despite the announced advantages of soil protection measures, academic literature shows ambiguous results as to whether they are effective at reducing impacts from extreme weather events (Martínez-Mena et al., 2020) and further adaptation is likely to be needed in such cases (Dilling, Daly, Travis, Wilhelmi, & Klein, 2015; Eekhout & de Vente, 2019).

Technical and conceptual debates on soil protection practices are ongoing, but the knowledge obtained to date about the socio-economic aspects of soil protection practices is equivocal. On the one hand, society as a whole bears larger costs than individual communities where degradation occurs (Nkonya, Mirzabaev, & von Braun, 2015). On the other hand, the scale of soil degradation costs or protection benefits for society will not be realised unless protection translates in practice into a willingness by farmers to implement such practices in their day-to-day activities (Emerton & Snyder, 2018). This highlights the need for farm level investment information to appropriately orientate economic incentives, especially for Europe, a region for which economic data on soil protection practices is relatively scarce. Some scholars, for instance Giger, Liniger, Sauter, and Schwilch (2018) find that *"a wide range of existing SLM practices generate considerable benefits"* (Giger et al. (2018), in abstract). In particular, the climate change community often refers to such soil protection practices as no-regret measures for the agricultural sector, which assumes that they are economically viable under all circumstances, including under climate change (Klik & Eitzinger, 2010; Watkiss et al., 2015). However, agricultural economists have found that the profitability of soil protection practices depends on the region under study, on soil indicators, on the crops to which they are applied and on economic assumptions (Branca, McCarthy, Lipper, & Jolejole, 2011; McCarthy, Lipper, & Branca, 2011; Nkonya et al., 2011). There are several other factors that also drive farmers' decisions, for example risk perceptions and initial endowments, so profitability is not always an appropriate indicator for soil protection implementation (Emerton & Snyder, 2018). New, multidisciplinary approaches to soil economics have therefore become necessary (Brevik et al., 2015; Conacher, 2009; Emerton & Snyder, 2018) to provide a meaningful understanding of soil dynamics, relate it to other domains of interest (Riché, 2021), and embrace more coherent, more sustainable policy interventions.

To help address this ambiguity, this chapter sets out to provide and discuss quantitative and qualitative insights on existing economic information for selected soil protection practices in Europe based on a literature review process. To that end, it proposes a new multidisciplinary framework for the economics of soil protection that looks at soil protection practices as overlapping, interlinked elements that span the three *Rio Conventions*. Thus, different economic approaches to soil protection practices provide cost and benefit information from different perspectives, for instance from the domains of climate change, soil degradation and biodiversity. The initial expectation was that this heterogeneity and the associated particularities of each research stream would be of value for the chapter, so this diversity is used as a foundation for this approach. This information may provide support for researchers, practitioners and policy-makers and appropriately guide investment decisions for more sustainable agricultural practice (Emerton & Snyder, 2018).

2.2 Material and methods

2.2.1 Soil protection in European croplands

The geographical region studied was chosen on the basis of the context within which this work began, as part of the European FP7 project *ECONADAPT* on the economics of adaptation to climate change (ECONADAPT Consortium, 2015). This chapter reports on investigations into preliminary results from that project. This choice was also influenced by the relative scarcity of economic information on soil protection practices applied to developed countries. The regional coverage results from the availability of cost and benefit data on the selected soil protection practices for Europe. The focus was primarily on soil protection on croplands, but have also included some activities on mixed crop and grazing lands as summarised in Sanz et al. (2017). This was done to highlight the potential of soil protection in the European agricultural sector, the significance of agriculture and its direct links with crop production, food security and health.

2.2.2 Data

2.2.2.1 Background of the literature reviewed and data points

Data on economic costs were extracted from 26 documents covering a period up to the beginning of 2017. 13 of them were peer-reviewed papers and 13 were project-related studies, including a doctoral thesis with a detailed focus on economic aspects of soil protection measures in Germany (Brand-Sassen, 2004). The quantitative analysis was based on a total of 14 studies comprising 3 548 data points, out of which 1 338 (9 studies) provided information on average costs and benefits and 2 210 (14 studies) provided information on $BCRs$ in specific European countries and sites. The data were not sufficient to elaborate on other economic metrics. Detailed information on each study including the region of application, associated hazard and soil protection measures considered, the methodologies and economic metrics used and the number of data points extracted can be found in Appendix A.

Most of the documents from which quantitative and qualitative information was retrieved looked at soil degradation in Europe, with soil compaction and soil erosion through water, wind or tillage being the primary hazards addressed by 13 of the 26 documents under study. Three studies were directly linked to the European Thematic Strategy for Soil Protection (Kuhlman, Reinhard, & Gaaff, 2010; Rickson, Deeks, Posthumus, & Quinton, 2010; Van-Camp et al., 2004). Others were related to national or European projects (Le Bissonnais et al., 2003; Le Garrec & Revel, 2004; Riksen, Brouwer, & De Graaff, 2003; van den Born, de Haan, Pearce, & Howarth, 2000) or regulations such as the Water Framework Directive (Berbel, Martin-Ortega, & Mesa, 2010; Panagopoulos et al., 2014). Some studies examined diffuse water pollution and pesticide risks (Borin, Passoni, Thiene, & Tempesta, 2010; Buckley, Hynes, & Mechan, 2012; Sieber et al., 2010) and mitigation strategies through soil carbon sequestration (MacLeod et al., 2010). 7 of the 26 documents addressed climate impacts (de Groot et al., 2006; Koschel et al., 2005; Sutton, Srivastava, Neumann, Iglesias, & Boehlert, 2013; Sutton, Srivastava, Neumann, Strzepek, & Boehlert, 2013; Sutton, Srivastava, Neumann, Strzepek, & Droogers, 2013; Tröltzsch, Görlach, Lückge, Peter, & Sartorius, 2012; van den Born et al., 2000). Links between soil degradation or water scarcity and climate impacts were found in several of these studies, but only van den Born et al. (2000) explicitly quantified the interactions between soil protection and climate change induced soil degradation.

2.2.2.2 Private vs. social costs and benefits

This inventory focused primarily on private and on-site costs and benefits of individual farmers. For this reason, whenever subsidies for SLMs were accounted for in original studies (Brand-Sassen, 2004; Le Bissonnais et al., 2003; Rickson et al., 2010) they were considered as individual benefits to the farmer. Wider benefits and costs were also included when authors distinguished between financial and economic costs and benefits (MacLeod et al., 2010; Rickson et al., 2010). Financial information is typically provided from the perspective of an individual farmer while economic assessments include costs and benefits of soil protection for society as a whole. In the review of documents, the consideration of costs to society was not encountered (for example, subsidies for soil protection measures regarded as a social funding pool or an economic cost to society). Rather, (economic) benefits to society were sometimes included in the form of avoided off-site costs of soil degradation if a specific soil protection technique was implemented (for instance, avoided sedimentation in locations outside the site under study). Off-site effects of soil degradation, however, were usually difficult to assess and quantify or not accounted for. Health effects are a case in point (see Section 2.4.2).

2.2.3 Towards a multidisciplinary approach to costs and benefits of soil protection

The approach taken comprises a review in research domains that have usually been considered separately, for instance in climate change, biodiversity and soil degradation research (IPCC, 2019; Sanz et al., 2017). Information about economic metrics of soil protection measures was drawn together from research areas that spanned the three *Rio Conventions*, namely, the *United Nations Convention to Combat Desertification*, the *Convention on Biological Diversity* and the *UNFCCC*. Integrating research streams that were developed under the auspices of these conventions enabled to standardise cost and benefit estimates within the database. It also offered the advantage of capturing different but reciprocal aspects of soil protection techniques, as well as various cost and benefit indicators investigated by the respective research communities which did not necessarily overlap.

2.2.4 A semi-systematic literature review

Soil protection practices have been studied by many research groups in different disciplines, using different methodological approaches and conceptualisations. Such differences usually pose problems of standardisation, but here this diversity was used to undertake a semi-systematic literature review, as motivated by (Snyder, 2019). It combined a quantitative data analysis with a discussion on the equally important qualitative aspects of the information collected.

2.2.5 Literature review process: from identification of soil protection practices to data analysis

2.2.5.1 Identification of soil protection practices

In the context of the *ECONADAPT* project, soil protection measures were firstly identified as being core elements for climate change adaptation action in the agricultural sector. Secondly, the list of soil protection practices investigated in the literature was constrained to those most relevant to croplands by screening the studies available in the project's library for which quantitative economic information was available. Finally, the list of practices was iteratively adjusted through the review process as more information on the terminology and availability of costs and benefits came to light.

2.2.5.2 Literature review and data collection

Soil protection practices are the focus of different research domains addressing multiple hazards, but the literature available in the *ECONADAPT* library primarily highlights climate related impacts and response actions. Given the scarcity of cost estimates and the objective to collect as much data as possible, the research was extended to include the Google Scholar search engine. This enabled to consider a wider array of papers researching soil degradation and biodiversity that could provide suitable information on the economics of soil protection action alongside the perspective given by climate adaptation approaches.

Initially, keywords such as *"costs"*, *"benefits"*, *"Europe"*, *"climate change"*, *"adaptation"*, *"mitigation"*, *"land degradation"*, *"soil degradation"*, *"soil protection practices"*, *"sustainable land management"* were selected. During the search process, different options encountered in the initial screening process were also covered, accounting for some of their different names. Chain searches were conducted, looking at publications cited in previously identified articles. For shortlisting studies, a clear delimitation was set in the form of investigation of farm-level information which provided annual per hectare indicators on costs and benefits of soil protection measures that could be inserted into a database.

Both peer-reviewed papers and grey literature were considered, including government documents and deliverables on projects commissioned by national or supra-national institutions such as the European Commission, assuming that such platforms ensured quality control. Documents written in English, French and German were analysed.

2.2.5.3 Categorisation of soil protection practices

Different soil protection alternatives can have similar names and, inversely, a single name can include different techniques in practice. In the absence of a standardised nomenclature of options (Derpsch et al., 2014; Gonzalez-Sanchez, Veroz-Gonzalez, Blanco-Roldan, Marquez-Garcia, & Carbonell-Bojollo, 2015; Van der Kooij, Zwarteveen, Boesveld, & Kuper, 2013), analysis usually requires a categorisation of measures. Categorisations into "technology groups" have been undertaken elsewhere in the literature, for example by Smith et al. (2014) and in the World Overview of Conservation Approaches and Technologies database[1].

The 22 different soil protection practices selected are shown in Table 1: *"Agroforestry"*, *"Contour ploughing"*, *"Cover crops"*, *"Crop rotation"*, *"Crop varieties"*, *"Cultivation perpendicular to slope gradient"*, *"De-compaction"*, *"Direct tillage"*, *"Earth banks and swales"*, *"Erosion control programme / Multi-options"*, *"Fertiliser management"*, *"High density planting and narrow spacing"*, *"Intercropping and catch crops"*, *"Irrigation"*, *"Land use change"*, *"Mulch sowing"*, *"Reduced stocking density"*, *"Reduced tillage"*, *"Timeliness"*, *"Tramline management"*, *"Vegetated buffer strips"* and *"Zero tillage"*.

To facilitate comparison between studies, clustering was also used, which is a method for segregating data with similar characteristics into clusters that may already exist in the literature. Measures were first grouped into five main categories of practices: *"Soil management"*, *"Vegetation management"*, *"Infrastructure"*, *"Water management"* and *"Systems"* (Table 2.1). It was chosen to distinguish between small group-clusters (which included many practices related to the same group, for example, irrigation

1. `https://wocatpedia.net/wiki/Portal:SLM_Technology_Groups`

Table 2.1: Soil protection practice by category (soil, water or vegetation management, infrastructure or systems) **and cluster type** (cluster or single-practice).

Soil protection practice (Category)	**Cluster type**	**Terminology of soil protection measures included in the quantitative analysis**	**Other terms used in the reviewed literature and *not* included in the quantitative analysis**	**References {Study ID*}**
Soil management				
Cover crops	Group cluster	Cover crops; Geotextiles; Good agricultural practice (cover crops)	Cover crops during winter/under sowing maize/ in orchards; Crop residues; Vinamul layers; Stubbles during winter; Overwinter stubbles followed by spring crop; Overwinter stubbles followed by low input spring crop; Winter stubbles after unsprayed crop; Rye grass seeding between maize rows; Residue management; Crop residues; Soil coverage during winter period	[2] [4] [14] *(1**) (6)*
De-compaction	Group cluster	Choice of adequate wheels; Coarser seedbeds; press; Limiting wheel load; Low ground pressure tyres (avoidance); Plough (alleviation); Subsoiling; Tracked tractors (avoidance); Tyre pressure regulation systems; Specific anti-compaction measure	Anti-compaction measures; Crawler tractors; Low pressure tyres; Subsoiling (general); Subsoiling (targeted); Deep ploughing of tyre tracks	[1] [2] [4] [8] [14] *(26)*
Direct tillage	Single-practice	Direct tillage	Direct tillage; Direct drilling; Direct sowing	[2] *(6)*
Mulch sowing	Single-practice	Mulch sowing; Mulch sowing; Mulching	Mulch tillage	[2] [4]
Reduced tillage	Single-practice	Reduced tillage	Superficial autumn harrowing; Light harrowing in autumn; No autumn tillage; Conservation tillage; Spring ploughing; Minimum tillage; Conservation tillage	[4] *(1) (3)*
Zero tillage	Single-practice	Zero tillage	No-till; No tillage	[4] *(3) (6)*
Tramline management	Single-practice	Tramline management	*na*	[4]
Reduced stocking density	Single-practice	Reduced stocking density	*na*	[4]
Fertiliser management	Group cluster	Optimising fertiliser use	Application of Exogenous Organic Matter; Adopting systems less reliant on inputs; Avoided N excess; Nitrification inhibitors; Separate slurry/manure; Reduce N fertilizer; Plant varieties with improved N-use efficiency; Use composts and straw based manure; Use biological fixation for N-inputs;	[20] [21] [22] *(1) (3) (9)*
Systems				
Agroforestry	Single-practice	Agroforestry systems	*na*	[4]
Erosion control programme / Multi-options	Group cluster	Erosion control programme; Buffer zone and crop rotation	Different types of combined measures for example: minimum tillage and intercropping; Non-inversion or mulch tillage and cover crops; Conservation programme; Cultivation perpendicular to slope and no-till/mulch till	[18] [23] *(1) (6) (7) (10) (11) (13) (24) (26)*

Soil protection practice (Category)	**Cluster type**	**Terminology of soil protection measures included in the quantitative analysis**	**Other terms used in the reviewed literature and *not* included in the quantitative analysis**	**References {Study ID*}**
Vegetation management				
Crop rotation	Single-practice	Crop rotation	*na*	[4] [23]
Crop varieties	Single-practice	Crop varieties	Choice of crop variety and genotype; Species introduction (including legumes)	[20] [21] [22] *(3) (11)*
High density planting and narrow spacing	Group cluster	High density planting; Narrow spacing	*na*	[2] [4]
Intercropping and catch crops	Single-practice	Intercropping and catch crops	*na*	[2]
Timeliness	Single-practice	Timeliness	*na*	[4]
Vegetated buffer strips	Group cluster	Vegetated buffer strips; Buffer strips in arable areas; Buffers strips in farming areas; Buffer strips; Buffer zones; Field boundaries; Green belts; Planting and conserving hedges and trees; Riparian buffer strips; Riparian buffer zones; Rough grass margins; Vegetated barriers; Windbreaks, hedgerows and field barriers; In-field buffer strips; Shelterbelts	Uncropped fallow margins; Streamside corridors	[2] [4] [23] *(1) (15) (16) (17)*
Water management				
Contour ploughing	Single-practice	Contour ploughing	Contour cultivation	[4] *(1)*
Cultivation perpendicular to slope gradient	Single-practice	Cultivation perpendicular to slope gradient	*na*	[2]
Earth banks and swales	Group cluster	Earth banks ; Swales and sediment traps	Retention areas; Water storage on farmland	[4]
Irrigation	Group cluster	Irrigation of cropland; Conveyance improvement; Deficit and drip irrigation; (New) drainage; Irrigation management practice using surface water; Precision agriculture and conveyance improvement; Service cost recovery in irrigation; Brackish rainwater for irrigation; Waste water reuse	Extension services for irrigators; Farming irrigation services: centre-pivot; Farming irrigation services: drip; Farming irrigation services: set-sprinkler; Strict water abstraction control; Subsoil drainage; Terracing; Wetting farmland: periodical wetting; Wetting farmland: structural wetting	[1] [4] [10] [11] [12] [19] [20] [21] [22] *(3) (9) (25)*
Infrastructure				
Land use change	Group cluster	Conversion of arable land: extensive cow husbandry; Decommissioning (low productivity Areas); Leasing; Extensive grass	Recreating grassland	[2] [4] *(1) (6)*

*References (Study IDs) are : [1] Kuhlman et al. (2010), [2] Brand-Sassen (2004), [3] MacLeod et al. (2010), [4] Rickson et al. (2010), [6] Van-Camp et al. (2004), [7] Lundekvam et al. (2003), [8] Tim Chamen et al. (2015), [9] Koschel et al. (2005), [10] Tröltzsch et al. (2012), [11] de Groot et al. (2006), [12] Panagopoulos et al. (2014), [13] Gonzalez-Sanchez et al. (2015), [14] Riksen et al. (2003), [15] Sieber et al. (2010), [16] Buckley et al. (2012), [17] Borin et al. (2010),[18] van den Born et al. (2000),[19] Berbel et al. (2010),[20] Sutton, Srivastava, Neumann, Iglesias, and Boehlert (2013),[21] Sutton, Srivastava, Neumann, Strzepek, and Boehlert (2013), [22] Sutton, Srivastava, Neumann, Strzepek, and Droogers (2013), [23] Le Bissonnais et al. (2003), [24] García-Torres and Martinez-Vilela (1998),[25] Rodrigues et al. (2013), [26] Riksen and De Graaff (2001). **References in italics and round brackets are studies for which only qualitative information could be retrieved and which were *not* used in the quantitative data analysis.

techniques) and single-practice clusters (for example, zero tillage). The data was broken down into group-clusters where similar techniques could be grouped together and where the separation of a too large number of practices would have made the results hard to read. However, it was possible to zoom in on selected single-practice clusters to check whether there were trends for individual measures within some of these groups. The breakdown to single practices was used to capture detailed information as to the type of practice and to provide a clear identification of what costs pertained to what practices.

2.2.5.4 Database and data treatment

In line with the availability of measurements per hectare per year, the main economic indicators gathered were minimum, maximum and average costs, benefits and net-benefits, the sum of discounted costs and benefits and NPVs, BCRs (sometimes also reported as cost-to-benefit ratios), Gross Margins and subsidies. Other metrics such as the total costs and benefits per area at risk and cost-effectiveness ratios were included.

Costs (benefits) are the burden (advantage) that a farmer perceives from the implementation of soil protection practices. Costs (benefits) can be of different types, for example direct or indirect, private or public, on-site or off-site. Economists usually value them in monetary terms and, despite multiple limitations (Wegner & Pascual, 2011), various techniques exist to account for those that have no direct monetary value (HMT, 2018). The present value of costs (benefits) is the total sum of annual costs (benefits) over the lifetime of an adaptation option implemented, to which a discount rate is applied. The NPV represents the net advantage to farmers, and is estimated by subtracting the total discounted costs from the total discounted benefits. BCRs are usually denoted as the ratio of the present value of benefits to costs, but other proxies can be used. BCRs express the relative size of benefits compared to costs: the higher the BCR, the higher the net benefit of the measure.

Three different strategies enabled to maximise the number of data points retrieved: firstly, where a sensitivity analysis was provided in original studies all individual results obtained for specific sensitivity factors were entered on separate lines in the database. Sensitivity factors included agronomic variables such as soil type, erosion rates, crops and crop rotations, the efficacy of practices and economic variables, for instance, discount rates, lifetime of analysis or subsidies accounted for. At the same time, the sensitivity factor and other assumptions associated with an economic metric were also inserted to relate data points to specific hypotheses or scenarios. Thus, more data points were obtained than the number of results presented for initial assumptions in the core analysis of a given paper. In practice, this meant that costs and benefits differed according to variables such as discount rates, erosion severity levels, soil types, crops and crop rotations, project lifetimes and combinations of these factors. For example, Tim Chamen et al. (2015) analysed costs and benefits of soil compaction alleviation and avoidance for four different soil types (clay, silt, sand and peat) and four assumptions on the efficacy of each option (25%, 50%, 75% and 100%). Each combination was entered in the database as a single entry. In the same study, additional information was provided on the effectiveness of measures to reduce environmental impacts such as nitrogen leaching, carbon dioxide equivalent from diesel and nitrous oxide, depending on the type of soil. This also enabled to calculate CE indicators. The results entered represent the ranges within which costs and benefits fluctuated.

Where enough information was provided, additional indicators were calculated. For example, wherever possible, total costs and benefits per area at risk were extracted to calculate a metric for annual cost per hectare. Unfortunately, the risk area was rarely indicated. Where only minimum and maximum figures were given, the simple averages were also reported. Where costs and benefits were not specified as either minima or maxima, it was assumed they are averages. If BCRs were not available in the studies, other indicators were used to calculate BCR proxies. This was done either by inverting the cost-benefit ratio where originally given or by calculating BCRs from studies where both minimum benefits and minimum costs were delivered simultaneously. The process was iterated for maximum and average costs and benefits, the sum of discounted benefits and costs and total benefits and costs for the area at risk reported in some studies.

The data on costs and benefits was standardised as far as possible. Where the measure involved farmers accepting buffer zones (Buckley et al., 2012), the financial and economic losses associated with the loss of land that could have been used for crops was treated as a cost. Further standardisation was achieved by reporting figures as annualised costs/benefits per hectare wherever possible and converted all the original figures collected to 2015 Euros adjusted by Purchasing Power Parity (PPP). Excel was used for data collection and analysis and *R Studio* for data visualisation.

2.2.5.5 Quantitative and qualitative data analysis

Most data points were available for average costs and benefits as well as for BCRs. A descriptive analysis of the data was undertaken and results were analysed and reported only for these two indicators, so as to provide insights into possible trends and the relative sizes of costs and benefits of soil protection at selected European sites. Some of the main limitations experienced when processing the data are then discussed. These are deemed important for understanding the scope of the results (see Section 2.4).

2.3 Results

2.3.1 Average costs and benefits

Figure 2.1 shows the average costs and benefits of the different soil protection practices and categories considered. Mean average costs of 106 EUR/ha/year and mean average benefits of 93 EUR/ha/year were observed. The bulk of the data points were located between those figures. This suggests that on average the measures do not pass the benefit to cost test. The spread of data points below and above the parity line (indicating equality between cost and benefit indicators) shows that benefits do not always exceed costs for all practices in all circumstances. With average costs ranging between 0 and 765 EUR/ha/year and average benefits between 0 and 3 440 EUR/ha/year the variability is high, so it is hard to draw conclusions, even in terms of orders of magnitude.

A look at the five categories of soil protection practices reveals that they are all homogeneously spread above and below the parity line except *"Systems"*. *"Systems"* is a combination of measures that includes multi-options, erosion programmes and agroforestry, which may have positive economic results due to the symbiotic effects of combining soil protection measures. The analysis shows that costs predominantly exceeded benefits for *"Vegetation management"*, which mainly covers vegetated buffer strips and observed a wide range of results, both positive and negative for *"Water management"*, which mainly includes data for various types of irrigation techniques.

More information was obtained by zooming in on specific de-compaction practices, different types of vegetated buffer strips and various tillage techniques considered in the literature and which were initially gathered together in clusters. The *"De-compaction"* cluster covers data for different types of de-compaction technologies, obtained from different sources and applied to various sites (Figure 2.2). Data in Figure 2.2 suggest that in most cases de-compaction is economically attractive in Germany independently of the technique applied (choice of adequate wheels and tyre pressure regulation systems). On the contrary, UK figures are less straightforward: on the one hand, using low ground pressure tyres always comes at low cost with economically advantageous results, while coarser seedbeds only generate economic losses to the same extent as ploughing. On the other hand, results for subsoiling and tracked tractors can be profitable, but in many cases these techniques also turn out being economically unviable.

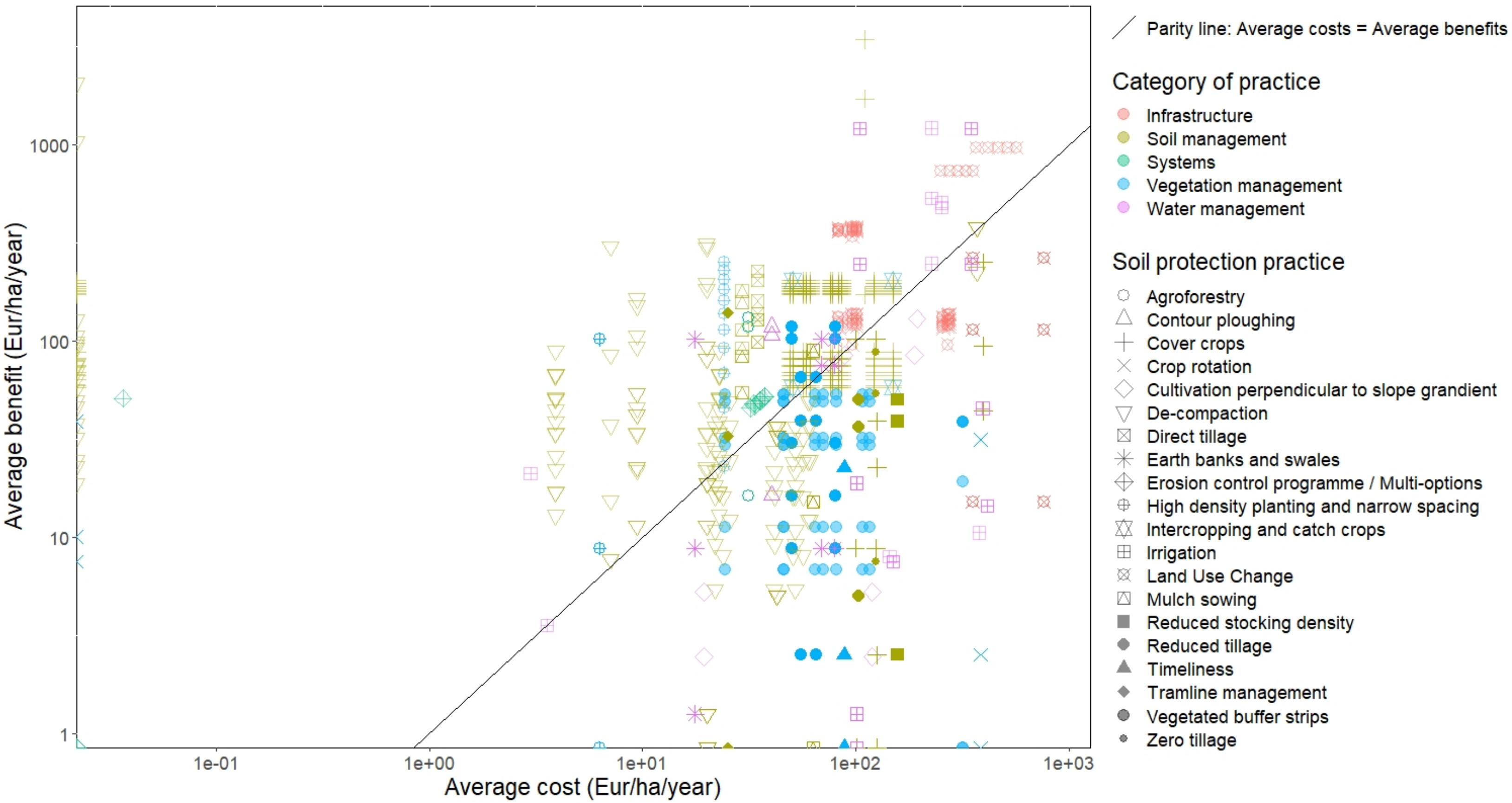

Figure 2.1: Average costs and benefits in 20 soil protection practices and five categories throughout selected European countries and sites. The points represent combinations of average costs (x-axis) and average benefits (y-axis) for different practices (see legend) reported in specific studies. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies. It proved possible to extract data on average costs and benefits from the following studies: [2] Brand-Sassen (2004); [4] Rickson et al. (2010); [8] Tim Chamen et al. (2015); [10] Tröltzsch et al. (2012); [11] de Groot et al. (2006); [12] Panagopoulos et al. (2014); [14] Riksen et al. (2003); [18] van den Born et al. (2000); [19] Berbel et al. (2010). Dark dots of the same colour denote overlapping data points.

Additional knowledge was gained about the *"Vegetated buffer strip"* cluster, for which data was found that distinguished between financial and economic indicators (Appendix B). From the studies where this differentiation was made, vegetated buffers could result in either net benefits or net costs independently of the financial or economic approach considered. This is because the original data develop different cost and benefit scenarios, so a financial estimate with minimal costs and maximal benefits could result in a more advantageous option than an economic estimate taking into account the highest costs and lowest benefits. Financial data, however, show that costs significantly exceed benefits. This makes vegetated buffers unattractive from a purely monetary perspective. Only specific financial data for shelterbelts and economic estimates for riparian and in-field buffer strips were found to show benefits in excess of costs. For tillage techniques, the benefits of direct tillage and mulch sowing were clearly higher than costs in Germany, but costs of reduced tillage, zero tillage and mulch sowing were found to exceed benefits in the UK (Appendix C). Overall, results show that soil protection practices were economically more advantageous in Germany than in the UK (Figure 2.3). Supplementary information was obtained on costs and benefits by grouping the few selected countries for which data was available into three European regions: North, Centre and South (Appendix D). The data points in the North region come almost exclusively from the UK, with cost and benefit information concentrated between 10 and 100 EUR/ha/year, making them similar to Swedish and Finnish data. Similarly, almost all the data points in the Centre region come from applications in Germany. The few data points obtained for France and Austria are of the same order of magnitude as German average figures. Information from the Netherlands stands out as being at the top end of the ranges for both average costs and benefits, indicating net benefits for these measures. Little cost information was detected for the South, despite the threat that climate change and soil degradation are reported to pose there, especially for water scarcity and soil desertification. A higher range of benefits was observed in the North and Centre regions than in the South. No data was found for Eastern European countries except BCRs for Moldova and two Balkan states provided by a World Bank study. This may suggest that there is a disconnect between data availability and expected threat, that reports could not be identified because they were published in local languages or that governments might have other priorities.

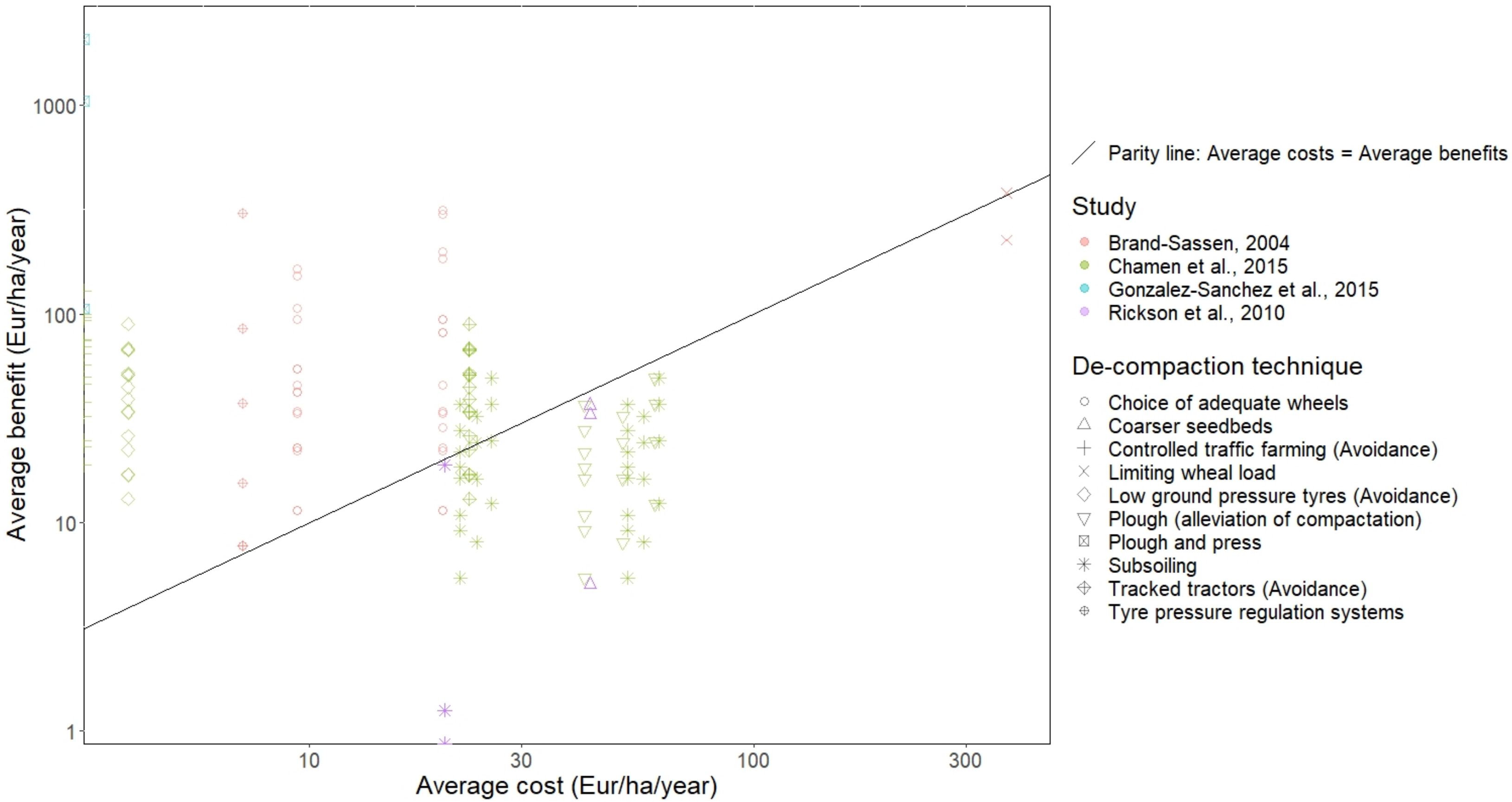

Figure 2.2: Average costs and benefits for de-compaction practices for different reference studies (related to specific sites). The points represent combinations of average costs (x-axis) and average benefits (y-axis) for different practices reported in specific studies (see legend). Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies. Dark dots of the same colour denote overlapping data points. Reference studies are indicated in the legend. Each reference study is related to a specific country [Brand-Sassen (2004) studies German data; Tim Chamen et al. (2015) and Rickson et al. (2010) study UK data; Gonzalez-Sanchez et al. (2015) study data from Spain].

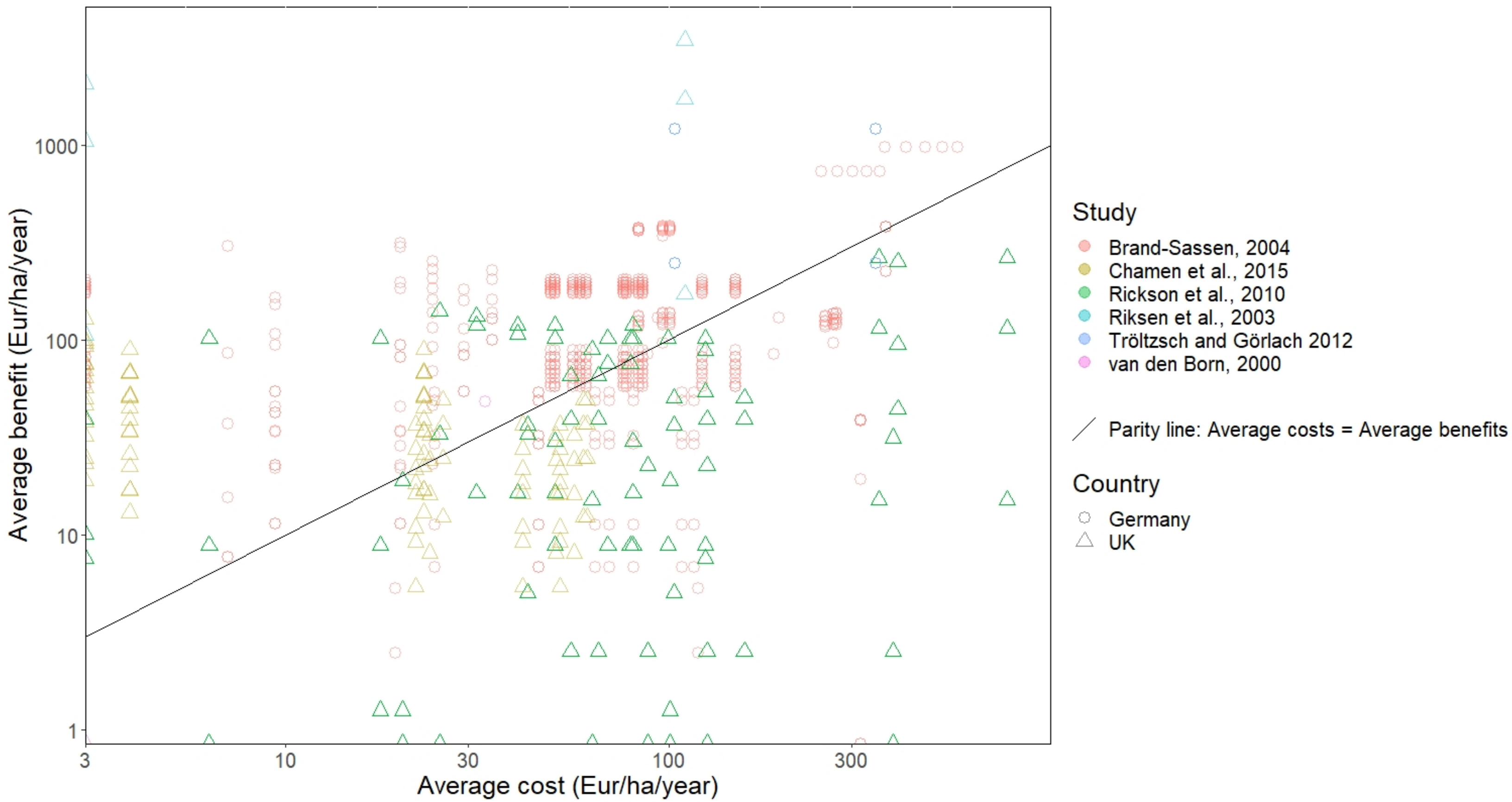

Figure 2.3: Average costs and benefits for soil protection practices for Germany and the UK as per reference studies. The points represent combinations of average costs (x-axis) and average benefits (y-axis) for different practices provided for Germany and the UK originating from different reference studies. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies. Dark dots of the same colour denote overlapping data points.

2.3.2 Benefit-to-cost ratios

As in the analyses outlined above, the results for BCRs show options that do not systematically feature net benefits (Appendix E). Most BCR estimates considered here were calculated using average costs and benefits, so we focus now on the additional information found from our analysis of this indicator. Analysing BCR gave us additional economic information on the costs and benefits of crop varieties and fertiliser management practices and information pertaining to different countries, including Macedonia, Albania and Moldova (Appendix E, Figure E.1). Crop varieties appear to be economically attractive in most cases in both Albania and Macedonia where we found high average BCRs of 55. Fertiliser management practices have both positive and negative monetary outcomes across Albania, but are positive in Macedonia. The average BCR for irrigation was found to be 23, but the highest was 1 958. However, the specific approach taken in the single World Bank study covering these three different states may well influence the results. Outcomes therefore need to be checked against different study assumptions to avoid biases (Appendix E, Figure E.2).

2.4 Discussion

This multidisciplinary approach is valuable in terms of obtaining rich perspectives on costs and benefits to improve policy guidance, but the heterogeneity of the economic data considered compounds the insufficiency of the data encountered and the other usual weaknesses of economic appraisals related, for example, to the monetisation of ecosystem services. This may restrict the statistical significance of results and the potential for making policy recommendations. However, this needs to be set against the backdrop of other important considerations that are common to economic assessments in general, including the potential generation of unintended consequences, which may lead to wrong decision-making.

2.4.1 Methodological limitations

The nature of literature reviews means that the results are dependent on the information available. Firstly, results show that few of the studies located were able to calculate and provide primary economic data on costs and benefits of soil protection practices. Even if the two studies containing the bulk of information for the UK (Tim Chamen et al., 2015) and Germany (Brand-Sassen, 2004) produce primary costs and benefits, many relied on secondary data extracted from other papers or literature reviews based on applications at other sites and in other regions and countries. Secondly, the economic information found is heterogeneous in geographical terms, because soil protection relates directly to the specific sites where it is implemented, in both agronomic and socio-economic terms. The diversity of the data used as a foundation for this chapter is a strength, but also a limitation for the generalisation of results and transferability. These outcomes support previous results in the literature which indicate that agro-economic performances are likely to be determined by geographical differences (Branca et al., 2011; IPCC, 2019; McCarthy et al., 2011) and which make cost-transfers across sites questionable if they are not carefully undertaken. Several authors have even concluded that no generalisation of costs is feasible and that analysis should be undertaken at farm or watershed levels, in interaction with the parties involved (Le Bissonnais et al., 2003). Thirdly, costs and benefits in the original studies were also calculated according to specific methodologies (Appendix A) and assumptions on discount rates, erosion severity levels, soil types, crops and crop rotations, project lifetimes and combinations of these factors, which may themselves have been determined by socio-economic site specificities. Finally, there are also limitations to the methodology developed in this chapter, which is linked to the decisions that had to be made for analytical purposes. For instance, considering costs and benefits provided as averages if not otherwise specified can introduce major biases in results. The challenge of soil protection practice categorisation and clustering, pooling potentially different measures under the same headline such as no till, reduced till, mulch till and non-inversion tillage may also lead results astray. Therefore, concluding that reduced tillage practices may have both positive and negative economic outcomes is of little significance if detailed information about the various types of these techniques is not found. Similarly, the wide range of economic outcomes of water management practices is likely due to the wide variety of possible water management practices. Irrigation techniques considered in Western economies are likely to be *hard*, capital intensive investments. By contrast, water management strategies in transition economies may also include *soft* irrigation technologies that favour water accumulation in soils and that involve less capital investment, for example drip irrigation and earth banks.

Altogether, these limitations point to the shortage of data encountered and the weak statistical significance of results that hinder policy recommendation. As a consequence, the advantageous economic results found for soil protection in Germany compared to the UK (Figure 2.3), for example, for de-compaction practices (Figure 2.2), need further investigation to determine whether economic differences are driven by study assumptions or by other agronomic and socio-economic factors. In that respect, results according to which avoidance of soil de-compaction is more advantageous than its alleviation need validation. More data is required to identify if results are driven by methodological choices of Tim Chamen et al. (2015) or if these advantages are real and can be extrapolated.

2.4.2 Partiality of soil protection costs and benefits

Estimations of benefits were often determined by the objectives of the studies reviewed. A study that investigates the climate mitigation potential of soil protection measures focuses on how far those interventions can reduce GHG emissions and may not account, for example, for the extent to which they reduce soil erosion. Different study objectives imply different performance indicators and different types of benefit: the benefit attributed to reduced tillage by Brand-Sassen (2004) is the avoidance of soil disturbance during extreme events, while that reported by MacLeod et al. (2010) is the carbon sequestration potential of the practice.

The difficulty of taking into account benefits of soil protection practices and ecosystem services in general is a common feature of economic assessments. However, this is a substantial limitation which is strongly underpinned by Wegner and Pascual (2011) *"in the context of ecosystem services for human wellbeing"*. In this analysis it is mirrored by higher ranges of variation within which average benefits fluctuate. It was also found for example that the costs of vegetated buffer strips predominantly exceed benefits, usually due to higher investment costs and medium- to long-term benefits that are not accurately measured or not accounted for in studies (Borin et al., 2010; Brand-Sassen, 2004; Le Bissonnais et al., 2003; Rickson et al., 2010; Sieber et al., 2010). Moreover, many benefits of land and crop management other than agricultural yield are not tangible and are therefore difficult to quantify. Specific examples of biodiversity valuation are in their infancy (Plaas et al., 2019) and accounting only for quantifiable benefits produces only limited results (Carpenter, Folke, Scheffer, & Westley, 2009). Importantly, there are other economic considerations (including private and social health aspects of soil protection) which were absent from the literature that was reviewed. Similarly, methods that value natural resources usually struggle to account for the full range of damage caused by degradation. Yet some medical scholars are starting to report costs of diseases with environmental influences (Heindel et al., 2015) which may be very costly to society (Hauser et al., 2015; Legler et al., 2015) and have geopolitical and moral implications.

2.4.3 Unintended consequences and the value of multidisciplinarity

This multidisciplinary approach reveals that the studies analysed may only provide partial insights into the costs and benefits of soil protection practices. Therefore, considering such practices as *no-regret* under a *one size fits all* rule may have considerable impacts in terms of unintended negative consequences or *maladaptation*: firstly, practices to protect soil can have opposite outcomes depending on context variables such as the location of implementation and baseline conditions as discussed above. Secondly, considering hazards separately from intervention objectives can also result in wrong recommendations because addressing one objective may lead to an intervention that has unintended consequences for another. For instance, irrigation interventions aimed at soil and plant recovery can potentially lead to salinisation of soils (Umali, 1993). In fact, the multiple-benefit nature of soil protection calls such single-objective approaches into doubt. Thirdly, costs were identified and assessed differently from one study to another. Cost estimates included, for example, investment, maintenance, opportunity costs, yield loss related to the implementation of practices, on-site and off-site costs, and/or a combination of these factors. Rarely, however, did estimates incorporate these different cost items *jointly*. This makes it impossible to provide a more comprehensive economic appraisal. Separate research communities may well be preventing more comprehensive assessments of the benefits (and costs) of soil protection practices. Individual investments are driven by the hazards that each farmer seeks to address, and the expected outcomes of the interventions planned. Analogously, soil protection practices are investigated from the viewpoint of different policy domains and research communities depending on their visions and interests (Brevik & Sauer, 2015). The authors considered were usually motivated by different objectives, so they chose to assess specific indicators as mentioned above. In practice however, this may lead to the omitting of costs and benefits because they belong to linked bio-chemical processes and indicators may need to be associated to account for a more complete picture of costs and benefits.

2.4.4 Beyond costs and benefits

The difficulty of accurately assessing the costs and benefits of soil protection has led some authors to conclude that adaptation costs are ultimately determined by the ambitions of authorities and institutions (Kuhlman et al., 2010). Rodrigues et al. (2013) assert that the rankings of alternative solutions were very sensitive to the decision-maker priorities. This suggests that knowledge and participative action beyond cost-benefit data are needed to upscale and incentivise soil protection measures and sustainable land management (Emerton & Snyder, 2018; Wegner & Pascual, 2011). Beyond pure monetary aspects of economics, there are moral questions as to whether it is socially preferable to prevent soil degradation or to remediate an irreversible phenomenon such as soil formation if alleviation practices prove to be economically more advantageous than prevention (Tim Chamen et al., 2015). The importance of moving beyond costs and benefits and engage in multidisciplinary and participative decision-making processes in order to incentivise soil protection is highlighted. Ultimately there is no advantage in either cost-effective soil protection practices or financial austerity if soils, which are the foundation for life, continue to be degraded.

2.4.5 Directions for future research

More data is needed to confirm the outcomes of this quantitative data analysis, minimise the impacts of study assumptions on results and reach a greater coverage for the European region. Compelling next steps for research could include:

- Extending the database with multidisciplinary approaches and enlarging the data sample so as to avoid using broad soil protection categories;
- Extending the analysis to identifying the factors that determine costs and benefits;
- Testing whether wider geographic transferability to areas where such data does not exist is justifiable given the importance of context specificities; and

- Moving towards holistic and participative decision-making approaches which include aspects other than costs and benefits, for example, human health and wellbeing and the broader socio-economic benefits of fertile soils.

Multidisciplinary research may make it easier to collect more appropriate information and may benefit effective decision-making in the agricultural sector.

2.5 Conclusions

This chapter presents a new, multidisciplinary, literature-based review of cost and benefit data on selected agricultural soil protection practices at selected European sites.

- Quantitative results show that the costs and benefits of soil protection measures do not systematically exceed costs for all options and in all circumstances.
- Data suggest positive economic results for *Systems* or *multi-options*, a negative trend for vegetated buffer strips across regions, a positive trend for direct tillage and mulch sowing in Germany, and generally, more advantageous economic results for soil protection in Germany than in the UK.
- Results however cannot be considered as definitive or generalised. Importantly, the small size and heterogeneity of the data sample prevents us from drawing statistically relevant conclusions.
- Cost and benefit estimates assessed by separate research communities prevent more comprehensive economic appraisals of soil protection techniques, which in turn may result in unintended consequences and wrong policy recommendations.
- Multidisciplinary and participative approaches in the economics of soil protection may reduce such estimation biases and improve policy guidance.
- Future research can expand this data base, focusing on multidisciplinary and participative approaches. It can also explore whether site-specific drivers of the costs and benefits of these measures can be identified and how economic drivers are linked to other socio-economic factors that are determinant for decision-making by farmers.

Chapter 3

Adaptation decision-making in Zanzibar's clove plantations: developing a cost-benefit analysis in a data scarce context

3.1 Introduction

The CBA has been predominantly used for decision-making (Boardman, Greenberg, Vining, & Weimer, 2018) and it has remained so for the prioritisation of environmental and climate investments. Its attractiveness may originate in its simple decision rule – benefits need to outweigh costs for an investment to make economic sense – which enables policy-makers to optimally allocate limited financial resources. CBA also offers a common ground to compare economic profitability across project alternatives on a monetary basis.

In this chapter, a cost-benefit model was developed for climate adaptation investment in Zanzibar's clove plantations, characterised by uncertainties due to the nature of the agroforestry systems in which clove trees grow and the climate change impacts for the region that remain unclear. The objective was to collect data in the field to reduce uncertainties of the model as much as possible and analyse whether reducing this information gap makes the cost-benefit model more appropriate for policy recommendation in this case. To do this, insights into the Zanzibar (United Republic of Tanzania) country and clove sector contexts are first presented, as well as the conceptual and methodological framework used for the consideration of uncertainties in the assessment of adaptation options in Zanzibar's clove plantations.

3.1.1 Background

Zanzibar's monopolistic clove forests have been a strategic sector to changing governments in terms of the foreign income it could attract and the national economic performance it could sustain (Martin, 1991; RGZ, 2003). Clove plantations were likely introduced by the Omani rule at the beginning of the 19th century in form of extensive monoculture, when the Zanzibar's Sultanate established a dominant trading position: at that time slavery provided free labour and there was a high demand for cloves in the world market, which, combined, made the clove sector a particularly attractive business (Crofts, 1959).

Nowadays, clove trees are mainly grown on Pemba island in complex agroforestry systems for subsistence farming (Indufor, 2013b). The clove monopoly is managed by the Zanzibar State Trade Corporation who is responsible for setting the price for cloves and collecting and trading the spice. In 2016 clove exports in value shared 68% of total exports of Zanzibar (OCGS (Office of the Chief Government Statistician), 2017) and represented the most important source of foreign exchange. The clove industry also sustains the livelihood of about 6% of the crop growing households in Zanzibar (RGZ, 2012). This is of importance, as Zanzibar is one of the least developed regions of the world with 44% of its population living under the basic needs poverty line set at about 1 US Dollar per day (USD/day) (OCGS, 2012).

Since the denomination of Zanzibar as a *Spice island*, the sector has experienced cascading difficulties (Martin, 1991; RGZ, 2004; Troup, 1932) conditioned by factors inherent to the clove tree species and to external factors such as the climate (Martin, Butler, & Dabek, 1988; Martin, Riley, & Dabek, 1987; Razakaratrimo, 2014) as well as by the clove market and local socio-economic conditions: price variability, increasing competition in the clove market (Indufor, 2013b) and land fragmentation due to the inherited land tenure system resulting from Zanzibar's independence. In the past few years there has also been increased concern about the impacts of climate change, erratic and more intense rainfalls as well as more frequent dry spells on clove plantations of Zanzibar (RGZ, 2014). While up to 20 000 tonnes of cloves could be harvested at the end of the 50's, production have oscillated around 5 000 tonnes since 2006 (OCGS, 2012).

Recently, the revival of the clove sector has been on top of the political agenda in Zanzibar. The latest clove development strategy has reintroduced the free distribution of clove seedlings to farmers (RGZ, 2004) and the most recent Agricultural Sector Review plans a rehabilitation of the sector with production objectives of 10 000 t/year by 2020 (RGZ, 2014) which seems difficult to achieve (OCGS (Office of the Chief Government Statistician), 2017).

3.1.2 Conceptual and methodological approach

This chapter provides insights into investment uncertainties in the clove sector from two perspectives: the aim was to collect information to fill the information gap and to identify and propose adaptation measures to jointly assist immediate development preferences and address future climate change by 2100.

For the identification of adaptation options in the clove sector of Zanzibar the development perspective of (Burton, 2004) was taken, arguing that both addressing drivers of vulnerability and climate change need to be considered as the one and only continuous process of adaptation (McGray et al., 2007). This is especially so as a development deficit exists, driven by other socio-ecological factors than climate change (Burton, 2006; Tol et al., 1998). This approach was considered to make sense given the clove rehabilitation strategy planned in Zanzibar, the development country and adaptation deficit context in which climate adaptation is one of a plethora of other development priorities to address, and the potential future climate risks in clove plantations of Zanzibar, such as potential droughts or cyclones. In this study, adaptation options are therefore proposed and assessed based on the idea of a continuum pathway between development practice and climate intervention (McGray et al., 2007). This includes adaptation options to address short-term climate variability and related production failures, others to address short-, medium- and long-term stressors and others to address long-term climate change and related production uncertainty.

3.2 Methodology, data and model assumptions

The intention was to quantify the monetary profitability for a one-hectare clove plantation that integrates different adaptation options under current climate and future projected rainfall and potential cyclones. Therefore, a CBA for a simplified agroforestry model was developed, including a baseline and four alternative agricultural practices and their viability under the present climate analysed. Subsequently, results were analysed from introducing future climate impacts in the form of rainfall projections and *What-if* scenarios of cyclones hitting the clove plantations at three different timings. Economic outcomes of all investment options that result under current, future climate and cyclone events were then compared. The remaining paragraphs of this section describe the cost-benefit model (Section 3.2.1), the data collection (Section 3.2.2), the assumptions of the models (Sections 3.2.3 and 3.2.4) as well as the sensitivity analysis (Section 3.2.5) undertaken to verify results under changing assumptions.

3.2.1 The cost-benefit model

Positive NPV is the most widely used investment rule in cost-benefit and optimisation-based decision analysis (European Commission, 2015). Its calculation is illustrated in Equation 3.1 (Eq. 3.1). In Eq. 3.1, B and C respectively represent per hectare benefits and costs of the clove plantation and DR the discount rate under a time horizon t of n years. The discount rate is supposed to mirror the time preference of individuals and is the inverse of the interest rate. The higher it is chosen the more important the present is assumed to be respective to the future. The decision rule states to invest in a project if the sum of the present value of expected flow of net benefits is positive (NPV>0).

$$NPV = \sum_{t=0}^{n} \frac{B^t - C^t}{(1+DR)^t} > 0 \qquad (3.1)$$

Starting with this rule, other decision indicators exist such as the BCR and the Internal Rate of Return which is the discount rate at which discounted costs equate the discounted benefits. In the CBA results section, mainly NPVs and BCRs are presented, which are considered most representative of absolute and relative profitability obtained for each unit cost spent. A sensitivity analysis was also undertaken by varying initial assumptions to observe the reactivity of economic indicators to various assumed parameters.

3.2.2 Data collection

The material for this chapter was collected in close collaboration with the Department of Forestry of the Ministry of Agriculture, Forestry and Natural Resources of Zanzibar during two field missions carried out in January and June 2016. It is a product from local stakeholder workshops organised for the development of the UK-funded Climate Change Action Plan of the Revolutionary Government of Zanzibar in the context of the Zanzibar Climate Change Strategy and 20 semi-structured interviews with main actors of the clove sector and clove farmers. More detailed information on the type of interview questions used and the actors met are to be found in Appendix F and Appendix G respectively.

3.2.3 Clove agroforestry model under current climate

According to the Zanzibar Woody Biomass Survey (Indufor, 2013a) and its Special Report on Cloves (Indufor, 2013b) 93% of clove trees of Zanzibar are presently grown on Pemba island. Clove trees mainly thrive on the western side of the island in Wete district, mostly in complex agroforestry systems, intercropped with banana stands, cassava, grapefruit, cinnamon and a multitude of other trees and crop varieties.

In view of the objective of this chapter, a simplified agroforestry model was constructed in which only limited intercrop species were accounted for. The idea was to capture the rationale of an agroforest system and avoid a high degree of complexity. Firstly, the baseline without adaptation was set under current climate to account for the average situation in Pemba today. Secondly, an adaptation pathway was accounted for that includes good management practices (GMPs), alternative intercrops with vanilla and cinnamon and a Windbreak (WB) with teak trees to account for short-, medium- and future climate hazards and related production variability. This enabled a comparison of economic results with and without adaptation interventions under different climate scenarios.

3.2.3.1 Baseline

The focus is on a farmer's investment in a new, one-hectare clove plantation and its viability under current climate. it was assumed that bare land is bought, and clove seedlings together with intercrops are all planted at once at the onset of the project in year zero. it was also assumed that the clove plantation has a lifespan of 30 years, a middle way between short-term visions in economic decision-making and the 80-years productive lifetime of the clove trees in Zanzibar (Indufor, 2013b).

In the baseline, intercropping with cassava and banana trees was accounted for during the first three years of the plantation's lifetime. These serve as shading, maintaining soil moisture and enabling appropriate survival rates. In fact, it was observed that the seedling stage and the three years after transplantation of seedlings into the field is the period during which clove trees are most sensitive, and this is especially so in case of dry soil conditions and direct sunlight (Thankamani, C. K. Sivaraman, Kandiannan, & Peter, 1994; Troup, 1932).

Survival rates were reported by farmers to be between 40% and 80%. A 55% weighted average of survival rate was used, slightly lower than the simple average to reflect the generalized tendency of plantation neglect in the past years which contrasts with good management practices for high survival of clove seedlings (Martin, 1991; Thankamani, C. K. Sivaraman et al., 1994). If the seedlings survive one year after transplantation, it was assumed that they will survive the complete life cycle, except pest incidences. The assumption was also made that farmers are aware of the survival rate, so that they plant additional seedlings necessary to obtain a plantation with the desired density. However, as taught during the field interviews, pests and diseases throughout the lifetime of the tree were considered by assuming 3% of them are affected starting year 6. Lower survival rates therefore reflect higher costs to farmers via higher seedling, transportation, digging and plantation expenses in the initial investment phase.

The main investment costs that farmers bear in the first year include land acquisition and preparation, costs of seedlings and their transportation to the farm as well as the digging and planting. Recurrent costs encompass weeding, seasonal harvesting, drying of cloves, felling of unproductive trees and replantation, harvesting being the most important recurrent cost.

In line with historical reports (Crofts, 1959; Troup, 1932), data obtained in the field indicate that harvesting amounts to about 62% of total annual expenses. All recurrent costs start together with production in year 6. Weeding is practiced every year and to account for scarce management practice and low survival rates in the baseline, it was assumed that weeding is implemented at 50% of the desired level, thereby reducing the costs by the same amount. Felling of unproductive clove trees and replantation were assumed to start in year 70 and were repeated every five years at 20% and 40% of trees respectively. In an analysis that considers shorter lifetimes these can therefore not be accounted for. For replantation the same survival rate as for initial plantation as assumed and no further shading, production and harvesting needs resulting from replanted crops. Regarding replantation, earlier renewal is likely to be needed to insure clove forests' sustainability. Because it did not seem to be an optimised replantation strategy in the region and consistent with low levels of plot management, the renewal of trees was kept in late years of the plantation's lifetime.

Clove trees start producing in year 6 at an increasing pace, reaching production maturity at 40 years, which is then sustained up to year 70. Again, models that account for shorter lifetimes may not consider the highest production potential of clove trees. Afterwards, production falls back to lower levels, before being considered null starting year 80 (Indufor, 2013b). On recommendation of actors in the field in Pemba, an average tree density of 100 trees/ha was applied. For consistency, the annual average production of 390kg/ha/year was used. This was obtained by computing the average of digitalised production figures from Martin (1991) downscaling them to the area of interest. Production figures served to derive harvesting and drying costs as well as the revenues from clove production. Cost and revenue items, their monetary values and respective timings used for the baseline are detailed in Table 3.1. All assumptions for the construction of the baseline can be found in Appendix H.

Table 3.1: Cost and benefit items of clove plantations in the baseline Exchange rate used: USD 1 = 2186.32 Tanzanian Shillings (TZS), verified on 28 August 2016. Pishi is the local basket that serves for clove harvesting and its measure. It is also used to remunerate seasonal workers based on the number of pishis harvested. One pishi is equivalent to about 2.3 kg of green cloves, 1/3 of which is dried cloves. A pishi thereby is about 0.76 kg of dry cloves.

	Option / Item	Quantity	Price (2016 TZS)	Timing
Economic Costs	Land purchase	1 ha	18 000 000/ha	Year 0
	Land preparation	1 ha	400 000/ha	Year 0
	Seedlings	182 units	2 000/unit	Year 0
	Transportation of seedlings to field	182 units	450/unit	Year 0
	Digging and planting	182 units	400/unit	Year 0
	Drying mats	40 units	4 000/unit	Year 0 and every 5 years
	Weeding 50%	1 ha	100 000/ha	Years 0 to 80
	Harvesting	513 pishi	2 000/pishi	Years 6 to 80
	Drying	513 pishi	1 000/pishi	Years 6 to 80
	Felling	20, 40, 40 trees	10 000/tree	Years 70,75,80
	Replantation	Felled trees/survival rate	6 400/tree	Years 70,75,80
	Intercrop with cassava			
	• Seedlings	5 000 units	20/seedling	Years 0,1,2
	• Dig and plant	1 ha	100 000/ha	Years 0,1,2
	• Weeding	1 ha	100 000/ha	Years 0,1,2
	• Harvesting	1 ha	30 000/ha	Years 0,1,2
	Intercrop with banana			
	• Seedlings	160 units	750/stem	Years 0,1,2
	• Dig and plant	160 units	2 000/stem	Years 0,1,2
	• Thinning/uprooting	160 units	700/stand	Years 0,1,2
	• Harvesting	160 units	500/stand	Years 0,1,2
	Lost production due to parasites/diseases	3% of production	/	Years 6 to 80
Economic Revenues	Clove	389.88 kg/ha	TZS 13 500/kg (high price)	Years 6 to 80
	Clove timber	20 trees (40, 60)	TZS 550 000	Years 70, 75, 80
	Cassava production	2 900kg/ha	TZS 500/kg	Years 0,1,2
	Banana production	2 000kg/ha	TZS 2 000/kg	Years 0,1,2

3.2.3.2 Adaptation pathway

In this chapter, the same precautionary principle as Burton (2004) was adopted to suggest that there is more of both adaptations to current and future climate to be done in clove plantations of Zanzibar. This was done to fully reveal their untapped potential through an adaptation pathway or a bundle of adaptation options that, in combination, simultaneously address short-, medium- and long-term climate related risks (Downing, 2012; Watkiss, 2015). The approach covers emerging and future risks that both require action despite or in view of the uncertainties faced.

Information was gathered about adaptation in Zanzibar with a double intention: to look out for how farmers already adapt to current and future climate variability and analyse to what extent it makes economic sense to expand these practices at larger scales. In the following paragraphs, agricultural techniques are referred to as adaptation options. These include (a) GMPs, (b) intercrop with vanilla, (c) intercrop with cinnamon and (d) a WB planted with teak trees (Table 3.2).

Table 3.2: Framework for an adaptation pathway or bundle of adaptation options in Zanzibar's clove plantations. Adapted from (Watkiss, 2015)

Adaptation option	Description	Intervention	Timeline	Benefits
GMP adaptation package	100 clove trees/ha and Shading with banana stalks Weeding (100%) Replantation starting year 60 Organic compost Timing of transplantation Mini-drip irrigation Cover crop: lemon grass Removal of parasites Pruning after harvest	Good development/addressing climate vulnerability	Short- term	Short-term
Intercropping - Vanilla	3 subplots of 20m*20m planted with vanilla and 70 clove trees/ha	Resilience for the future	Medium-term	Short-, medium-term
Intercropping - Cinnamon	50 % clove trees and 50% cinnamon trees/ha	Resilience for the future	Medium-term	Short-, medium-term
Windbreak (WB)	The clove plantation is fenced with 2 lines of teak trees: 64 teak and 36 clove trees/ha	Capacity for the future	Long-term	Long-term

During the field missions, GMPs stood out as the most important characteristic for healthy and sustainable clove plantations. These options are already partly practiced throughout the region, the most expanded being mini drip irrigation. In the model GMPs are represented through an adaptation package including organic compost, right timing of transplantation from nursery to the field, mini drip irrigation, lemon grass mulching reported to be the only solution to prevent termite mounds, removal of parasites from trees and pruning of damaged branches after harvesting. Even if these techniques are more expensive, they enable the farmer to obtain higher survival rates of up to 80%. As a consequence, plantation costs are decreased and clove bud production is increased by 20% based on discussions with local farmers and experts from the Ministry of Agriculture, Forestry and Natural Resources.

Intercrop with vanilla is a less frequent practice in Zanzibar which is likely to be caused by high maintenance and manual pollination costs. Vanilla is a climbing plant which is usually planted on support-trees with a distance of 4m x 4m. Given the field investigation, it seemed therefore reasonable to assume in the model three vanilla subplots of 20m x 20m with a distance between vanilla supporting trees of 4m x 4m and 25 vanilla plants on each subplot. As clove trees are usually interspaced at 10m x 10m, vanilla subplots imply the reduction of four mature clove trees per subplot or 12 clove trees for the entire farm. As compared to the baseline, this was expected to reduce total clove plantation costs and revenues to 88% and additional costs specific to vanilla plantation were added. These included additional land preparation costs for maintenance of vanilla support-trees every five years and considerable annual costs from additional weeding and manual pollination. Vanilla production was assumed to start in the third year of the plantation and to be constant throughout the considered time frame.

Cinnamon intercropping reflects one of the farmers' diversification strategies most observed on the islands. To integrate cinnamon intercropping in the agroforestry model, a 50% cinnamon and 50% clove tree distribution was assumed, with an identic density for both species, equal to the baseline. Costs and revenues from clove production were therefore reduced by 50% while additional costs and revenues from cinnamon were accounted for, including for weeding. Cinnamon trees were assumed to start production in year 5 and produce at 50% of their productive potential till year 20. Afterwards they produce at maximum potential of annual 875t/ha.

To protect the plantation from strong winds and cyclones a WB was proposed (Thankamani, C. K. Sivaraman et al., 1994). On all its sides the land plot was supposed to be fenced off by two lines of teak trees, a species much valued for its hard wood. Assuming the same density is required for both clove and teak species and land area available remains identical, clove plantation reduces to 36 clove trees, the remaining being replaced with 64 teak trees. This reduces clove trees related costs arising throughout the lifecycle to 36% of initial amounts. Cost of plantation and felling are the same for both tree species therefore the model was maintained identical for most items. Weeding at 50% of application and survival rates of 55% were kept identical to the baseline. Clove revenues were shortened to 36% while the teak trees only provide benefits in latest mature years: either from the commercialization of its hard wood when trees are replaced, or from avoided damage costs that only potentially materialize in case of a cyclone events. All assumptions that serve to construct the adaptation models in the CBA are to be found in Appendix H.

As a starting point the focus was on results provided by fixing the analysis parameters as follows: DR=10%, P=high, n=30. The discount rate was set to 10% because it is current practice by the UK Department for International Development; n=30 to reflect a middle way between short-term perspectives as currently practiced in decision-making on the one hand, and long lifetime of clove trees on the other hand; a high clove price which prevailed on the clove market at the time of the data collection. A sensitivity analysis was then done to verify how outcomes vary with these parameters.

3.2.4 Climate projections and impacts

There are high uncertainties regarding future climate projections in Zanzibar, and the Zanzibar Climate Change Strategy reports an absence of a simple precipitation trend across the archipelago (RGZ, 2014). The Zanzibar Climate Strategy however reports future increasing rainfall during the rainy season (massika) from March to May and a decreasing trend during the dry season (vuli) from June to October. This strengthens existing precipitation trends with higher precipitations during rainy seasons and lower precipitations during dry seasons which will likely disadvantage rain fed agriculture (RGZ, 2014).

In addition, there is so far little in the literature helping to understand the sensitivity to and magnitude of climate impacts on the growth of clove trees, triggering losses that plantations could suffer. Two previous studies investigate the reasons of clove trees' production variability, and the weather impact on clove production (Martin et al., 1988; Miraji, 2013). However, studies are partially incomplete with contradictory and unsatisfactory results for the analysis.

As an alternative, real world uncertainties were allowed in the analysis by stipulating What-if scenarios and conducting sensitivity analysis looking at a range of possible impacts. Here, the products of the field missions were used to make guesses and simulate potential impacts of dry spells and cyclones on clove plantations.

3.2.4.1 Dry spells

Limited by the complexity of biophysical interactions and the lack of knowledge on the climate response of clove trees, sensitivities reported by farmers during the field missions were used for scarce rainfall. An average annual rainfall of 1 800mm/year that clove trees require to grow was employed and a minimum annual rainfall of 1 000mm was applied to make the guess that production is reduced by 70% below this threshold. In reality, climate impacts may depend on non-linear distributions rather than rainfall averages. Also biophysical, ecological and socio-economic interactions are likely to be more complex than those with rainfall considered in isolation. Rainfall is considered to affect the type of clove produced and therefore its quality. Too much rainfall or too low rainfall can also kill young and mature trees and increase the risk of the dieback (Baser and Hüsnü (2004), p. 111).

To model climate impacts, downscaled climate projections for Zanzibar were used, based on CMIP5 models provided by the Climate Systems Analysis Group. Focus of the analysis were middle of the road Representative Concentration Pathway (RCP) 4.5 and the worst case scenario RCP 8.5 applied to Model 4 (FGOALS-s2) which results in lowest projected annual rainfall in both RCPs among the eleven available models. Total monthly rainfall simulations for 1960 to 2099 were used, considering the historical and future projection simulations stretch from 1960 to 2015 and from 2016 to 2099 respectively. Monthly rainfall under both RCPs for the period 1960 to 2099 were then aggregated, in order to obtain annual rainfalls to which a dry impact could be applied according to a hypothesis or *"guess"*.

In the model, climate change projections translate into impacts on the clove plantation both without adaptation options and with different options in place, so that the economic consequences of climate change when adaptation options are implemented can be compared to the case no investments in climate adaption is made. In addition to the benefits they harness under recurrent climate condition, and despite being impacted by lower rainfall, GMPs were assumed to reduce drought impacts on clove plantations from 70% to 50%. For simplicity, additional impacts or benefits for vanilla and cinnamon intercrop in the case of rainfall were not modelled.

For more clarity, the first focus was on the same parameters as in the baseline (DR=10%, P=high, n=30) and the RCP 4.5 with a *"high impact"*, assuming herewith that the dry spells reduce clove production by 70%. In the sensitivity analysis variations in these parameters were introduced to reflect uncertainties in model assumptions and in order to observe how economic outcomes change.

3.2.4.2 Cyclone

Zanzibar lies just off the cyclone pathways in the South-West Indian Ocean and the hurricane that hit land in 1872 is mostly believed to remain exceptional. Results from the IPCC Fifth Assessment Report indicate there is no compelling evidence for changes in the risk of tropical cyclones specifically over the Zanzibar region (Christensen et al., 2013). Risk assessments might however account for more recent reviews that project a reduction in total cyclone frequency, but an increase in the intensity of the most intense cyclones, in terms of wind speed and precipitation rate (Walsh et al., 2015). Previous work citing the Tanzania Meteorological Agency reports (RGZ, 2014) observed changes in wind speeds for the Zanzibar station on Unguja between 1988-1997 and 1998-2007. Evidence is provided on increasing wind speeds on the region, and three recorded cyclones that have made landfall on the Tanzanian coast (Mahongo, Francis, & Osima, 2011). Expected sea level rise might also increase the impact of waves and storm surges associated with tropical cyclones on the islands (Mahongo et al., 2011). Uncertainties about climate change impacts on cyclone activities in the region and unknown probabilities about whether it is frequency or intensity of cyclones or both is expected to increase. In addition, low probability of occurrence does not imply a zero risk nor justifies inaction (Editorial, 2016) and delaying implementation is coming at a higher cost (Lemoine & Traeger, 2016).

Here, the perspective that decision-makers need to be informed and anticipate possible impacts from extreme events including from low probability / high impact cyclones was taken. As the economic utility regulator Ofwat (2015) is pointing out, some type of risk will not be accounted for in historical investment and therefore *What-if* scenarios need to be planned for. In the absence of scientific cyclone activity projections, What-if scenarios were therefore used to simulate a cyclone in the CBA by impacting production costs and revenues.

During the field missions, few farmers could report on the sensitivity of clove trees to strong wind impacts, especially at seedling stage. Despite their strong trunks the trees are characterised by fragile branches prone to structural damage and infections by pathogens ultimately causing the sudden death disease (Baser & Hüsnü, 2004). Reports from Madagascar confirm clove trees suffer consequences of cyclones in that region (Danthu et al., 2014; Levasseur, 2012).

In the absence of probabilities of cyclone occurrence, What-if scenarios were developed for illustration purposes and simulations of a potential cyclone occurring in year 7. The cyclone was also simulated to occur in year 15 and in year 30 to illustrate how results defer depending on the timing of potential cyclones. As a plausible assumption, it was modelled that the cyclone reduces the baseline production by 80% in the first seven years after the event. This impact was diminished to a production reduction of 60% in the five following years. Production then settles at 40% and at 20% of the initial production in each of the following 10 years to reach its original volume afterwards. This reduces production revenues at a decreasing rate after the extreme event. This impact was averaged from information provided by newspaper archives dating back to the 1872 cyclone hitting the islands. Therefore, impacts of cyclones were modelled to be of 80% from year 7 to 13, 60% from year 14 to 18, 40% from year 19 to 29 and 20% in year 30.

As an anticipatory adaptation response, a WB was suggested, designed to slow down wind and reduce cyclone impacts on clove plantations (Baser & Hüsnü, 2004). The teak tree WB was assumed to be planted in two rows around the clove plantation which is compensated by a reduction of 64 clove tree plants. It was also assumed that the WB reduces cyclone impacts from 80% to 20%. However, these benefits depend on the maturity of teak and clove trees at the time the cyclone hits.

The results were calculated in case the cyclone hits in years 7 and 15. In those cases the baseline remains impacted by 80%. The WB instead provides lower impact in terms of reduced damages on the plantation which has implications on both minor additional costs and benefit reductions. Because the WB is not mature in year 7 it does not grasp its full potential to reduce cyclone impacts. An impact of 60% was applied in case the cyclone hits in year 7 and 40% in case it hits in year 15.

3.2.5 Sensitivity analysis

For the CBA, a sensitivity analysis was undertaken to show the effect of main model assumptions on adaptation performances and stress test results on the range within which economic performance indicators might oscillate. Applications considered were the following:

- Low price (1.6 USD/kg) as opposed to the reference high price scenario (6.17 USD/kg),
- Rainfall impact on clove production reduction that ranges between 40% (low impact) and 70% (high impact),
- Discount rates of 3.5% and 13% representing different valuations depending on the source and purpose of the funding as compared to initial 10% and
- lifetime of the project and timeframe for the CBA: 30-years vs. 80-year.

3.3 Results

In this section, CBA results with and without adaptation investment are presented under current (Section 3.3.1) and future potential climates (Sections 3.3.2 and 3.3.3). Thus, the comparison of economic advantages or disadvantages that result from investment options compared to the *"do nothing"* solution enabled to identify and prioritise investments depending on uncertain climate outcomes. Results are given for the selected parameters as described above. All detailed CBA results including sensitivity analysis can be found in Appendix I.

3.3.1 CBA under current climate: baseline and adaptation options

The baseline consisted in the establishment of a simple clove plantation. This included land preparation, seedling purchase and plantation as well as intercropping with banana stems and cassava in the first third years of the plantation for shading purposes of the clove seedlings. The specificity of the baseline is that weeding is not undertaken at its full potential as desired for a thriving plantation.

Results from the analysis in Table 3.3 show that the most interesting adaptation option to implement appears to be vanilla intercropping, with a relative BCR of 1.65 compared to the baseline, meaning this option yields 1.65 times more benefits than the baseline. The second most interesting option according to the economic indicators used are good management practices with a relative BCR of 1.09 compared to the *"do nothing"* option, while the cinnamon intercrop seems to be economically equal to the baseline. Contrary, the less advantageous investment is the wind break which gives 28% less benefits than the baseline. The explanation of such a result is tied to the high vanilla price and the WB being designed for potential future benefits that do not materialise in this case. These include avoided damages from wind storms on the one hand, and additional revenues from traded teak timber.

Table 3.3: Economic results for baseline and adaptation options under high clove prices, DR=10%, n=30 years. All present value revenues and costs and NPVs are expressed in USD 2016 PPP.

	Baseline	GMPs	Vanilla intercropping	Cinnamon intercropping	Windbreak
PV Revenues (USD 2016)	20 388	23 101	46 463	17 908	11 920
PV Costs (USD 2016)	14 894	15 426	20 581	13 039	12 095
NPV (USD 2016)	5 493	7 675	25 882	4 869	(-) 175
BCR	1.37	1.5	2.26	1.37	0.99
BCR relative to Baseline	1	1.09	1.65	1	0.72

Under low clove prices (Table 3.4), only vanilla and cinnamon intercropping remain profitable (the vanilla and cinnamon prices were assumed to remain constant). Vanilla starts production in the third year of the cycle and is sold at USD 57/kg which generates high annual cash flows throughout the lifetime of the plantation. Cinnamon is also a no-regret candidate despite the relatively low price applied for cinnamon compared to vanilla, as its BCRs are always higher than under the baseline. Planting vanilla and/or cinnamon on clove plantations is therefore an economic diversification that can buffer uncertainties, for example on clove prices.

While the wind break remains unprofitable under low clove prices, GMPs become disadvantageous too with low clove prices as their net present value becomes negative. However, GMPs remain more interesting to implement than the baseline as its BCR is relatively higher (Table 3.4). Implementing GMPs therefore seems to be a *no-regret* option as they appear to be economically preferable to the baseline even when clove prices are low. This is likely so because the increasing revenues in terms of higher survival rates and 20% additional production which are both inherent to the implementation of the modelled GMPs outweigh the additional costs incurred by GMPs in the cost-benefit model.

Table 3.4: Economic results for baseline and adaptation options under low clove prices, DR=10%, n=30 years. All present value revenues and costs and NPVs are expressed in USD 2016 PPP.

	Baseline	GMPs	Vanilla intercropping	Cinnamon intercropping	Windbreak
PV Revenues (USD 2016)	13 855	15 262	30 600	13 207	9 352
PV Costs (USD 2016)	14 698	15 426	20 409	12 941	12 024
NPV (USD 2016)	(-) 844	(-) 164	10 191	262	(-) 2 772
BCR	0.94	0.99	1.5	1.02	0.78
BCR relative to Baseline	1	1.06	1.6	1.09	0.83

Lower DRs are always associated with higher BCRs independently of low or high prices (Appendix I). This is because the choice of lower discount rates reflects higher values of the desired returns from projects with long time horizons such as clove plantations, thus a higher value on benefits that accumulate in the long term, and because most of the costs are upfront. In fact, clove plantations provide continuous benefits throughout the productive lifetime of clove trees (6-80 years) which is better accounted for when applying low discount rates. In other words, the benefits that arise in the long term have more weight in the calculation of present values that applies low discount rates. Thus, high prices with a lower discount rate (3.5%) make the cinnamon intercropping economically more advantageous than the baseline compared to a higher discount rate. Similarly, when a higher lifetime of 80 years is used, results do not change significantly, except that the cinnamon intercropping becomes again more interesting than the baseline (Appendix I). Under low prices, vanilla and then cinnamon intercropping are always the two first best options to implement before GMPs and the baseline as they enable to buffer the low crop price independently of the discount rate and the length of the lifetime used for the analysis.

3.3.2 CBA under climate change: dry spells

The analysis confirms that in decreasing order of economic preference, vanilla intercropping, GMPs and cinnamon intercropping are options that best protect clove farmers from economic losses that may emerge from low rainfall (Table 3.5). As the WB is designed to protect the plantation from cyclones rather than from droughts (see Section 3.3.3) the WB remains the less interesting option (Appendix I). Under dry spells the baseline remains viable (BCR=1.10) though it is ranked forth and least good option to consider. GMPs and cinnamon keep their second and third ranking positions as under current climate and globally investments to adapt to climate change seem to make economic sense according to these results.

Table 3.5: Economic results for baseline and adaptation options under RCP 4.5 low rainfall with high impact. We assume DR=10%, P=high, n=30 years. All present value revenues and costs and NPVs are expressed in USD 2016 PPP.

	Baseline	GMPs	Vanilla intercropping	Cinnamon intercropping
PV Revenues (USD 2016)	16 936	20 143	38 261	16 182
PV Costs (USD 2016)	15 390	15 426	21 018	13 331
NPV (USD 2016)	1 546	4 717	17 244	2 851
BCR	1.1	1.31	1.82	1.21
BCR relative to Baseline	1	1.19	1.65	1.1

By applying a low impact to the rainfall projections (40% of clove production reduction as compared to 70% under high impact), only small variations in BCRs are obtained, respectively 1.2 for the baseline, 1.42 for GMPs, 1.99 and 1.27 for vanilla and cinnamon intercropping respectively. However, all options are more interesting than the baseline, making adaptation investment advantageous. The variation of discount rates applied provide different results when combined to the rainfall impact. Most importantly, the baseline becomes unviable under high discount rates (DR=13%) and high production reductions - high climate change impact - (Appendix I), confirming the interest of implementing adaptation options such as GMPs, vanilla and cinnamon intercropping in such cases.

Variations in the ranking positions of cinnamon intercropping and GMPs are observed when applying longer time horizons (n=80 years) and low discount rates (DR=3.5), in which cases cinnamon becomes more interesting than GMPs (Appendix I). This is likely because in the CBA model, additional benefits from productive wood from old cinnamon trees are assumed at the end of their lifetime. These are discarded in 30-year time horizons and have less weight when high DRs with short-term focus are used. However, cinnamon intercropping is always more advantageous than GMPs under low clove prices disregarding climate scenario (RCP 4.5 and RCP 8.5), discount rates and production impacts. This confers to intercropping a powerful intervention to buffer plantations against climate and price variations, even when NPVs become negative in which cases, intercropping helps limiting the losses. When combining high rainfall impact and low clove prices, the vanilla intercrop remains the most interesting option to consider with BCRs of 1.25 (Appendix I). It is however the only advantageous option as GMPs and cinnamon intercrop result in BCR's lower than one. Nevertheless, all options except the WB result in better economic outputs than the baseline.

Most interestingly, the percentage changes observed for each option in response to the climate impact are considerably lower than the percentage changes in reaction to a price shock (Tables 3.6 and 3.7). For example, low rainfall results in BCR percentage reductions of the baseline between 6% and 29% depending on the scenario and parameters considered (Table 3.6), while the reduction response to a price shock ranges between 23% and 41% (Table 3.7).

3.3.3 CBA under climate change: cyclones

Results show that when considering a cyclone to occur at the end of the lifetime of the project (n=30 years), the model behaves as if there was no extreme event. In fact, results are similar to the case in which there is no climate change: the baseline is more advantageous and the NPV of the WB is negative, making it undesirable even in absolute terms (Table 3.8). This result persists unless it is simultaneously considered

Table 3.6: BCR percentage changes, as compared to the no climate change scenario (high clove price).

(a) DR=3.5, n=30 years

	Baseline		GMPs		Vanilla intercropping		Cinnamon intercropping	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Low impact	(-) 15%	(-) 18%	(-) 6%	(-) 8%	(-) 14%	(-) 18%	(-) 9%	(-) 11%
High impact	(-) 23%	(-) 28%	(-) 14%	(-) 18%	(-) 22%	(-) 29%	(-) 14%	(-) 17%

(b) DR=10, n=30 years

	Baseline		GMPs		Vanilla intercropping		Cinnamon intercropping	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Low impact	(-) 12%	(-) 14%	(-) 5%	(-) 6%	(-) 12%	(-) 15%	(-) 7%	(-) 8%
High impact	(-) 20%	(-) 22%	(-) 13%	(-) 15%	(-) 19%	(-) 25%	(-) 12%	(-) 12%

(c) DR=13, n=30 years

	Baseline		GMPs		Vanilla intercropping		Cinnamon intercropping	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Low impact	(-) 12%	(-) 12%	(-) 5%	(-) 5%	(-) 11%	(-) 14%	(-) 7%	(-) 8%
High impact	(-) 18%	(-) 19%	(-) 12%	(-) 12%	(-) 18%	(-) 23%	(-) 11%	(-) 11%

Table 3.7: BCR percentage changes for a low price shock, in the case of no climate change scenario (n=30 years).

	Baseline	GMPs	Vanilla intercropping	Cinnamon intercropping
DR = 3.5%	(-) 38%	(-) 41%	(-) 37%	(-) 33%
DR = 10%	(-) 31%	(-) 34%	(-) 34%	(-) 26%
DR = 13%	(-) 28%	(-) 30%	(-) 32%	(-) 23%

that: i) the cyclone occurs earlier, ii) life cycles are long and iii) discount rates are low (Appendix I). All three conditions need to be realised concomitantly for the WB to become an interesting investment opportunity. This is because longer lifetimes and lower discount rates better account for long-term benefits of the WB while at the same time shocks have more weight in the cost-benefit analysis due to the economic *preference for the present*.

Table 3.8: Economic results for baseline and windbreak in case of a cyclone hitting in year 30. (n=30 years, DR=10%)

	Baseline with shading	Windbreak
PV Revenues (USD 2016)	20 277	11 699
PV Costs (USD 2016)	14 924	12 102
NPV (USD 2016)	5 353	(-) 403
BCR	1.36	0.97
BCR relative to Baseline	1	0.71

In the case of a low clove price, the WB becomes advantageous even if the cyclone hits later in the future (Table 3.9). This occurs only under a low discount rate. If, instead, the cyclone hits early (year 7) the WB is always economically advantageous disregarding the discount rate or the time horizon applied (Tables 3.10 and 3.11). The explanations of this result lies on the one hand in the translation of the *"preference* *for the present"* mirrored by higher discount rates and the higher risk represented by cyclones when they occur early in time. On the other hand, this result is linked to the substitution of the clove trees by teak trees which partly buffers the low price shock of the baseline.

Table 3.9: Economic results for baseline and windbreak in case of a cyclone hitting in year 30 - low clove price. (n=80 years)

	Baseline with shading			Windbreak		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	32 135	14 108	11 683	20 868	9 615	8 512
PV Costs (USD 2016)	28 378	15 183	13 493	17 690	12 217	11 502
NPV (USD 2016)	3 758	(-) 1 075	(-) 1 810	3 179	(-) 2 602	(-) 2 983
BCR	1.13	0.93	0.87	1.18	0.79	0.74
BCR relative to Baseline	1.13	0.93	0.87	1.04	0.85	0.85

Table 3.10: Economic results for baseline and windbreak in case of a cyclone hitting in year 7 - low clove price. (n=80 years)

	Baseline with shading			Windbreak		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	26 461	10 331	8 850	18 834	8 604	7 774
PV Costs (USD 2016)	28 601	15 419	13 700	17 949	12 409	11 664
NPV (USD 2016)	(-) 2 139	(-) 5 088	(-) 4 850	885	(-) 3 805	(-) 3 890
BCR	0.93	0.67	0.65	1.05	0.69	0.67
BCR relative to Baseline	0.93	0.67	0.65	1.13	1.03	1.03

Table 3.11: Economic results for baseline and windbreak in case of a cyclone hitting in year 7 - low clove price. (n=30 years)

	Baseline with shading			Windbreak		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	14 912	9 690	8 637	11 169	8 309	7 680
PV Costs (USD 2016)	21 836	14 964	13 543	15 150	12 224	11 601
NPV (USD 2016)	(-) 6 923	(-) 5 274	(-) 4 906	(-) 3 981	(-) 3 915	(-) 3 920
BCR	0.68	0.65	0.64	0.74	0.68	0.66
BCR relative to Baseline	0.68	0.65	0.64	1.09	1.05	1.03

3.4 Discussion

In this chapter, a CBA for climate adaptation investment in Zanzibar's clove plantation was developed. The model is characterised by a developing country context with relatively high data uncertainty. Results are in line with other literature sources that suggest clove production is not profitable when clove prices are low (Crofts, 1959; Martin, 1991; Troup, 1932). This is probably why, during the field missions, farmers were often found to plant clove trees in complex agroforestry systems, the variety of species enabling them to compensate potential economic losses from some species with gains from others. CBA results also indicate that vanilla and, interchangeably, cinnamon intercropping and GMPs are *no-regret* options that perform well under the different scenarios analysed (high prices, low prices, drought under RCP 4.5 and RCP 8.5 under low and high impact) including when climate change is not considered. Instead, the WB is only financially advantageous under specific socio-economic circumstances: this occurs when jointly considering long time scales of project implementation (80 years compared to 30 years), early occurrence of the cyclone (year 7 or year 15) as well as when low discount rates are applied (3.5%). As expected, the later the cyclone occurs, the less economically viable the WB becomes according to the CBA. Thus, BCRs of the WB exceed that of the baseline with a result of 1.78 compared to 1.45 in the case of cyclone in year 7 and a 80-year project lifetime, while it exceeds the baseline only by a few points if the cyclone occurs in year 15 (1.64 compared to 1.62). This is slightly different when clove prices are low, in which case the WB becomes economically viable also under 30-year project lifetime considerations. This is so because the remuneration of clove production does not exceed the benefits from the cyclone impact reduction by so much compared to the situation in which clove prices are high.

As mentioned previously, clove prices are volatile and depend on multiple interacting factors that cannot be easily controlled and accounted for in a CBA: the varying crop cycles and climate conditions, the trade position of Indonesia as the driving clove producing and consuming country, the Indian demand for Zanzibar cloves as well as the position of the Zanzibar State Trade Corporation which, as a state monopoly, is able to regulate the country specific price of cloves in Zanzibar (Indufor, 2013b; Martin, 1991). An analysis of expected returns and their variances with price distributions for all crops may show the benefits of crop diversity under variable crop prices. Some may also argue that modelling cyclones as probability events rather than What-if scenarios may better reflect the reality – if probabilities were known.

Due to the research objective of the study, the choice was made to avoid complexity by only conducting a financial CBA. This model therefore does not account for potential economic costs that could arise, for example from harvest injuries and deaths. Neither did the model count in less tangible yet important benefits that can potentially be grasped from the diversification of cultivation and improved food security (Mbow, Van Noordwijk, et al., 2014) as well as from reduced GHG emissions and erosion control of forests (Abbas et al., 1995; Mbow, Smith, Skole, Duguma, & Bustamante, 2014) and which are likely to be substantial (Mbow, Smith, et al., 2014; Mbow, Van Noordwijk, et al., 2014).

However, even if this information had been integrated, a variety of other uncertainties would likely have persisted and challenged the analysis. In fact, there are a number of other variables that are tied to high uncertainty such as the type, frequency and magnitude of climate change occurrences and their possible impacts on clove plantations but also the prices, climate reaction of the variety of other crops that build the agroforestry system, as well as a number of additional agronomic aspects linked for example to their susceptibility to thrive or to disappear, create synergies or negative symbiosis with other crops. Importantly, this model is simplified to that of a decision-maker taking a decision once and for all. This is disregarding the possibility they can change their minds and adapt to new socio-economic circumstances. Decision-making in the real world consists in infinite decision periods and alternative investment options for which many more complexities need to be accounted for than those that could be modelled in this study. In addition, adaptation investments such as a windbreak to protect from potential cyclones may be at stake in *regional* investment planning that would allow costs to be distributed across actors at risk rather than born by an individual farmer seeking to protect its own plantation. Of course, this comes in addition to ethical questions as to whether the preference for the present truly prevails in intergenerational and public investments and which is relevant in the concept and structure of cost-benefit models.

Modelling the investment in a one-hectare clove plantation therefore requires to account for many variables simultaneously – partly requiring expert knowledge – and this is challenging for an analyst. Relatedly, it may be difficult to identify an exhaustive list of all costs and benefits and the trade-offs they may imply. This is partly due to the nature of modelling which requires to set boundaries of a system under analysis, which does not exist in reality thus challenging the analyst in its cognitive limitations. For instance, there could be incomplete knowledge as well as ignorance about a complex agroforestry systems and clove plantations. Partly, this may also be due to the simplification that modelling requires and which was mentioned earlier. Thus, even by reducing the information gap, certain uncertainties are likely to remain unavoidable and this has always needed to be dealt with in decision-making.

In this cost-benefit model as in real world economic assessments, many assumptions are taken and many may also be deliberately or un-deliberately discarded. In both cases, important factors are likely neglected at the cost of biasing the analysis. In other words, the reality of an investment and its possibly irreversible consequences is dictated by a model of questionable constructs (Zyphur & Pierides, 2020). This comes in addition to the weaknesses that have already been mentioned in the literature regarding CBAs (Wegner & Pascual, 2011) despite its numerous advantages that are reported for policy appraisal. It is likely for this reason that in some places, CBAs have been avoided in environmental assessments (Joseph, Gunton, Knowler, & Broadbent, 2020). Nevertheless, the methodology may remain complementary to alternative project appraisal techniques such as impact assessments, multi-criteria analysis or robust decision-making techniques. In any case, it is imperative that policy-makers and stakeholders are always made aware of model assumptions and uncertainties underpinning the cost-benefit models and which directly determine results (Tennøy, Kværner, & Gjerstad, 2006).

3.5 Conclusions

In this chapter a CBA was applied to the integration of climate adaptation in the rehabilitation of clove plantation. This was recognised as a priority of action for policy-makers of the Revolutionary Government of Zanzibar during the National Adaptation Action Plan process in the summer 2016. From the field work and semi-structured interviews undertaken with different actors of the clove sector in Zanzibar, good management practices, cinnamon, vanilla and a WB were found to be possible options for adapting to climate change. These are already implemented on Pemba island in a fragmented way and the intention was to investigate if they are economically viable to be generalised. From a methodological point of view, this chapter's objective was to evaluate whether the CBA is an appropriate economic assessment tool or whether high uncertainty contexts reduce the CBAs relevance for policy recommendation. NPVs of the current (baseline) and future climate situation (low rainfall and cyclones) were analysed and a comparison was done between the cases with- and without adaptation investment in order to understand the economic consequences of adaptation investment and which option, if at all, is most economically interesting according to the cost-benefit model.

Results showed that all adaptation options except the WB make economic sense even under no climate change. Specifically, the economic advantage of the WB is directly dependent on model assumptions. Thus, the preference of the present assumed in shorter time horizons and higher discount rates of the model make this option unviable even if in absolute terms a WB would intuitively make sense to be implement both for its preventive action against potential cyclones in the present as well as in the near and far future, and for other economic benefits it may grasp.

If the CBA remains an interesting economic decision-making tool, important limitations persist, and CBAs should be accompanied by a transparent analysis of the entire spectrum of assumptions and uncertainties that underlie the analysis, as well as by other project appraisal tools that provide different but complementary perspectives to decision-makers. Thus, we conclude the following:

- The quantitative outcomes from this analysis remain illustrative and should be taken with care in case policy recommendation is envisaged.
- The quantitative analysis can be improved and complemented with other assessment methodologies to serve for policy recommendation.
- The qualitative approach to model assumptions and uncertainties should accompany the CBA in all circumstances.
- More improvements are needed to incorporate decision periods in the CBA, as well as the introduction of path dependency, reversibility and irreversibility in decision-making.

Chapter 4

Adaptation decision-making in Zanzibar's clove plantations: extending the cost-benefit analysis to decision diagrams

4.1 Introduction

Uncertainties make investment decisions difficult because of limited knowledge or understanding about future expenditures and profits as well as their drivers, which constitute the main reason for investment (Dixit & Pindyck, 1994). There is evidence that human ability to predict is restricted (Hallegatte et al., 2012; Pindyck, 2006). Researchers have also found that there are important discrepancies between the services an investment output is designed to supply and its ability to do so during its lifetime which is due to changing boundaries of the context or system in which the investment output evolves, especially in the case of long investment design lifetimes (Neumann et al., 2015). Uncertainties originate from classical socio-economic circumstances that make investments risky, such as price volatility, preferences or political circumstances (Pindyck, 2006). The list has recently expanded to incorporate climate change in view of sound adaptation decision-making (Ranger, 2013).

The objective of this study was to expand the CBA developed in the previous chapter in the attempt to illustrate complexity in ways that make information more accessible, easy to understand and to interpret for non-experts and decision-makers. Another objective was also to investigate whether and how introducing uncertainties may improve the information base of the CBA. Therefore, the CBA for climate adaptation in Zanzibar's clove plantations was modified to include two decision periods instead of one, to incorporate probabilistic occurrences of uncertain variables and to allow for flexibility in investment decisions. The analysis was done by calculating probabilistic NPVs based on Markandya (2016) and by constructing decision diagrams or decision trees using a backward approach to decision-making based on Hertzler (2007).

4.2 Methodology, data and model assumptions

In this study, uncertainty was integrated by applying data from the previous chapter to the methodology as proposed by Markandya (2016) and illustrated using decision diagrams as developed by Hertzler (2007) and Sanderson, Hertzler, Capon, and Hayman (2016). Results were compared and discussed by verifying the relevance of this methodology for the Zanzibar case study and development project applications more globally. The approach is illustrative and seeks to complement the CBA by revealing underlying assumptions and showcasing uncertainties related to the CBA variables. It is also intended to be practical and user-friendly for development practitioners. Both policy recommendations and formal applications of these methodologies which are highly computational and resource intensive were not the object of this study.

4.2.1 Decision diagrams

According to Dixit and Pindyck (1994) the NPV criterion assumes the investment is either recoverable or it is irreversible in which case the investment is a *"take it or leave it"* decision. According to these authors, most investment decisions are in reality characterised by irreversibility, uncertainty and timing, and these can play an important role on the investment decision made.

As a consequence, the NPV rule requiring present value of the stream of net benefits to exceed zero as in Eq. 3.1 is extended (NPV_{option}) to allow for the possibility the decision-maker has to wait – or not – for more information, according to associated risks. The decision diagram approach suggests that the benefits from investment need to exceed the costs by the value of keeping the investment option (Hull, 2009). Therefore, investment should proceed if the sum of the net benefits of investment exceed the benefits from keeping the option of investing later (Eq. 4.1).

$$NPV_{\text{option}} = \sum_{t=0}^{n} \frac{B^t - C^t}{(1+DR)^t} - \text{Option Value} > 0 \leftrightarrow NPV > \text{Option Value} \qquad (4.1)$$

With decision trees, uncertainty and flexibility can be illustrated because possible alterations or alternatives to an initial investment decision can be modelled and compared. Decision trees or diagrams are visual illustrations of decision processes with multiple intricacies which enable to better disclose complex and incomplete knowledge about the *"states of nature"* (Hertzler, 2007) and related investment possibilities. They are a visual communication tool that assists in the reflection about complex decisions under risks and uncertainties and can help farmers and decision-makers to manage risk (Hertzler, 2007). In practice, this implies that results from a CBA can differ from those of the decision-tree approach. Two different types of results can emerge: a simple NPV can either indicate to immediately invest where decision-tree analysis conclude it is worth waiting for better information. On the opposite, it can indicate an investment is not cost-efficient where decision trees indicate it might make more sense to invest now (Mediation, 2013; Pindyck, 2006)). The extension of the CBA proceeded in two steps to integrate assumed and exogenous uncertainties of climate change occurrence and clove prices as developed by Markandya (2016) and to illustrate different possible decision pathways in the form of decision diagrams as sown by Hertzler (2007).

Decision trees are simplifications of decision pathways, yet they are complex. The illustrative example was therefore limited to the GMP and WB options. Calculations of expected values are detailed for the GMP example as compared to the baseline in Appendix J. Analogical calculations were done for the WB. The ranking of all options used in the CBA goes beyond the objective of this study.

4.2.1.1 Calculations of expected values

In the earlier analysis investment decision were made once for all in the first year, year 0 in this case. Decision diagrams are illustrations of decision pathways composed of different periods in which adaptation decisions can be made. For simplicity, we therefore adjusted the one-period CBA to construct a two-period decision tree as follows.

- Period 1 (P1) covering years 0 to 5
- Period 2 (P2) years 6 to 30.

It was considered that the first period covers a reasonable length of time during which the investment context can be monitored for new information to arise, in order to make adequate investment decisions previous to the second period. Prior to the beginning of each period, the investor may make an investment decision for the upcoming period with the available information they have. Firstly, it was assumed that there is no climate change in P1 and climate change occurs with probability Pr_{CC} in P2. According to this information, the investor has the option to invest in GMPs or in the WB in either period. Secondly, for each of these periods P1 and P2 as well as for each investment option, the CBA model from Chapter 3 was used to calculate discounted costs, discounted benefits and NPVs in the case of no climate change (no CC) and climate change occurrence (CC). For the GMP case, climate change in form of low rainfall under RCP 4.5 high impact (70%) was used. For the WB calculations, a *what-if* scenario of a cyclone hitting in year 7 was considered. Costs and benefits in the first year of both periods were discounted by a factor of one. Thirdly, to reflect the climate uncertainty different probabilities for climate change were applied as in (Markandya, 2016) and expected values of these investments under different possible climate probabilities were calculated (Table 4.1). Fourthly, to facilitate the calculation of expected values for different decision pathways, specific subscripts were assigned to each of the NPVs calculated from Table 4.1 in order to identify the assumptions under which NPVs occur (Table 4.2). Only considering climate change as a source of uncertainty results in six different NPV realisations depending on assumptions about adaptation (B or GMP), climate (CC or no CC only in P2) and period (P1 or P2). Finally, using results from Table 4.3, expected values were calculated that account for different possible decision pathways in P1 and P2: B and GMP throughout both periods which are noted $E_{1B,\ 2B}$ and $E_{1GMP,\ 2GMP}$ respectively, as well as pathways that account for reversibility: GMP in P1 combined with B in P2, noted $E_{1GMP,\ 2B}$ and conversely $E_{1B,\ 2GMP}$. $E_{1B,\ 2B}$ and $E_{1GMP,\ 2GMP}$ can also be interpreted as not investing (keeping B) and investing (in GMP) throughout both periods.

Considering probabilities for climate change and no climate change, to respectively be Pr_{CC} and Pr_{noCC}, following expected values were obtained in Eq. 4.2 – Eq. 4.5 as follows. Eq. 4.2 reflects the fact that if a farmer decides not to invest in any adaptation option in P1 nor in P2 the expected result $E_{1B,\ 2B}$ is the sum of expected value of not investing in P1 and the expected value of not investing in P2. Both expected values will depend on the probability of CC (and noCC) occurring in P1 and P2.

$$E_{1B,\ 2B} = NPV_{1B}^{noCC,H} + NPV_{2B}^{noCC,H} \times Pr_{noCC} + NPV_{2B}^{CC,H} \times Pr_{CC} \quad (4.2)$$
$$E_{1B,\ 2GMP} = NPV_{1B}^{noCC,H} + NPV_{2GMP}^{noCC,H} \times Pr_{noCC} + NPV_{2GMP}^{CC,H} \times Pr_{CC} \quad (4.3)$$
$$E_{1GMP,\ 2B} = NPV_{1GMP}^{noCC,H} + NPV_{2B}^{noCC,H} \times Pr_{noCC} + NPV_{2B}^{CC,H} \times Pr_{CC} \quad (4.4)$$
$$E_{1GMP,\ 2GMP} = NPV_{1GMP}^{noCC,H} + NPV_{2GMP}^{noCC,H} \times Pr_{noCC} + NPV_{2GMP}^{CC,H} \times Pr_{CC} \quad (4.5)$$

Tables 4.1 to 4.4 were used as working tools to feature these computations in which high clove prices were assumed and a discount rate of 10% as a middle of the road scenario considered in the CBA. Climate change reflects the low rainfall projected under RCP 4.5 Model 4. This process was iterated for the scenario of low clove prices in order to introduce clove prices as a second uncertainty in the analysis along climate change. The following equations Eq. 4.6 to Eq. 4.9 were used to calculate the combined expected values that account for both climate and price uncertainty in P2:

$$E_{1B,\ 2B} = NPV_{1B}^{noCC,H} + \left(NPV_{2B}^{noCC,H} \times Pr_{noCC} + NPV_{2B}^{CC,H} \times Pr_{CC}\right) P_H + \left(NPV_{2B}^{noCC,L} \times Pr_{noCC} + NPV_{2B}^{CC,L} \times Pr_{CC}\right) P_L \quad (4.6)$$

$$E_{1B,\ 2GMP} = NPV_{1B}^{noCC,H} + \left(NPV_{2GMP}^{noCC,H} \times Pr_{noCC} + NPV_{2GMP}^{CC,H} \times Pr_{CC}\right) P_H \left(NPV_{2GMP}^{noCC,L} \times Pr_{noCC} + NPV_{2GMP}^{CC,L} \times Pr_{CC}\right) P_L \quad (4.7)$$

$$E_{1GMP,\ 2B} = NPV_{1GMP}^{noCC,H} + \left(NPV_{2B}^{noCC,H} \times Pr_{noCC} + NPV_{2B}^{CC,H} \times Pr_{CC}\right) P_H + \left(NPV_{2B}^{noCC,L} \times Pr_{noCC} + NPV_{2B}^{CC,L} \times Pr_{CC}\right) P_L \quad (4.8)$$

$$E_{1GMP,\ 2GMP} = NPV_{1GMP}^{noCC,H} + \left(NPV_{2GMP}^{noCC,H} \times Pr_{noCC} + NPV_{2GMP}^{CC,H} \times Pr_{CC}\right) P_H + \left(NPV_{2GMP}^{noCC,L} \times Pr_{noCC} + NPV_{2GMP}^{CC,L} \times Pr_{CC}\right) P_L \quad (4.9)$$

4.2.1.2 Decision diagram illustrations

In a second stage, the work developed by Hertzler (2007) was adapted to produce decision diagrams and visually illustrate the possible decision pathways according to different available climate information in P2. Essentially, the decision trees use the information calculated in step 1 to illustrate the decision problem.

Figure 4.1 shows the structure of a decision tree. At the bottom of the diagram are the descriptions of the different stages of the system. These include the different possible decisions that can be made (squares) as well as the different states of nature that describe the decision environment, the context and the information that drives a specific decision (circles) as described in Hertzler, 2007. Decisions that can be made are B or GMP and the decision environment are climate and no climate change occurrence. Each stage initiates with a state of nature followed by a decision. States of nature are linked to a decision by dashed lines while decisions are linked to subsequent states of nature by continuous lines. Near those lines the probabilities of occurrence of the different states of nature were recorded. Unlike for example process maps, decision diagrams are drawn backwards from P2 back to P1, as explained by Hertzler (2007): in P2, climate change can be realised or not, resulting in different net revenues depending on the option chosen in the final stage of the diagram (right hand side of the figure). The farmer can decide whether to invest in GMPs or not, given the climate information available to them at that moment. The analysis therefore began by considering the four possible investment decisions in P2 (fourth column in Figure 4.1). For each case, the sum of discounted costs was reduced from the sum of discounted benefits for each newly introduced decision period to calculate the NPV.

	Period 1				Period 2				Pr_{CC}	Expected Value
	Costs		Benefits		Costs		Benefits			
	No CC	CC	No CC	CC	No CC	CC	No CC	CC		
B		/		/					10%	$E_{1B,\ 2B}$
GMP		/		/					10%	$E_{1GMP,\ 2GMP}$
B		/		/					50%	$E_{1B,\ 2B}$
GMP		/		/					50%	$E_{1GMP,\ 2GMP}$
B		/		/					90%	$E_{1B,\ 2B}$
GMP		/		/					90%	$E_{1GMP,\ 2GMP}$

Table 4.1: Calculation of expected values without investment reversibility - two periods - two climate scenarios (no CC and CC - low rainfall). Period 1 includes year 0 to year 5 and period 2 yeas 6 to year 11. Adapted from (Markandya, 2016).

	Period 1		Period 2		Pr_{CC}	Expected Value
	NPVs		NPVs			
	No CC	CC	No CC	CC		
B	$NPV_{1B}^{no\ CC,H}$	/	$NPV_{2B}^{no\ CC,H}$	$NPV_{2B}^{CC,H}$	10%	$E_{1B,\ 2B}$
GMP	$NPV_{1GMP}^{no\ CC,H}$	/	$NPV_{2GMP}^{no\ CC,H}$	$NPV_{2GMP}^{CC,H}$	10%	$E_{1GMP,\ 2GMP}$
B	$NPV_{1B}^{no\ CC,H}$	/	$NPV_{2B}^{no\ CC,H}$	$NPV_{2B}^{CC,H}$	50%	$E_{1B,\ 2B}$
GMP	$NPV_{1GMP}^{no\ CC,H}$	/	$NPV_{2GMP}^{no\ CC,H}$	$NPV_{2GMP}^{CC,H}$	50%	$E_{1GMP,\ 2GMP}$
B	$NPV_{1B}^{no\ CC,H}$	/	$NPV_{2B}^{no\ CC,H}$	$NPV_{2B}^{CC,H}$	90%	$E_{1B,\ 2B}$
GMP	$NPV_{1GMP}^{no\ CC,H}$	/	$NPV_{2GMP}^{no\ CC,H}$	$NPV_{2GMP}^{CC,H}$	90%	$E_{1GMP,\ 2GMP}$

Table 4.2: Terminology and subscripts for NPVs and respective expected values. This table uses benefit and cost figures from Table 4.1 to calculate NPVs and expected values.

Sources of uncertainty	Period 1		Period 2	
	B	GMP	B	GMP
CC	$NPV_{1B}^{no\ CC,H}$	$NPV_{1GMP}^{no\ CC,H}$	$NPV_{2B}^{no\ CC,H}$	$NPV_{2GMP}^{no\ CC,H}$
	/	/	$NPV_{2B}^{CC,H}$	$NPV_{2GMP}^{CC,H}$

Table 4.3: Terminology and subscripts for NPVs and expected values including price information. $NPV_{1B}^{noCC,H}$ stands for the NPV in P1 for the Baseline (B) under no climate change (no CC) and high prices (H). NPVs are calculated as the sum of discounted benefits minus the sum of discounted costs.

		Period 2	
		B	GMP
Period 1	B	$E_{1B,\ 2B}$	$E_{1B,\ 2GMP}$
	GMP	$E_{1GMP,\ 2B}$	$E_{1GMP,\ 2GMP}$

Table 4.4: Terminology and subscripts of expected values with investment reversibility. $E_{1B,\ 2B}$ stands for the ”Expected value of not investing in P1 and/if not investing in P2”.

The NPVs were then transcribed a step back in the corresponding state of nature with or without climate change (third column in Figure 4.1). To these results, hypothetic climate probabilities were applied to calculate the expected values for P2, provided uncertainties and new information about climate change can arise at the beginning of that period (arrows between P1 and P2 in Figure 4.1). To calculate the overall expected values that cover investments in P1 and P2 (second column in Figure 4.1) the NPV of each investment decision in P1 was added to the expected value for P2. As in step one, the highest expected value over P1 and P2 represents the best investment decision according to this methodology. This led to the resolution of the overall expected value over the two periods of time, which consisted of adding the climate change probability-weighted NPV in P2 to the NPV in P1 (second column in Figure 4.1). Continuing backwards, the first period begins with the current climate and the current production system without any adaptation. Analogically, the decision tree with two uncertainties in P2 – climate and price uncertainties – was then constructed to obtain a decision diagramme as shown in Figure 4.2.

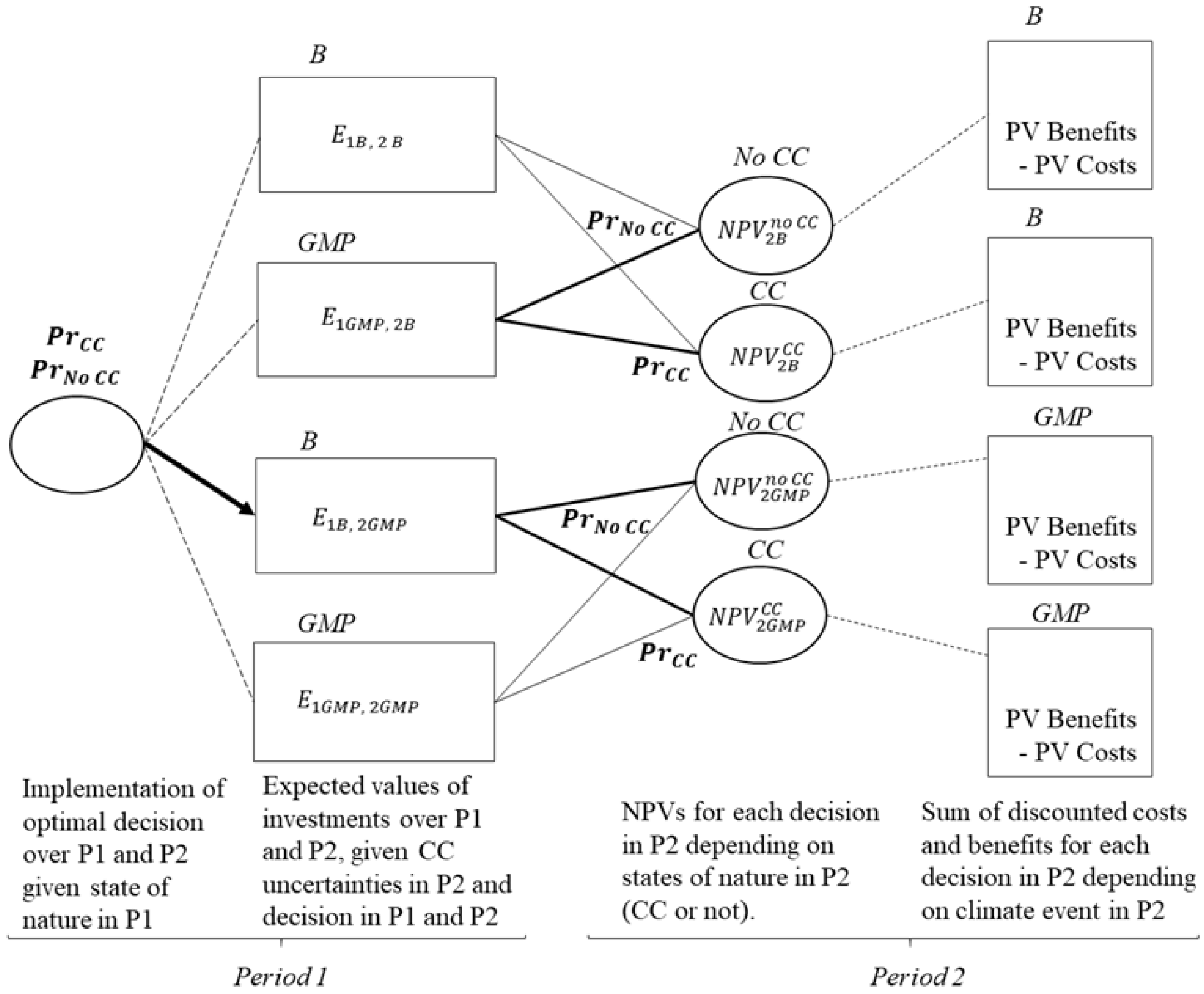

Figure 4.1: Structure of a decision diagram for optimal investment given climate uncertainties in P2. Probability for climate change in P2 is Pr_{CC}. Decisions can be made prior to year 0 for P1 and prior to year 6 for P2. In P2 only climate change is a source of uncertainty. In P1, prices were assumed to be high and there is no climate change.

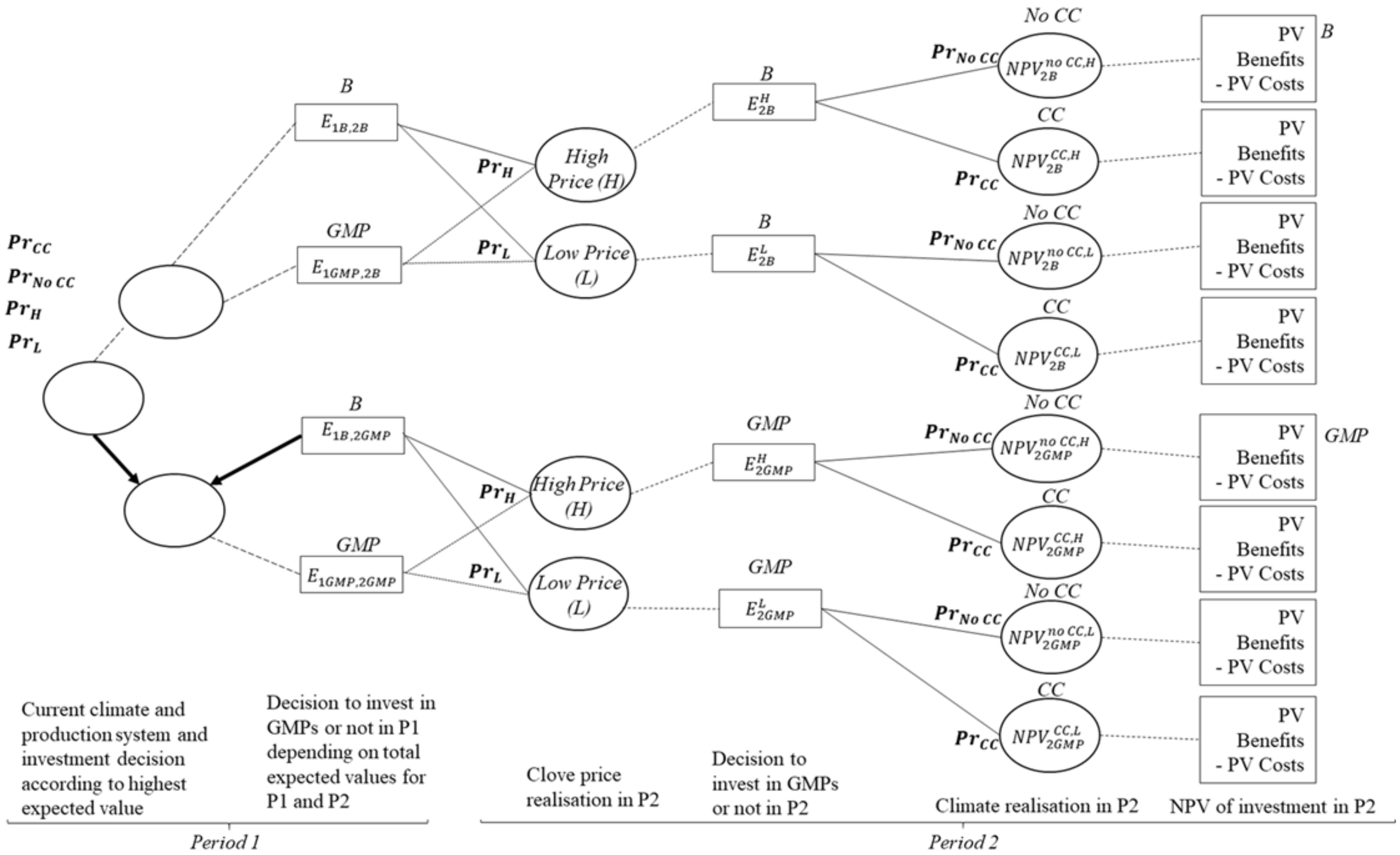

Figure 4.2: Structure of a decision diagram for optimal investment given climate *and* price uncertainties in P2. The probability for climate change (no climate change) in P2 is Pr_{CC} (Pr_{noCC}). The probability for high (low) clove prices in P2 is Pr_H (Pr_L). Decisions can be made prior to year 0 for P1 and prior to year 6 for P2. In P2, both climate change and clove prices are sources of uncertainty. In P1, prices were assumed to be high and there is no climate change.

4.2.2 Sensitivity analysis

In Chapter 3, a sensitivity analysis was undertaken for the CBA results to show the effect of main model assumptions on adaptation performances and stress test the results on the range within which economic performance indicators might oscillate. This was applied to the low vs. high clove prices, to the magnitude of the rainfall impact on clove production, to the discount rates and the project lifetime considered.

As regarding the decision trees, two main changes are made. Firstly, the climate probability was varied from low (0.1) to high (0.9). Secondly, a second uncertainty was added to the analysis moving high clove prices to low clove prices, using CBA results obtained in the previous analysis. Finally, results were verified combining high climate change probabilities with high probabilities of low clove prices to analyse economic results under a worst case scenario. The structure of the decision tree that includes climate and price uncertainties is shown in Figure 4.2.

4.3 Results

In this section, the outcomes from decision diagrams using the CBA product as a basis are presented. All CBA results that built the foundations for the decision diagrams and the sensitivity analysis can be found in Appendix I. Detailed methodological steps of calculations and illustration of decision trees are presented for the GMP in Appendix J.

4.3.1 Good management practices

By accounting for climate uncertainty which initially assumes 70% production reduction in case annual rainfall is lower than 1 000mm, results previously obtained with the CBA without uncertainty are confirmed: GMPs are always superior to the baseline if climate change probabilities are included in the form of drought conditions: by increasing the climate change probability, the expected values of GMP over P1 and P2 always exceed the expected values of the baseline over the same periods (Table 4.5 and Appendices J.1 and J.2). This is because the benefits from GMPs are high enough to compensate the initial investment they require as well as the potential impact of drought on clove production.

	Period 1		Period 2		Pr_{CC}	Expected Value
	NPVs No CC	NPVs CC	NPVs No CC	NPVs CC		
B	(-) 3 375	/	15 558	8 729	10%	11 500.1
GMP	(-) 3 787	/	20 106	14 864	10%	15 794.8
B	(-) 3 375	/	15 558	8 729	50%	8 768.5
GMP	(-) 3 787	/	20 106	14 864	50%	13 698
B	(-) 3 375	/	15 558	8 729	90%	6 036.9
GMP	(-) 3 787	/	20 106	14 864	90%	11 601.2

Table 4.5: NPVs and expected values for GMP and Baseline investments without decision reversibility - High clove prices. Two periods and climate scenarios, No CC and CC. NPVs are expressed in 2016 PPP USD.

However, results are different when calculating the combined expected value where decision reversibility between P1 and P2 is introduced. In that case, the rule of the highest expected value shows that it is economically advantageous to remain at baseline in P1 and wait for new climate information to arise to invest in GMP in the second period (Figure 4.3). This is so for both low and high climate change probabilities (Appendices J.4 and J.1 and Appendices J.5 and J.2 respectively) as well as for the application of low clove prices (Appendices J.9 and J.3). Implementing GMPs throughout both periods becomes a second best option in those cases.

According to this analysis, the optimal choice of the farmer is to maintain the baseline in the first period in all cases considered. They take advantage from waiting for new information to arise in period 2. Given the assumptions made in this model, not investing in the first period leads to investing in GMPs in the second period because $E_{1B,\ 2GMP} > E_{1B,\ 2B}$. This means GMP investments in the second period plays a crucial role in decision pathways, especially when climate change probabilities are high.

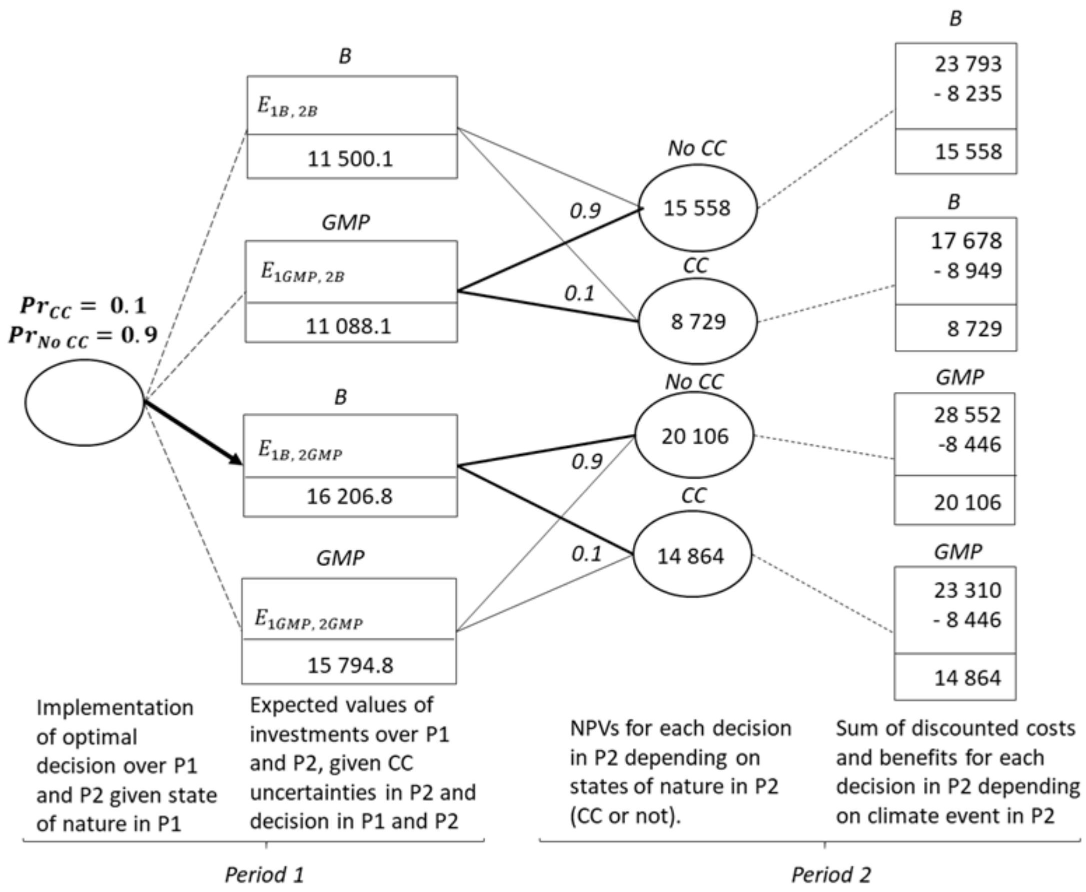

Figure 4.3: Decision diagram for optimal investment (GMP or Baseline) given climate uncertainties in P2. Probability for climate change in P2 is $Pr_{CC} = 0.1$. Decisions can be made prior to Y=0 (P1) and Y=6 (P2). Only climate change is a source of uncertainty in P2. In P1, prices were assumed to be high and there is no climate change. NPVs are expressed in 2016 PPP USD.

4.3.2 Windbreak

Introducing probabilities of occurrence of a cyclone that hits the island in year 7 does not change results obtained in the CBA in the first place. Thus, the WB firstly appears to never be economically advantageous even when increasing likeliness of cyclones (Table 4.6).

By allowing for decision reversibility between P1 and P2 expected values over P1 and P2 result being equal both for the baseline and for an investment in the WB in P1 and return to baseline in P2 (11221.7 USD PPP) (Figure 4.4). This means that according to the rule of the expected value, the decision-maker should be indifferent between investing in the baseline or in the WB in the first period, given that they will be investing in the baseline in the second period. Analogically, results for investing in the WB throughout P1 and P2 appears to be equal to investing in the baseline in P1 and then moving to WB in P2. This would mean that, counter-intuitively, keeping the baseline in P1 results to be more beneficial despite the cyclone impacts on the plantation at the beginning of P2. Similar results were obtained when applying high climate change probabilities , though expected values are more than three times lower in that case (for $E_{1B,\ 2B}$ and $E_{1WB,\ 2B}$ = 3531.3 USD vs. 11221.7 USD for high and low climate change probabilities respectively). Such results may be firstly attributed to the fact that both baseline and the WB are modelled in the CBA to require the same investment costs in the first period along with equal to zero benefits which only start in P2. In addition, the plantation of teak tree replaces 64% of the initially productive clove tree cover and reduces its production by the same percentage. This constitutes a substantial amount of forgone revenues for the plantation, which cannot be recovered by the amount saved through reduced cyclone impacts as modelled in the CBA.

	Period 1		Period 2		Pr_{CC}	Expected Value
	NPVs No CC	NPVs CC	NPVs No CC	NPVs CC		
B	(-) 3 375	/	15 558	5 945	10%	11 221.7
WB	(-) 3 375	/	12 704	5 034	10%	8 562
B	(-) 3 375	/	15 558	5 945	50%	7 376
WB	(-) 3 375	/	12 704	5 034	50%	5 494
B	(-) 3 375	/	15 558	5 945	90%	3 531.3
WB	(-) 3 375	/	12 704	5 034	90%	2 426

Table 4.6: NPVs and expected values for WB and Baseline investments without decision reversibility - High clove prices. Two periods and climate scenarios, No CC and CC (Cyclone occurs in year 7). NPVs are expressed in 2016 PPP USD.

	Period 1		Period 2		Pr_{CC}	Expected Value
	NPVs No CC	NPVs CC	NPVs No CC	NPVs CC		
B	(-) 3 375	/	4 446	- 3 378	10%	288.6
WB	(-) 3 787	/	1 239	3 414	10%	(-) 1 918.5
B	(-) 3 375	/	4 446	- 3 378	50%	(-) 2 841
WB	(-) 3 787	/	1 239	3 414	50%	(-) 1 048.5
B	(-) 3 375	/	4 446	- 3 378	90%	(-) 5 970.6
WB	(-) 3 787	/	1 239	3 414	90%	(-) 1 918.5

Table 4.7: NPVs and expected values for WB and B investments without decision reversibility - Low clove prices. Two periods and climate scenarios No CC and CC (Cyclone occuring in year Y=7). NPVs are expressed in 2016 PPP USD.

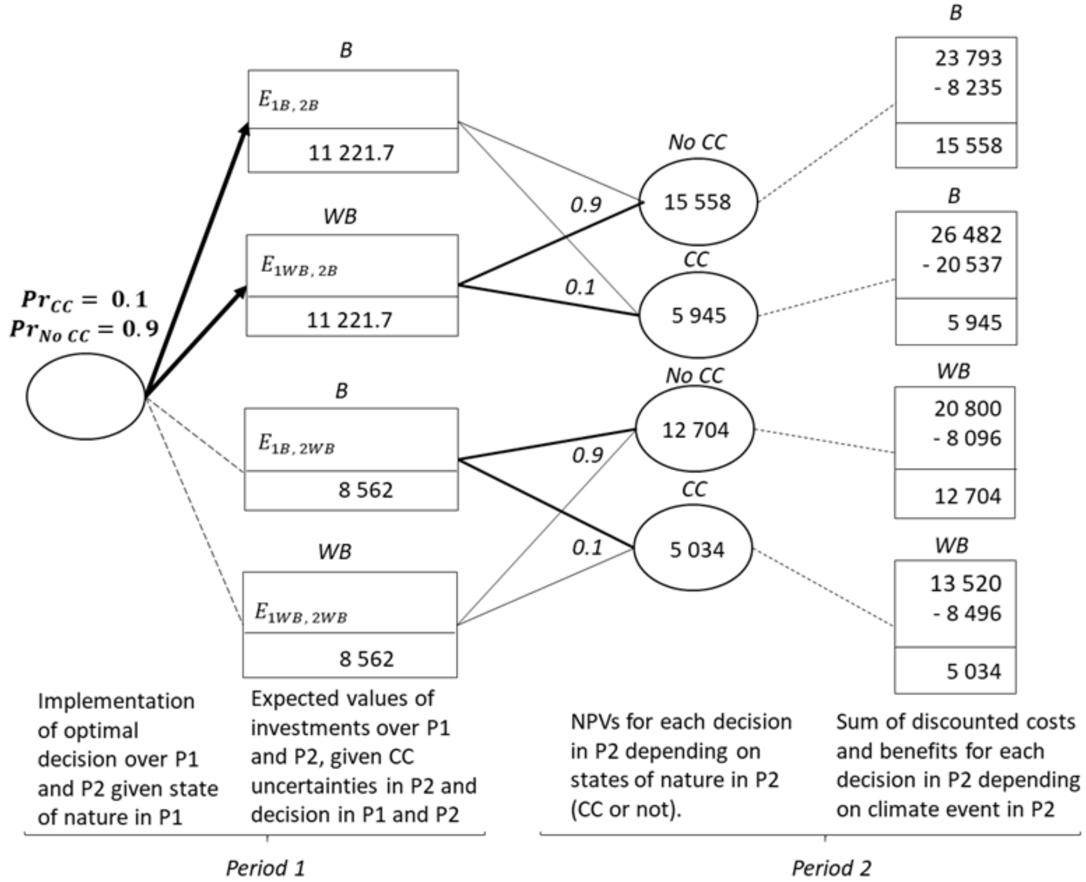

Figure 4.4: Decision diagram for optimal investment (WB or Baseline) given climate uncertainties in P2. Probability for climate change in P2 is $Pr_C C = 0.1$. Decisions can be made prior to Y=0 (P1) and Y=6 (P2). Only climate change is a source of uncertainty in P2. In P1, prices were assumed to be high and there is no climate change. NPVs are expressed in 2016 PPP USD.

When considering low clove prices however, the WB becomes relatively more advantageous than the baseline with increasing likelihood of climate change (Table 4.7). This means that the WB helps to buffer the combined impact of climate and price effects. Including price uncertainty therefore reverses the previous result in which B was the most profitable option in P2 independently of the choice in P1 and WB becomes the most advantageous option in P2 disregarding the decision made in P1. According to the rule of the expected value the decision-maker is indifferent in investing in WB or B in P1. Again, this is due to the equal cost and benefit structure of WB and B in the cost-benefit model as well as to the fact that with low clove prices, the revenues from clove are exceeded by the impact reduction of the WB when the cyclone hits the plantation at the beginning of P2.

4.4 Discussion

In this study an expansion of the CBA to decision diagrams was proposed in order to widen the information base that supports decision-makers in their investment choices. The CBA represented a model in which the farmer is able to make a decision once for all. Everything kept equal, this is disregarding the possibility they can change their minds and adapt to new socio-economic circumstances. In contrast, the decision diagrams enable the farmer to consider several time periods in which they can make decisions. Only two periods are modelled for simplicity, yet in reality these are actually a continuum of points in time in which a farmer can adapt to new information. Considering they can switch from an option to another between two periods, drawing decision diagrams enables them to visualise the different and combined decision pathways they can follow, and calculate their expected values as investment information change. From there, the farmer can calculate the option value of their investment in P1 that will optimise investment over both periods.

The decision diagram analysis shows that processing the complexity of investment information is important to reveal new information with alternative and illustrative methodologies. This firstly allowed to illustrate and better acknowledge assumptions of the CBA. Secondly, it may enable to make complexity more accessible to the non-expert community in which case it can become a useful and complementary tool for decision-making.

There are however important limitations to this CBA extension. Firstly, and most importantly, calculating combined expected values for two investment periods that are built from a unique cost and benefit sequence can possibly be misleading. In reality, creating two periods out of the CBA time sequence results to be complex if the objective is to combine the NPVs of different adaptation options. In this examples, it is assumed that waiting for new information to arise before making a new investment decision does not change NPVs in the second period so that second period costs and benefits of all options behave as if the same option was implemented in the first period. This may not always be verified because each cost-benefit time sequence entails a rational. If this can be assumed to be true for GMPs which do not require high capital investment, this distorts the reality of the WB investments which require high investment with long lifetimes. If we consider the expected value of remaining at B in P1 and deciding to invest in WB in P2 then the analysis requires to construct a new NPV that accounts for the full investment costs of that adaptation option. This also applies in the case in which the decision-maker invests in WB in P1 and then decides to get back to B in P2. Such transition requires to consider a new cost and benefit sequence of for example felling the teak trees and possibly account for timber revenues that enable then to replant clove trees. Put it differently, this model does not feature any path dependency ((Hallegatte et al., 2012)). This means that any decision in P1 can be changed assuming no cost. In fact, investment decisions can be irreversible and transition costs high enough to influence decisions. This may explain counter-intuitive results such as the indifference of the farmer to invest in WB or keep the baseline despite high cyclone probabilities in year 7. In fact, we expected to find a financial advantage for the farmer to invest in the WB in period 1 as opposed to remaining at baseline.

Even by introducing such changes, the structure of the CBA may be distorted, especially when considering the climate impact which is modelled to occur in specific years and which can be displaced in time with such adjustments. In fact, the decision diagrams result heavily depend on assumptions made under the CBA framework. The counter-intuitive results obtained for the WB is bound to the hypothesis made in the cost-benefit model: assumptions about the number of teak- that substitute clove trees, the relative loss this produces in terms of clove production compared to the reduced cyclone impact that the WB grasps, as well as on the climate projections and impacts. In reality, it may be more productive to protect more than one plantation with a WB which would increase the impact reduction effect while maximising clove production on all plantations and distributing costs among different farmers. Benefits of a windbreak in case of cyclones may also cover and protect a much greater area than just the clove plantation alone.

Secondly, modelling the investment in a one-hectare clove plantation also requires to account for many additional variables, especially the economic and social costs and benefits linked to clove production. It is difficult to identify an exhaustive list of these costs and benefits and the trade-offs these may imply. This is partly due to the nature of modelling which requires boundaries and which challenges the analyst in its cognitive limitations. For instance, there could be incomplete knowledge as well as ignorance about a complex system such as agroforestry systems and clove plantations. Partly, this is also due to the methodological choices made to avoid complexity, for example by only conducting a financial CBA. For instance, potential economic costs that could arise from harvest injuries and deaths were not accounted for. Neither were taken into account less tangible yet important benefits that can potentially be grasped from the diversification of cultivation and improved food security (Mbow, Van Noordwijk, et al., 2014) as well as from reduced GHG emissions and erosion control of forests (Abbas et al., 1995; Mbow, Smith, et al., 2014). These may however be substantial (Mbow, Smith, et al., 2014; Mbow, Van Noordwijk, et al., 2014). Starting with improving the CBA therefore may be a first step in simultaneously improving the complementary decision diagram analysis.

Thirdly, decision-making in the real world consists in infinite decision periods and alternative investment options for which many more complexities need to be considered than those that could be modelled in this study. Even for the analyst, such complexities may become quickly difficult to manage in a three dimensional world.

As a consequence of such limitations, this study should be used with care especially for policy recommendation. Instead, the decision diagram application has an important potential to be used in decision-making along with, and in complement to CBAs. Despite being potentially resource demanding which might prevent development practitioners to be willing to adopt such frameworks, decision diagrams enlarge the world views and possibilities that are modelled with a CBA. This is done in terms of decision pathways and sequences (several decision periods) but also in terms of states of nature that can prevail in a decision context (possible climate occurrences or price fluctuations). This is valuable information to support decision-making because it represents a more realistic description of reality in which there is a higher degree of reversibility and flexibility in decisions made.

4.5 Conclusions

This study suggested to extend a financial CBA to decision diagrams in order to complement results and verify if the decision diagram framework is increasing the knowledge base a CBA provides to inform decision-making. By including uncertainty and the possibility of the farmer to change their mind and adapt to new socio-economic circumstances after the initial GMP or WB investment decision, the decision diagrams brought a new perspective into the analysis. The two-period analysis confirms that GMPs are no-regret investment options when introducing both climate and price uncertainty. However, the decision-tree framework also revealed that the farmer would we better off by waiting for new information and keeping the baseline in the first period before investing in GMP in the second period. Nuanced results were also obtained for the WB compared to those of the CBA. The consideration of climate uncertainty showed that with increasing climate probability the WB becomes advantageous when clove prices are low, to the extent that it limits the combined impact from low clove prices and extreme events. However, counter-intuitive results were also obtained from the decision diagrams according to which the farmer is indifferent to investing or not in WB in the first period given they are sure to invest in WB in the second period.

Overall, results indicate that decision diagrams may be complementary to other investment appraisal tools in supporting decision-making. If the CBA remains an important economic decision-making methodology, then decision diagrams may support in revealing the complex and dynamic nature of decision pathways and decision contexts. In a nutshell:

- The quantitative outcomes from this analysis should be taken with care.
- The quantitative analysis can be improved to serve for policy recommendation.
- The qualitative approach of decision diagrams add value to the decision process in that it considers to optimise decisions in a more integrated manner.
- More improvements are needed in the CBA time period division process, the construction of periodical NPVs as well as the introduction of path dependency.

Chapter 5

Multiple perspectives of resilience: a holistic approach to resilience assessment using cognitive maps in practitioner engagement

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5.1 Introduction

Resilience has been at the centre of recent reflections on sustainability in the water and wastewater sector. It expands the usual scope of service reliability under standard loading to exceptional low probability/high impact events which have traditionally been neglected (Butler et al., 2017). The concept of resilience has become increasingly popular and is used in investment decisions. However, the focus of resilience in the water and wastewater industry is still predominantly technical in nature (Mullin & Kirchhoff, 2018).

In addition, despite interdisciplinary ambitions of the resilience community, the scientific literature shows that there are important dialectical forces at play between the natural/engineering sciences (resilience) and the social sciences (vulnerability) that are shaped by different world views and interpretations (Olsson et al., 2015). The distinction between engineering resilience, which aims at maintaining *"efficiency of functions"* and ecological resilience which aims at maintaining *"existence of functions"*, *"are so fundamental, that they can become alternative paradigms whose devotees reflect traditions of a discipline or of an attitude rather than a reality of nature."* (Holling, 1996). Similarly, resilience has different meanings in wastewater management, depending on the specific domain and objective it is applied to (Juan-García et al., 2017).

In this chapter, it is intended to move beyond the variety of definitions that exist in the literature (Juan-García et al., 2017) and do not seek a precise definition of resilience at the onset of the study. in the aim is to reveal how wastewater management practitioners perceive vulnerabilities and resilience of the wastewater system they are working in. The goal is twofold: firstly, to propose to practitioners a methodology that contributes to a better understanding of the wastewater system under study, bringing together various points of view that usually do not meet. Secondly, to contribute to addressing some of the gaps that Juan-García et al. (2017) identified in the wastewater sector (Table 5.1), to foster incorporation of resilience in wastewater management practice.

To do this, an approach is developed in which, starting from open-ended questions, cognitive maps in an engagement process with wastewater professionals are obtained. Cognitive maps are graphical illustrations of a person's "internal associative representations" (S. A. Gray et al. (2015), page 2). Such representations are elicited with logical structures such as causal diagrams. This new approach is tested for the Belfast area with Northern Ireland Water (NI Water) where multiple perspectives of resilience are obtained, informed by a wide range of agents, both internal and external to the water utility. This approach enables to identify opportunities for change, conflicting issues as well as potential barriers and unintended consequences of resilience interventions which may not be revealed by more narrowly defined resilience perspectives. It facilitates the development of a *"reflective"*, *"inclusive"* and *"integrated"* view of resilience, features that have been found to be largely missing in current practices (Juan-García et al. (2017), page 156). This permits to obtain a broader view in which human driven resilience

Table 5.1: Gaps identified in the literature and how we expect this study to contribute to addressing them. Gaps identified are based on the literature review of Juan-García et al. (2017)

Gaps identified in the literature on resilience of wastewater systems	**How this study is expected to address these gaps**
There is no common definition of resilience.	Each participant can present her/his personal view on resilience depending on her/his experience, knowledge and beliefs. It is not sought to define resilience at the onset of the study. Participants' subjectivity is used to elicit multiple perspectives of resilience.
Properties of resilience need to be *"reflective, inclusive and integrated"*.	The approach facilitates an assessment of resilience that is *reflective* (reflects experiences of practitioners in a discussion with the analyst that includes a cognitive mapping exercise of causal networks), *inclusive* (invites and includes participants of diverse responsibilities covering relevant internal and external actors), *integrated* (enables to account for feedbacks to and from other urban resources and frameworks; the comparison of the maps allows to obtain an integrated view across departments).
A comprehensive study of stressors to understand all potential vulnerabilities is lacking.	A wide set of agents is identified and invited in order to obtain a holistic view on potential vulnerabilities. Participants interpret the word "resilience" themselves and specifically include drivers that work on different spatial and time scales.
Resilience assessments are usually focused on physical stressors and technical interventions. There is a lack of qualitative assessments that integrate legal, social and governance variables into the physical assessment and that help understand extreme uncertainties.	Departments such as human resources, financing, legal, governance, environmental regulation are included to avoid over-focus on physical stressors and technical/engineering aspects of resilience.
Complementarity, connection and feedback of the wastewater framework to other systems, urban resources or broader asset management plans is missing.	External agents such as sister departments, for example, roads, energy, infrastructure, transport, environment are included. Encouraging participants to take a wide view on how the wastewater sector is embedded in urban and natural landscapes and processes.
There is a need for a standardised resilience framework that is flexible enough to capture specificities and allow its application in different case studies and enable comparison between cases.	The application of this approach to different contexts and sites will naturally highlight different dominating themes. Thus, qualitative comparisons are made possible. In addition, by adapting the interview question the approach has the potential of transferability to a broad range of specific subjects and domains.
To test the effectiveness of interventions, these have to be assessed holistically.	By facilitating a holistic assessment and eliciting propagation mechanisms of resilience through multiple causal networks that reveal feedback loops, the identification of unintended consequences is facilitated.

complements technical resilience and in which different urban systems and resources are interlinked (Table 5.1). The holistic assessment therefore may uncover more meaningful resilience interventions that address vulnerabilities at their origin. The methodology is intended for screening purposes prior to targeting specific resilience aspects with more technical and quantitative approaches including statistical and phenomenological modelling (Carpenter et al., 2009; Oppenheimer, O'Neill, Webster, & Agrawala, 2007).

The following sections present the resilience screening approach proposed (Section 5.2 and the results from its application to the Belfast wastewater system (Section 5.3). Section 5.4 discusses to what extent this study contributes to address some of the gaps identified in the literature and its potential value added for the water industry in general. Section 5.5 concludes suggesting possible pathways for future research about remaining challenges.

5.2 Methodology, materials and case study

With origins in cognitive psychology, which studies human learning and behaviour, cognitive maps are graphics for structuring and illustrating knowledge and beliefs (S. Gray, Zanre, & Gray, 2014). Cognitive maps are drawn around a specific question of interest by agents that are familiar with this domain. Thus, participants can structure, visualise and share their experience, understanding and interpretation.

5.2.1 Fuzzy Cognitive Mapping

Fuzzy cognitive mapping is an extension of cognitive maps, characterised by the use of cause-effect relationships to link cognitive concepts (Axelrod, 1976). In addition, FCM enables to indicate the perceived strength of cause-to-effect relations (Kosko, 1986) including for complex and abstract variables such as responsibility or political will which may be difficult to quantify otherwise (Özesmi & Özesmi, 2004).

Fuzzy cognitive maps have been reported to be of particular interest in domains characterised by complexity, vagueness, uncertainty, subjectivity and data scarcity (S. Gray et al., 2014). As cognitive maps, FCM allows to capture knowledge, experience and beliefs from participants about the functioning of a specific system to *"make [such] implicit assumptions (or mental models) explicit"* (A. J. Jetter and Kok (2014), p.

6). This is done during interviews in which professionals identify core variables and their interrelations using causal diagrams. Participants characterise the influence of one variable onto another by assigning a positive or negative sign and a metric between 0 and 1 (where 0 indicates "no influence" and 1 a "very strong influence").

Interviews are based on one or several open-ended questions that are the leading thread through the entire mapping process. The analyst's role is to guide the participants through the mapping exercise and mediate between the practical experience of practitioners and the requirements of the elicitation methodology. Participants take part in the process either in individual interviews or in working groups. In the latter case, participants discuss their views, cause-to-effect relationships, signs and strengths of each connection that altogether lead to a common model.

Because there are no requirements on the interview question itself, FCM is a flexible tool with many different possible applications. Beyond its initial use in the psychological realm, FCM has also been applied to topics as varied as the potential deployment of photovoltaic solar panels (A. Jetter & Schweinfort, 2011), vulnerability assessments of livelihoods (Murungweni, van Wijk, Andersson, Smaling, & Giller, 2011), risk assessments (Medina & Moreno, 2007) including financial systemic risk (Mezei & Sarlin, 2016), environmental management applications and ecology (Mehryar, Sliuzas, Sharifi, Reckien, & van Maarseveen, 2017; Özesmi & Özesmi, 2004), water resources management (Kafetzis, McRoberts, & Mouratiadou, 2014) and climate change research (Olazabal, Chiabai, Foudi, & Neumann, 2018; Reckien, 2014).

5.2.2 A holistic resilience assessment approach

5.2.2.1 Defining the objective and interview questions

To set up the participatory experiment, a questionnaire was designed (Appendix K) that seeks to address the problematic at hand while guiding the participants through the mapping process. The development of the questions resulted from interactions with NI Water senior managers and reflections about the focus and objective of the study on capturing multiple resilience perspectives and obtaining a broad set of potential interventions. The interview guidelines address two questions that would be elicited during the interviews:

Question 1. According to your experience, knowledge and expertise *how are drivers and characteristics of the system affecting resilience* of wastewater management at Northern Ireland Water (NI Water) for the Belfast area in the short-, medium- and long term?

Question 2. According to your experience, knowledge and expertise *which interventions/changes could increase resilience* of wastewater management at NI Water for the Belfast area in the short-, medium- and long term?

It was deliberately chosen to leave *the system*, *resilience* and *Belfast area* undefined, with the intention that the participants specify boundaries and reveal their own interpretations of these concepts. Besides, the notion of timescales was introduced (*short-, medium- and long term*), in order to capture the widest possible range of resilience drivers that can be identified and reduce the bias towards short-term priorities that professionals deal with on a daily basis.

5.2.2.2 Identifying relevant participants

Motivated by the idea of widening the range of resilience perspectives, the aim was to conduct mapping sessions with representatives from all departments and several hierarchical levels of the wastewater utility. In addition, principle agents were identified as potential interviewees outside NI Water. In view of identifying relevant participants a series of preliminary meetings was conducted with the heads of departments at the water utility. In some cases, one professional was selected to represent a department and individual interviews were conducted. In other cases, several people representing different areas of responsibility within the same department were nominated to participate in a group interview.

5.2.2.3 Planning the mapping sessions

Resilience mapping sessions were planned to last 90 minutes with the interest of encouraging experts' participation balancing their limited time availability with the need to introduce them to the methodology and develop the narratives and maps. At the beginning of the mapping sessions, the analyst needed to guide the participants step-by-step through the interview guidelines (Appendix K) and to clarify any questions and doubts that could arise. During the interviews the analyst needed to assimilate as well as possible the knowledge of the participants and ensure it is correctly captured according to the requirements of the FCM methodology. This necessarily demanded a dialogue between the analyst and the participants.

5.2.2.4 Conducting mapping sessions

Mapping sessions were structured in three different phases (Olazabal et al., 2018) (see Appendix K). In a first phase, participants were given time to individually brainstorm on the first interview question about drivers and characteristics of the system that affect resilience. They were then invited to start drawing the map with one of the concepts they have identified and to then add further concepts revealing the cascading cause-to-effect relations. If participants did not feel comfortable with the drawing process, the analyst could step in and draw the map based on the instructions of the participants. The process finalised once participants felt they have covered all their concerns. In the second phase, the same process was followed with the second interview question on resilience interventions. In the third phase, interviewees were asked to reflect on the sign and strength of each connection. The positive sign of a relationship refers to a positive influence of one variable on another (variables move in the same direction) while a negative sign means a negative influence (variables move in opposite directions). Weights were proposed to be a decimal number on a scale between 0 and 1 referring to the strength of each cause-to-effect linkage between two variables.

5.2.2.5 Narratives of resilience maps

To be able to capture the storyline revealed in the interview agreement was solicited from the participants to be able to voice-record the sessions that are later transcribed by the analyst (for confidentiality reasons these are not available to the reader). These recordings and transcripts served to develop a qualitative narrative that supplements the maps and facilitates comparison between them. This also allowed to obtain clarifications of elicited resilience drivers and rationales of system mechanisms and to revise maps if necessary.

5.2.2.6 Digitalisation of resilience maps

The digitalisation process consisted in a post-processing of hand-drawn maps. It included a structuring of the information, clarifying of concepts, removing relations that are double counted, revising incoherencies encountered and the translation of the causal diagrams into matrices.

5.2.2.7 Storylines and analysis

To complement the maps, the accompanying narratives were captured. In order to do this, the transcripts of the interviews were used to develop two types of accompanying documents. For each meeting the *Storyline* provides a summary of resilience mechanisms as uncovered in the original interview and the *Analysis* provides information about i) *Content*: analysts' interpretation of debated topics that are seen as potentially valuable points to further explore (content) and ii) *Methodology*: FCM related issues that may have been encountered during each interview (methodology) (Appendix N).

5.2.2.8 Comparing resilience maps

The analysis of multiple perspectives of resilience was obtained by comparing maps and storylines across interviews and by disentangling various resilience and vulnerability propagation mechanisms as elicited by the participants. To do this main themes that were discussed in all interviews were initially identified. Each map was then screened for concepts that relate to each of these themes so that resilience variables could be grouped accordingly. Any new theme that was not previously listed and that surfaced through the single-map analysis could be added. For each resilience theme the analyst then identified common and divergent mechanisms at work in the different resilience perspectives within and across maps.

5.3 Results

5.3.1 Belfast case study

In this case study 15 mapping sessions were conducted with a total of 31 internal and external participants from different backgrounds and areas of responsibility (Appendix L). The mapping sessions took place during November 2018.

The analyst needed to clarify the methodology to agents as these were often more familiar with process engineering diagrams rather than with causal diagrams. The analyst also invited participants to elaborate further on their explanations to be able to capture their rationale. Recordings and transcripts ensured that the original information could be accessed when processing the data. The analyst worked with the resulting maps (Appendix M), narratives and storylines (Appendix N) in parallel, in order to clarify resilience mechanisms and to analyse core themes as well as similarities and differences between resilience discourses that are examined in Section 5.3.2.

5.3.2 Emerging resilience themes in Belfast

This section examines what kind of information the suggested approach allows to reveal. In this analysis of resilience issues with regard to wastewater management specific to the Belfast area we identify and explore in the next paragraphs seven relevant resilience themes. In each subsection similarities and divergences across maps are disentangled. Additionally, the interconnectivity among themes is explored.

5.3.2.1 Capacity

In Belfast, capacity emerged as a central cross-cutting issue touching upon the different aspects of resilience. Illustratively, map M.10 (Figure 5.1) displays typical capacity limitations that are usually considered in the wastewater system: drainage capacity and wastewater treatment plant capacity (in terms of volume and quality). It specifically relates capacity with investment for storm tanks, maintenance of ageing assets to avoid sewer blockages and technology to improve effluent quality and monitoring. In other maps, participants related *capacity* to other complementary issues that are further elaborated in other sections. They include:

- divergent interests and a lack of alignment among governmental departments that may generate inefficiencies (see Section 5.3.2.3),
- the misuse of sewers that create frequent blockages and opportunity costs for the utility as well as illegal discharges into sewers and water bodies (see Section 5.3.2.4),
- the capacity to meet standards (see Section 5.3.2.5),
- skills and labour capacity that may put service delivery at risk and slow down innovation (see Section 5.3.2.6).

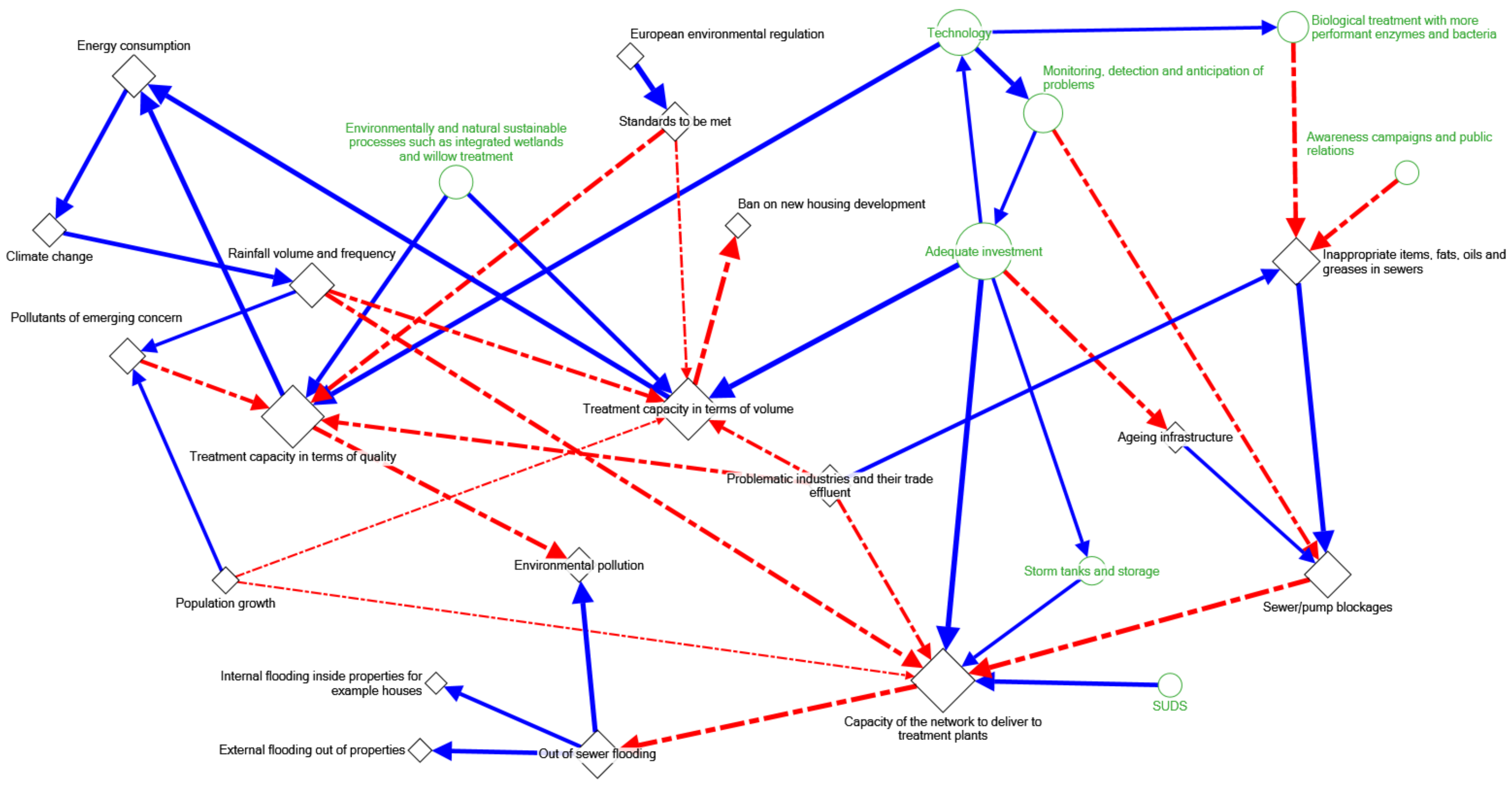

Figure 5.1: Capacity limitation types in wastewater infrastructure and propagation mechanisms of resilience drivers. Blue (full) arrows indicate a positive influence (for example an increase in concept A leads to an increase in concept B) whereas red (dashed) arrows indicate a negative influence (an increase in concept A leads to a decrease in concept B); black diamonds are system concepts related to resilience and vulnerability; green circles indicate elicited interventions to increase resilience. The size of each diamond and circle reflects the centrality which is the sum of the absolute values of all incoming and outgoing connection weights (degree centrality).

Various insights on unintended consequences were obtained. Firstly, incineration effluents of sludge treatment can potentially put a wastewater treatment plant at risk of insufficient capacity (map M.5). Secondly, as a consequence of shutting down frequently spilling combined sewer overflows, more water is diverted to treatment plants exacerbating the capacity of networks and treatment (map M.5). Thirdly, as improvements in treatment efficiency lead to better effluent quality, regulations may be further tightened which puts additional pressure on the utility (map M.1). Lastly, increased drainage and treatment capacity is considered to allow for economic growth which is commonly regarded as a driver of social welfare. However, economic development can have major consequences on the production of wastewater as well as on the acceleration of storm water runoff through increased soil imperviousness (map M.11). This then reduces drainage and treatment capacity (map M.2), eventually putting a strain on development objectives (map M.8, map M.13, map M.14). Such negative feedbacks can also be envisaged alternatively: if economic growth is oriented towards appropriate channelling of funding (map M.14), for example towards solutions such as sustainable urban drainage system (SUDS), then development constraints themselves can become opportunities for further economic growth (map M.7).

The portfolio of interventions to increase capacity spans across various domains (see Table 5.2). Besides engineering- and *hard* infrastructure solutions, *soft* interventions emerged to be equally important. Examples include the value of human capital in order to retain fundamental knowledge in the company (map M.4) and policy alignment to foster coherent policies in separate departments.

5.3.2.2 Costs, finance and investment

Limited funding in the Belfast wastewater sector has been historically leading to considerable investment needs (map M.15 and narratives in Item N). To address these, the Living with Water Programme (LWWP) has recently proposed a drainage and wastewater investment programme with a budget of approximately £ 900 M over the next 10 years (map M.12). Its objectives are to reduce the flooding risk in Belfast, comply with environmental legislation (for example, the Urban Wastewater Treatment Directive and the Water Framework Directive) and enable regional growth that has been constrained due to a lack of drainage and treatment capacity.

Ten out of 15 maps acknowledge funding and investment as a central component for resilience (map M.1, map M.2, map M.3, map M.5, mapM.6, map M.8, map M.10, map M.12, map M.13, map M.15). The wastewater sector is highly capital intensive and constantly forced to keep pace with change: firstly, urban development puts the wastewater sector under pressure because of the associated increasing sewer and drainage capacity requirements (see Section 5.3.2.1). Secondly, the wastewater sector needs to permanently adapt to tightening discharge standards (map M.1, map M.5, map M.10, map M.11) (see Section 5.3.2.5). This involves a complex dynamic between how fast the capacity requirements of the wastewater sector can react to changing demands from economic growth and shifting societal behaviour and norms. At the same time, the frequent drain blockages generate recurrent repair interventions in the city (map M.3, map M.11, map M.12) which represent a high opportunity cost in terms of regular base maintenance (map M.11).

It was highlighted that as a state-owned company, regulated by a regional economic regulator, the utility has little financial autonomy on budgets and decisions regarding total, capital and operational expenditures (TOTEX, CAPEX and OPEX) as well as on salary levels (see Section 5.3.2.6). According to some interviewees there is also a strong political barrier regarding the introduction of sewage and water charges that could reduce wastewater volumes due to lower water consumption (see Section 5.3.2.3).

Alternatively, some participants argued that even when the utility does not get all the funding it requests, the most important investments usually do get funded and that together with re-prioritisation (map M.12 and Item N) as well as risk management the highest possible value for the money invested can be obtained (map M.13 and Item N). Other participants, identified drivers that can facilitate a more effective use of available funds (map M.9): it was argued that accurate information (map M.9), network data (map M.6) and monitoring (map 10) may demand some initial financial support (map M.10) but in turn may improve justification for funding requirements and therefore facilitate budget approval. In other maps, interdepartmental policy alignment and collaboration are seen as levers to optimise the use of funding (map M.2, map M.8, map M.12) (see Section 5.3.2.3).

Table 5.2: Interventions that improve capacity directly or indirectly

Type of intervention	Intervention	Map
Awareness	Awareness campaigns	1, 10
	Awareness programmes celebrating pilot projects with successes and the promotion of positives	6
	Awareness and social responsibility for wastewater production and sewage usage	11
	Customer awareness to affect behaviour including water consumption	13
Structure	Sustainable urban drainage systems	5, 7, 8, 10, 12, 14
	Strom separation	15
	Storm tanks	7, 8, 1, 15
	River catchment management	5, 10
	Environmentally and natural sustainable processes	8
	Integrated Constructed Wetlands	10
	Runoff attenuation schemes by private developers	12
Funding	Funding and human resources	1
	Government budget for wastewater management	2
	Capital funding	3, 6, 8
	Adequate investment	10, 12
	Investment in surface water management and drainage	12
	Water and wastewater charges	6, 8, 13
Human resources	Funding and human resources	1
	Access to labour	2
	Diversity of employment pool, School campaigns for students in subjects such as science, technology, engineering and maths, Career development plans, Phased retirement policy, Training of new young workers	4
Policy alignment	Interdepartmental policy alignment (building regulations and planning, road services, public realm)	6, 11
	Alignment of investment proposals and aspirations	9
	Policy alignment (Rivers Agency legislation, Agricultural	11
	Department and diffuse pollution)	12
	Adequate urban planning to include and address wastewater	2, 8, 12
Technology	Technology	10, 15
	Artificial intelligence	14
Maintenance	Maintenance, management and replacement	1
	Maintenance of drainage infrastructure	8
Information accuracy	Network data accuracy	6
	Optimisation and integration of information	9
Others	Appropriate legislation	11
	Political will	8
	Climate change mitigation	8
	Monitoring for detection and anticipation of problems	10
	Regional Community Resilience Group	12

5.3.2.3 Governance and legal capacity

Policy alignment and cooperation between governmental departments was mentioned in many interviews as crucial for improving resilience. It was argued that cooperation favours coherent decision-making among policy departments, leads to a more effective use of funding as well as to incentives that foster a more responsible use of water resources and assets. The recent LWWP was seen as successful in addressing this issue, because it takes a basin wide perspective for drainage and deliberately set up a board of various governmental authorities that are committed to working together. Cooperation between governmental departments was deemed important to foster a common understanding of problems and identification of adequate solutions (map M.9 and Item N). In this way, synergies and economies of scale may be generated through a more effective use of funding (maps M.3, M.9, M.11, M.12). Examples include:

- River desilting by the department for rivers would reduce flooding (map 3) which would provide NI Water with additional discharge capacity into natural water bodies (map M.11 and Item N).
- Cooperation between the urban planning and rivers departments to prevent new urban developments in flood risk areas (map M.12).
- Appropriate desilting of sewers by road services would reduce maintenance costs for NI Water (map M.3).
- The need for integrated (catchment wide) water quality control was identified, especially the recognition of diffuse pollution from agricultural land use (map M.11). Sharing the burden with the agriculture sector could release pressure on the utility with a positive impact on water quality compliance (map M.9), the environment as well as on human health and wellbeing (map M.11).

Policy alignment and collaboration would also facilitate the identification of appropriate incentives for wastewater management as well as negative externalities that can arise from other socio-economic sectors. For example, wastewater services provided to residential users are financed through general taxes. This means that customers may not be aware of the value provided by the services and that there are no explicit stimuli that promote a responsible water consumption. However, although water charges could sensitise customers to an appropriate use of the wastewater system through lower water consumption, it was argued such charges have always been unpopular in Northern Ireland (map M.2 and Item N, map M.6) (see Section 5.3.2.4).

In addition, many participants identified that political will, resistance to change and civil responsibility are part of more complex societal processes that eventually affect the resilience of the wastewater system. As an example, Figure 5.2 (map M.6) is illustrated in which such dynamics are made explicit. For instance, legislation developed at higher levels of governance paves the way to social responsibility of individuals on the one hand and to coherent policies within governmental and non-governmental bodies on the other hand (map M.6, map M.9, map M.12).

In Northern Ireland the current absence of a functional government (map M.2, map M.6, map M.8) confers little credibility regarding the scope of policy to address the public interest (map M.6 and Item N) and this in turn provides little motivation for individuals to change behaviours.

Besides, it was also stressed that NI Water depends on decisions taken at higher political levels: its competitiveness relies on budgets and salary regulations decided by the central government which provides limited autonomy and thus limited space for innovation within the water utility (map M.6). Such influences of decisions at higher governance levels also become visible with the *"Brexit"* process which increases uncertainties about NI Water's logistical procurement modalities and costs (map M.2).

In other maps, participants argued that governance can also be driven by *"Individual action"*. This may be influenced by a societal context with increased public awareness about the imperatives of protecting natural resources and in which preferences of socially responsible individuals and businesses prevail. In this perspective, the voice of individuals plays a crucial role in striving for policy changes (map M.2). A counter-example was illustrated by the challenges of implementing SUDS. Currently, there is no clear assignment of responsibility for their maintenance (map M.8). Though SUDS should increase resilience in theory, they may therefore end up introducing new vulnerabilities (map M.8) (see Section 5.3.2.7).

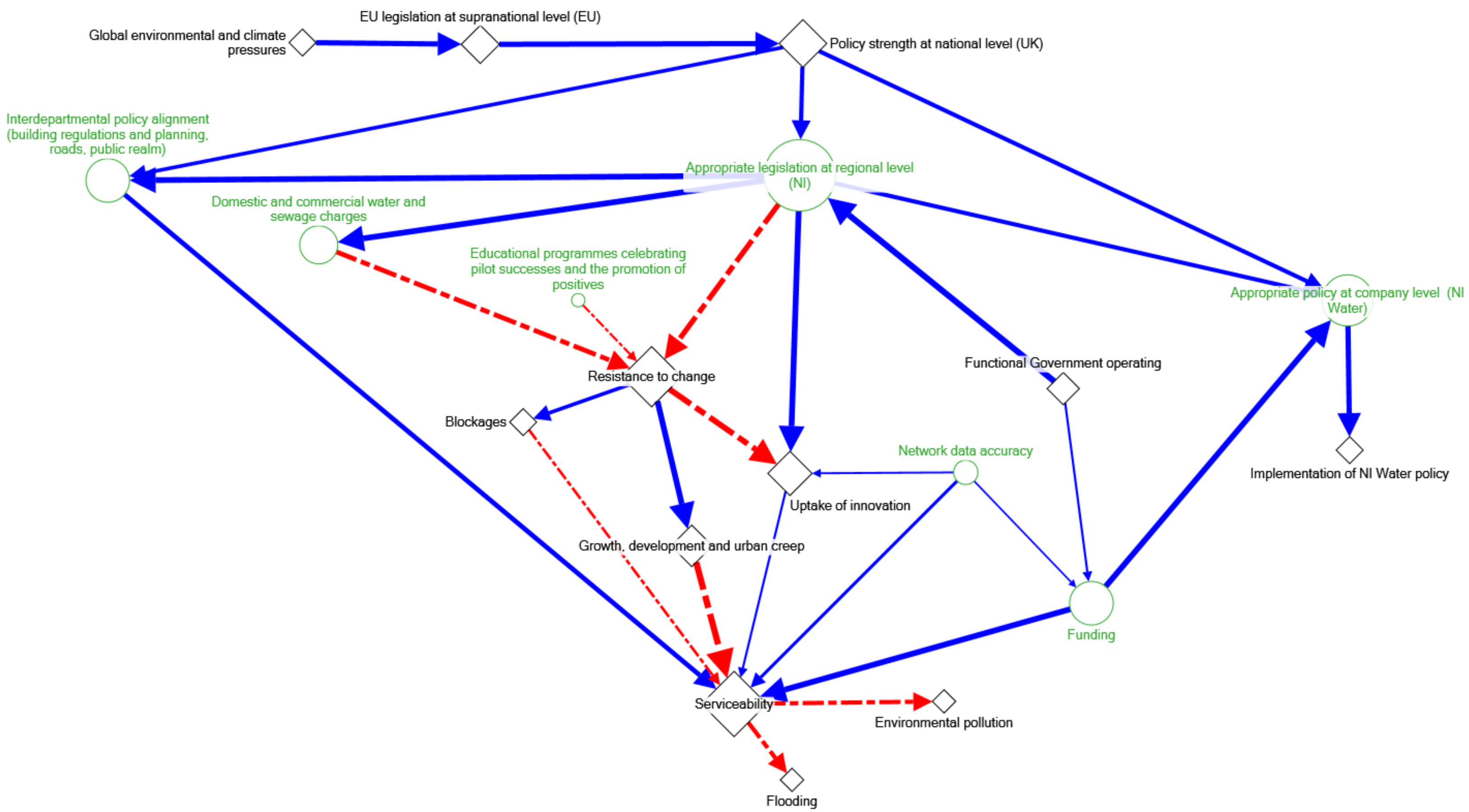

Figure 5.2: Resilience embeds governance and legal capacity in more complex social dynamics (map M.6). Blue (full) arrows indicate a positive influence (for example, an increase in concept A leads to an increase in concept B) whereas red (dashed) arrows indicate a negative influence (an increase in concept A leads to a decrease in concept B); black diamonds are system concepts related to resilience and vulnerability; green circles indicate elicited interventions to increase resilience. The size of each diamond and circle reflects the centrality which is the sum of the absolute incoming and outgoing connection weights (degree centrality).

5.3.2.4 Customer behaviour and responsibility

The misuse of sewers was identified as a core vulnerability in Belfast's wastewater system (map M.1, map M.11). Blockages are frequent due to inadequate amounts and types of solids in the network such as fats, oils and greases (FOGs) or inappropriate materials the system is not designed to cope with (baby wipes, clothes or kitchen paper). This was mentioned to be caused by a lack of awareness of the general public. The misuse of sewers often leads to in-street or out-of-sewer flooding and to combined sewer overflow discharges that pollute water bodies.

Participants highlighted that in Northern Ireland there are issues of illegal discharges into the sewer network and also directly into the environment. These come either from industries searching to reduce costs or from illegal activities. In Northern Ireland, high electricity costs and taxes do not incentivise industries to discharge wastewater correctly (map M.1). Neither does the absence of awareness about the impact of such discharges (map M.1, map M.2, map M.6, map M.11, map M.13). Interviewees reckoned that not all hotels or "fast-food" chains would make the effort of legal discharges if more convenient otherwise, even if discharges were free of charge (map M.1). In Northern Ireland, there is also illicit diesel produced through a transformation of agricultural diesel. Toxic by-products stemming from this illegal activity are released into the environment or into sewers. Conversely, it was argued that individual behaviours can also influence and promote legal changes through civil engagements, lobbies and the media (map M.2) (see Section 5.3.2.3).

5.3.2.5 Standards and compliance

Tightening of environmental standards were identified as a potential vulnerability for the utility as changes in standards can often occur at a faster pace than the infrastructure upgrades of wastewater facilities. At the same time, population growth and development make it more and more difficult to maintain the required thresholds. The associated increased likelihood of non-compliance can eventually lead to development constraints (map M.9) or to legal prosecution of the utility (map M.1, map M.5, map M.15). This leads to a permanent pressure on the utility to keep up with increasing demands (map M.15) (see Section 5.3.2.1).

It was observed, that both worsening and improving surface water quality can trigger a tightening of standards. Standards may tighten even if the performance of water utilities in terms of the quality of their final effluent increases, as water companies are expected to further improve on their performance (map M.1). This constitutes an unintended consequence for the water utility as, by performing well, it puts further pressure on operations to address increasing expectations. This is especially relevant in a catchment with sensitive water bodies such as Belfast.

5.3.2.6 Human capital

Continued high quality delivery of wastewater services relies heavily on human capital. With about 30% of NI Water personnel expected to leave the utility in the next ten years, the company faces potential vulnerabilities in terms of human resources as shown in Figure 5.3 (see also the map's narratives in Item N).

According to the interviewees the company needs to prepare for substantial changes. On the one hand, the ageing workforce at NI Water, and a competitive labour market, with high turnover rates among new employees may trigger a loss of skills and knowledge within the company (map 5.3). This was said to particularly affect the wastewater side of the company as its ageing profile is higher than average. On the other hand, senior workers may become less familiar with new technologies leading to barriers in their implementation and maintenance. In this regard, SUDS are already seen as a barrier for resilience (see Section 5.3.2.7) because they require a different expertise compared to historical drainage infrastructure (map M.12).

However, the participants also identified drivers beyond the control of the company. For instance, the “Brexit” process may limit the company’s access to skilled labour (map M.2). NI Water is also limited by the public sector pay agreement and decisions at central government reducing leeway to increase the competitiveness of salaries within the company (map 5.3). Participants provided the example of difficulties in recruiting electricians at NI Water because the company could not offer sufficiently competitive salaries.

Phased retirement policies, training of new and young workers, career development plans and school campaigns to attract students into a diverse employment pool for NI Water were suggested as interventions to address this potential “brain drain” within the utility.

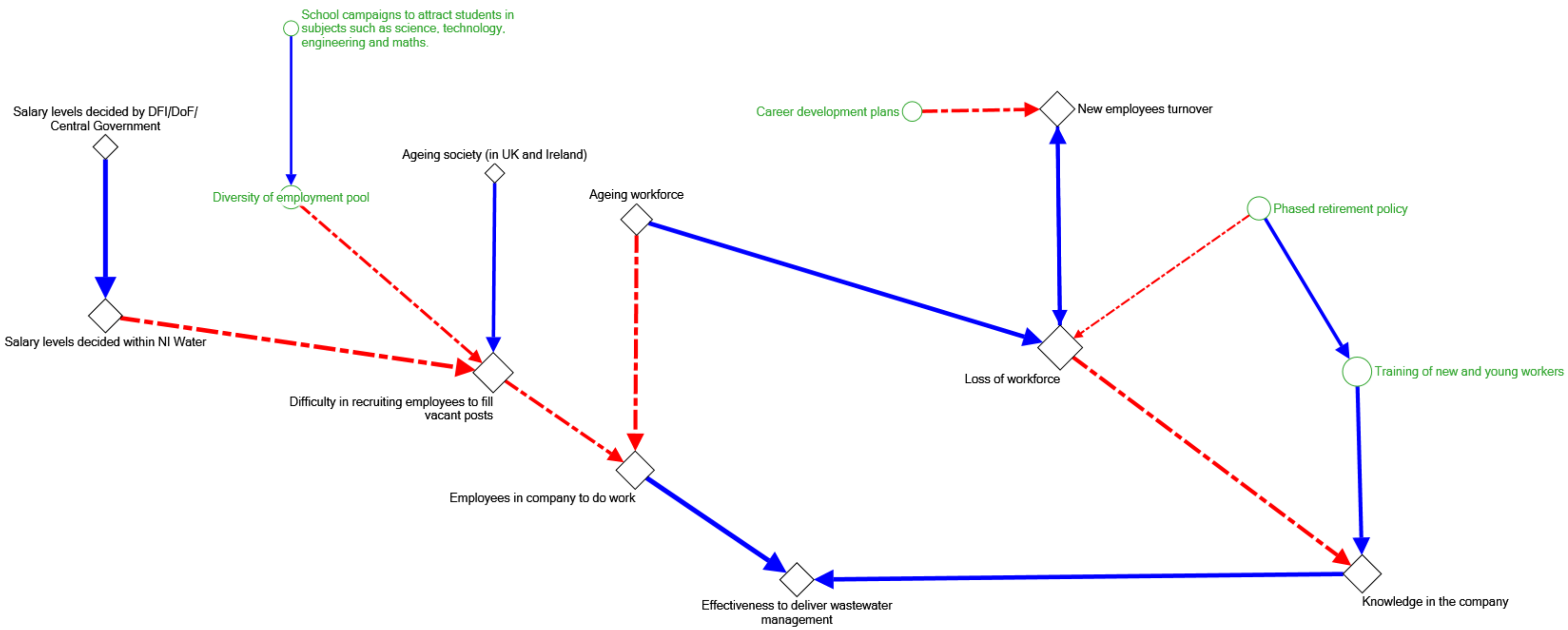

Figure 5.3: Human resource aspects of resilience and vulnerabilities (map M.4. Blue (full) arrows indicate a positive influence (for example, an increase in concept A leads to an increase in concept B) whereas red (dashed) arrows indicate a negative influence (an increase in concept A leads to a decrease in concept B); black diamonds are system concepts related to resilience and vulnerability; green circles indicate elicited interventions to increase resilience. The size of each diamond and circle reflects the centrality which is the sum of the absolute incoming and outgoing connection weights (degree centrality).

5.3.2.7 Knowledge and uncertainties

The lack of knowledge and the uncertainties it creates were identified as a fundamental barrier to resilience in the wastewater sector. Map M.9 particularly unpacks this theme in more detail. Participants suggested that uncertainties about local climate change impacts, economic development as well as lack of sewer network data hinder the appropriate assessment of network needs. Participants pointed to trade-offs between drainage and treatment capacity that need to be well understood in order to make optimal investment decisions on storm water separation vs. treatment capacity. If there are higher expenditures on discharge arrangements in the catchment, implying longer outfall and different discharge points, more water can be captured and less water may need to be drained and treated. Conversely, reduced discharge arrangements require to increase drainage- and treatment capacity. However, there are deemed to be insufficient drainage area studies and models that can inform such decisions. This applies also to diffuse pollution: water bodies are polluted not only by wastewater effluents but also by road- and agricultural drainage, thus, accurate knowledge of the sources and pathways of pollution are deemed to be required (map M.9, map M.11). Uncertainties were also linked to political processes, such as the outcomes of the "Brexit" negotiations (map M.2, map M.11) (see Section 5.3.2.3).

Ultimately, the lack of information and knowledge can lead to cascading vulnerabilities: inaccurate information may lead to resilience deficiency of solutions entailing for example increased energy consumption, sub-optimal investment decisions (see Section 5.3.2.2), non-compliance with requested water quality standards (see Section 5.3.2.5), lower capacity to cope with exceedance (see Section 5.3.2.1) or a degradation in well-being and human health (map M.9).

It was argued that in the face of new societal challenges like climate change, innovation uptake is required for resilient solutions (map M.6). Yet, technological transition periods are inherently associated with uncertainty. For instance, despite promising results in terms of flood risk reduction, there is currently uncertainty about the effectiveness of SUDS in Northern Ireland (map M.8). Given the multitude of typologies and settings of SUDS, these may require a shift in expertise of water utility staff as well as real estate developers - accompanied by increased funds - compared to what has traditionally been done (map M.12) (see Sections 5.3.2.3 and 5.3.2.6).

5.3.3 Participant feedback

Questions and observations from participants provided insight into some of the methodological issues linked to FCM.

5.3.3.1 Weighting of connections

One of the most frequent issues raised concerned the quantitative scoring process of FCM. In some instances, the interpretation of the weights was not clear. In such cases the analyst suggested participants to *"subjectively define the strength of relationships according to their own experience and knowledge"* and provide their rationale as proposed by the interview guidelines (Appendix K).

In some cases, the weights were interpreted by participants as being dynamic or conditional upon circumstances. In some cases, questions were raised as to whether the weights should reflect the current situation in the Belfast area or what should occur in an ideal case. Participants recognised the subjectivity of the process as well as their imperfect knowledge about specific weights. For example, participants were uncertain about the role of wastewater services for the global attractiveness of the city or the consequences of pollution on human health. Similarly, some interviewees considered the effectiveness of specific interventions to be uncertain, such as the effects of human resource policies within the water utility, policy change at governmental levels or the awareness campaigns to change customers' behaviour.

Different interpretations of scores were also related to the temporal and spatial scales that resilience drivers refer to. For example, while some argue that there is a strong link between wastewater treatment and GHG emissions, other participants consider the impact negligible because Belfast's wastewater system contributes little to global emissions. The two interpretations reflect different but equally legitimate cognitive reasonings of the participants. There is a priori no reason to discard either of them. Providing the accompanying storylines (Appendix N) can help in reducing such ambiguities.

5.3.3.2 Complexity and limitations of FCM structure

The bulk of resilience concepts and connections that were expressed during the interviews could be drawn as networks. In some cases, however, conditionality, dynamics, non-monotonous relations that were touched upon during interviews could not be mapped, and needed to be reflected in the storylines (Appendix N).

5.3.3.3 Consensual and conflicting issues

Within group sessions no conflicting issues were experienced. This is attributed to having nominated the participants together with NI Water senior managers, selecting participants within current working teams. However, when comparing the perspectives across interviews, cases with divergent views were identified. This was observed for example around the issue of who holds the responsibility of water pollution. Depending on the interview this could be the water utility, farming, individual customers, decision-makers within the agricultural department or policy-makers at other levels of governance. A second example with conflicting views was the question about the sufficiency of funding or the necessity to better manage granted funds. A third example was the issue about who should be responsible for SUDS implementation.

5.4 Discussion

In this study a new approach was proposed that systematically screens for sources of vulnerability and simultaneously identifies resilience interventions. This approach is believed to be useful as it integrates a wide range of perspectives to identify possible vulnerabilities as well as resilience actions in a wastewater utility that could not be easily detected with purely quantitative methods.

5.4.1 Complementary views and the value of subjectivity

As from this experience in Belfast, resilience was usually better understood by participants through its vulnerability lens. This suggests that for wastewater practitioners the academic divide between natural sciences (resilience lens) and social sciences (vulnerability lens) actually represents two complementary facets of the same coin. For the wastewater practitioners, resilience was perceived not to be necessarily associated to extreme conditions but to drivers related to daily practice, including for instance governance, human capital and civil responsibility. Failures in these domains may amplify failures of the wastewater system under extreme events. In this study it was sought to move beyond the different existing definitions of resilience that exist in the literature (Juan-García et al., 2017) and elicit subjective views of what resilience implies for different actors.

Eliciting diverse views allows to capture topics and reveal connections that are not necessarily obtained by single and tightly defined impressions, by consensual perspectives or by quantitative approaches of resilience (Carpenter et al., 2009; Oppenheimer et al., 2007). In such approaches, concepts such as *"Political will"* and *"Civil responsibility"* could be difficult to capture. Ultimately, the resulting wide range of resilience perspectives obtained can be used to screen for issues that warrant a more detailed exploration using traditional quantitative assessments based on statistical analysis or phenomenological modelling.

Resilience views are necessarily those of the participating agents. The outcomes therefore are a reflection the choice of the interviewees. Thus, it is important to be explicit and transparent about which agents were selected and why (Appendix L). This selection should be done together with the final beneficiary of the study (for example the senior management of the wastewater utility). Despite this subjectivity, the approach is open, in that it allows for addition of further participants to include more backgrounds and hierarchical levels.

5.4.2 Sensing complexity

The approach develops a network view of a complex system. The building blocks are simple cause-to-effect relationships revealed by the reasoning of participants. In this way they are able to develop a complex model which could not be held in the mind in its entirety. Studying such a network provides the possibility to better appreciate how interventions may propagate in unexpected ways and even produce feedbacks. By revealing interconnectivity, the methodology can also uncover potential unintended consequences which may be central in determining whether interventions increase resilience globally or whether it improves it in one domain while reducing it in others.

Because of FCM limitations in capturing dynamic, non-monotonous and conditional relations, it is proposed that the maps should necessarily be evaluated together with the accompanying narratives which provide the rationales for the choices made when drawing the maps.

5.4.3 Reflectiveness, inclusiveness and integration

This participatory process is regarded as leading towards a more *"reflective"*, *"inclusive"* and *"integrated"* view of resilience compared to existing resilience approaches (Table 5.2). It is reflective and inclusive in that it reflects on experiences and knowledge of a variety of actors. It recognises resilience perspectives across hierarchical levels as equally legitimate to be accounted for. It is also integrated, because it considers wastewater management as part of a more complex urban system in which multiple domains interact. For instance, results show that resilience in the wastewater sector may be strongly influenced by issues in water supply, agriculture and in political and cultural domains which are often underrepresented in technical resilience studies.

5.4.4 Transferability and flexibility of approach

The flexibility of this approach allows for transferability to other locations, zooming in and out to different levels of detail and aspects of the water system. Importantly, as resilience perspectives are a reflection of the knowledge of participants, the application of the approach to different sites will naturally highlight different dominating themes than those encountered in Belfast. Thereby, the approach simultaneously addresses the need for a standard framework with the necessity of being case specific, *"making possible comparisons between cases"* (Juan-García et al. (2017), p. 159). By linking sources of vulnerability with drivers of resilience the methodology illustrates perceived relationships between stressors, impacts and interventions which makes it intuitively applicable by practitioners. By doing this, the approach can also be used to operationalise other existing frameworks such as the *"safe-to-fail"* framework developed by Butler et al. (2017).

5.4.5 Ancillary benefits and implications for practice

The suggested approach can empower the involved participants to better appreciate the complexity of the system they work in and may improve the communication between departments with different interests and perspectives. In this study both strategic and operation managers mentioned the benefits of such an exercise as the participants reflect on their system in a way they are not accustomed to do.

The results consisting of maps and narratives may be used to inform and initiate discussions between department heads, risk- and asset managers of water utilities as well as their external partners such as funders, regulators or associated departments (transport, agriculture, energy, etc.). It might prove to be especially useful for studying nexus issues, for instance when addressing complexities at catchment level. It might prove equally beneficial to employ it as a monitoring tool by repeating the screening process periodically with changing agents. This type of exercise is deemed to be a useful precursor to the identification of specific issues of concern that may then be studied in more detail with more traditional quantitative methods.

5.5 Conclusions

Taking a systems perspective, a methodology is suggested to capture a wide spectrum of different understandings and interpretations of resilience in a wastewater system. In an engagement process with practitioners, cognitive maps were elicited. The methodology elicits major drivers of vulnerability, their propagation mechanisms and identifies resilience measures. This vulnerability screening approach is believed to support directors, risk- and asset managers of wastewater utilities to identify interventions from an integrated system perspective.

- This approach facilitated a participatory process that is *"reflective"* (capturing reflexions of practitioners in a discussion with the analyst), *"inclusive"* (that includes internal and external participants with diverse responsibilities) and *"integrated"* (that enables to account for feedbacks to and from other departments of the water utility and in interrelation to larger urban resources and networks, such as legal, social and governance systems).

- The questionnaire used for this assessment can be adapted for studying other issues at different spatial scales, levels of detail and domains in the water sector, for instance, in the context of pollutants of emerging concern.
- This approach may be useful to decision-makers for *risk screening*, including the identification of different issues of concern, shared or conflicting points of view, feedbacks to and from other systems, including detecting unintended consequences of measures that may increase resilience in one sector while reducing it in another.
- The methodology with the resulting maps and narratives can be a useful precursor to more quantitative and detailed resilience assessments.

Chapter 6

Discussion

In this thesis, a CBA was used as a starting point of attempts to suggest ways of improving the information base in support of decision-making, especially in the context of complex and uncertain information. Within these reflections, it was also investigated how the knowledge may be extended by moving beyond the realm of the economics of climate adaptation to include broader environmental change.

Adaptation is closely linked to our ability as human beings to resonate and behave in our relationship to others and our environment (Adger et al., 2009). It is also inter-connected to sustainability, resilience and vulnerability in complex ways (Folke et al., 2010; Gallopín, 2006; F. Miller et al., 2010) although these concepts also have their own specificities (Gallopín, 2006; Nelson, 2011). Adaptation associates closely to the specific social context of each of our lives and is related to the education we receive through transmission, the mental models we create and our ability to acknowledge the existence and legitimacy of other beliefs (Adger et al., 2009). Adaptation is also related to our physiological and biological health that impacts on how we think and how we make decisions (Riché, 2021; Young et al., 1989), which have likely conditioned the first adaptation mechanisms we experienced as humans and which keep us alive (Young et al., 1989).

Compared to such complex and inter-connected realities current policy making, the science-policy interface as well as the business-as-usual model have limitations. Firstly, deep uncertainties defy most models and decision tools used until now because many are based on predictions (Marchau et al., 2019). In this context, scholars suggested for example that the linear mental model usually applied is not adapted to complex environments (Cavallo & Ireland, 2014; Forrester, 1971) and that there is a lack of system- and holistic thinking which is more appropriate in the real world (Sterman, 2002; Weinstein et al., 2013). Secondly, no decision-making tool is comprehensive and a panacea on its own. Each has its weaknesses and strengths for which results of this thesis suggest to use them in a complementary way.

In the following paragraphs some major reflections that have arisen as a result of my PhD journey are developed. Section 6.1 relates to the flexibility of mental constructs which may facilitate our decision-making. Section 6.2 suggests that embracing uncertainty rather than being fearful with its regard may be important to render traditional decision tools more integrative. Sections 6.3 and 6.4 highlight respectively the importance of multidisciplinarity and the relevance of accounting for the dynamics of systems in order to elicit complex information as decision-support. Finally, Section 6.5 opens other perspectives of decision-making that emerged in the psychological research and practice, providing different insights into how to best guide sound decisions under uncertainty.

6.1 Flexibility: questioning mental constructs

The literature on decision-making under uncertainty has identified flexibility as one of the major characteristics for resilient systems (Ranger, 2013; Woodward, Gouldby, Kapelan, Khu, & Townend, 2011). It is likely the advantages of flexible systems not only apply to dam constructions, wastewater plants, management techniques and decision-making techniques but also to our capacity as human beings to reflect, make decisions and behave.

Morgan and Henrion wrote in 1990 that *"Policy analysis is generally performed within some broader philosophical framework but it is easy to forget this and assume that analytical procedures, such as the maximization of expected net benefit, reflect some universal social truth"* (G. Morgan et al. (1990), page 24). *"They do not"* the authors argue, *"because these echo 'normative choices' that have resulted from anthropologic evolutions and bear important consequences for the nature of societies"* (G. Morgan et al. (1990), page 24). Expected utility or expected net gains, the authors continue, are not the only things that can be maximised. Other criteria or choices exist such as minimising the chance of the worst possible outcome independently of the costs and benefits involved. Different alternative decision criteria to the utility-based prescriptions can be imagined, thus as rights- (Derek, 2013; Peel & Osofsky, 2018; Rajamani, 2010), technology-based decision criteria or a hybrid of all (G. Morgan et al., 1990).

However, from a social perspective, subjective values make-up a common history and understanding of societies. These function within established boundaries that render some choices more socially acceptable than others (Tinoco, Gianola, & Blasco, 2018). According to Spash (2020), community beliefs and institutions (conventions, norms, rules and regulations) affect their own content and behaviour and are therefore underlying the emergence of paradigms and the difficulties to overcome them. The sociological aspects of paradigms mean that the engagement, including of scientific communities, to *"shared ontology, assumptions, theoretical beliefs, values, instruments and techniques. This makes paradigms inherently conservative because they define what unites a scientific community and what is 'normal' in the scientific practice of a given field of knowledge"* (Spash (2020), page 12). Spash (2020) further refers to Kuhn's work on *The structure of Scientific Revolutions* to argue that in such *"periods of normalised science, scientists and laypeople sidestep the unconventional and defend the mainstream beliefs"* and that *"[s]cientific revolutions, or paradigm shifts, only occur when anomalies become overwhelming. A period of revolutionary crisis then arises, and is resolved when a new paradigm attracts enough scientists and the old one is abandoned"* (Spash (2020), page 12). This perspective is relevant for decision-making in two ways: firstly, it may create tensions within and between communities that share a *paradigm* and those who advocate for a *paradigm shift* (Tinoco et al., 2018). The *"stress"* generated by such tensions influences on decisions and decision outcomes, especially in complex and unpredicted situations (Fradin, 2008) (see Section 6.5). Secondly, it calls for all visions to be accounted for, be they pertaining to a paradigm or not, because all are equally valid to be considered and may help revealing complexities and uncertainties.

It is likely that climate change policy defies many of the current practices founded on predominant beliefs that have long been considered as immutable principles. Examples of such belief systems are the predominance of risk management strategies founded on probabilistic models (Marchau et al., 2019), or the the over-reliance on quantitative approaches even in domains where commensurability is difficult (Carpenter et al., 2009). In addition, consensus-based decision-making would take advantage from integrating more marginal, alternative and un-consensual world perspectives that may defy given paradigms (Oppenheimer et al., 2007). Decision-making approaches based on these values have been standardized and institutionalised due to their ease of use in decision-making and questioning them may require deeper transformations (see also Section 6.5). However, no single decision-making tool can provide the best approach to decision-making. In addition, as we saw in Chapter 2, standard tools are not necessarily sufficient as contexts change with time and location. Alternative methodologies exist and as we could see throughout the last chapters they all provide multiple perspectives into decision-making problems. Their complementarity is advantageous for decision practice, especially in complex information environments. They provide multiple insights and therefore a plurality of possible solutions to problems that have multiple stressors and drivers. In addition, using decision-support tools in a complementary way may facilitate the identification of unexpected consequences of what neuroscientists call *"automatic decisions"* (see Section 6.5).

6.2 Embracing uncertainty and complexity

Traditionally, it has been thought that politicians can take on the knowledge produced by the scientific and engineering expertise and decide upon those "facts" (G. Morgan et al., 1990). However, some scholars assert that climate and ecosystem sciences are too complex to expect most sophisticated models to predict with certainty its future evolution (Rey, 2020). Scientists even discern *"that often research identifies unforeseen complexities, and thus, at least for a while, can increase rather than decrease uncertainties"* (M. G. Morgan and Mellon (2011), page 710).

From the application of the cost benefit model we learnt that climate – if climate projections are correct – can be a *"marginal"* stressor to communities or societies compared to other socio-economic drivers (Chapters 3 and 5). Thus, price variations, geopolitical variables such as trade positions and specific consumption patterns or political turmoil can cascade into major hazards that undermine possibilities to adapt, along with climate changes themselves. This is not to say that climate change is a minor problem but that it should be considered concomitantly to and along with other drivers of vulnerability which necessarily interact. Such inter-connectivity of drivers needs also to be accounted for in economic adaptation appraisals without which results and policy recommendation may be flawed and relevant information discarded. CBAs and/or decision-tree analysis could for example be informed by contextual information gathered through the FCM approach. Chapter 4 showed that illustrating uncertainty and complexity of decision-making is useful for decision-makers to gain awareness about decision choices they are confronted to and Chapter 5 showed it is possible to visualise and disentangle their possible upstream drivers and downstream consequences. These elicit complexity mechanism that could not be produced by a single methodology alone. They appreciate how vulnerability nodes and interventions can propagate in unforeseeable ways and thus identify root causes of vulnerability and potential unexpected consequences that may improve resilience in one way but reduce it in others.

Waiting for more information may help making sound decisions in some cases as explored in Chapter 4 of this thesis. However, Rey (2020) argues that waiting for perfect information before acting is not always the most rational option if it is clear that uncertainties are too complex to be understood in a lifetime or more. It may be possible to act in the present according to the best scientific knowledge available and sometimes, it is necessary to do so. This means to not wait for an ideal set of information, but to be aware and listen to what extant knowledge teaches us. For this reason, ignoring uncertainty may not be an option anymore. The complementarity of decision tools may facilitate disentangling and catalysing available information that may not be revealed by a CBA, a decision-tree or a FCM approach alone. It may also compensate for each methodological weakness and build on each of their strengths. Ultimately however, it is decision-makers and us as human beings who decide (see Section 6.5).

6.3 Multidisciplinarity: deliberating with multiple actors

Some decades ago, the emergence of the socio-ecological or human-environment system framework of political economy provided evidence about the close inter-linkages and the complexities in coupled relations between nature and societies. Integrated studies of coupled human and natural systems expose new and complex features of reciprocal interactions and feedback effects that are not evident when studied by social or natural scientists separately (Liu et al., 2007). Without the integration of multidisciplinary insights to elicit complexities and links between research or policy domains, as investigated in Chapters 2 and 5, unintended consequences that result from such omissions may create new uncertainties and generate maladaptation or new problems (G. Morgan et al., 1990). In addition, this may contribute to addressing symptoms instead of root causes of crises which can lock societies down into maladaptive and unsustainable pathways of development (Brown, 2011).

Results from Chapter 2 revealed that seeking for costs and benefits of adaptation may only find partial answers. Research- and policy making communities oftentimes undertake their endeavour in silo according to separate goals and interests, whereas the fundamental bio-physical or social processes at stake are deeply inter-connected. Chapter 5 provided evidence that by reflecting on, including and integrating the knowledge and experience of various actors, complementary and equally valid views of resilience mechanisms can be elicited. Though FCM does not address the same decision questions and has its own weaknesses (Chapter 5) it provides a deliberative approach with more space for system thinking which is useful and complementary for complex decision environments (Weinstein et al., 2013), including in combination of CBA.

Neglecting plural perspectives to the benefit of a single belief, though socially accepted, resumes to neglect complexity (Tinoco et al., 2018). At the same time, this implies also neglecting the voices and opinions of those who have different views (Wegner & Pascual, 2011). Though they may be inconsistent, different perspectives are equally valid understandings of the same available knowledge (Sluijs et al., 2010). The plurality of methodologies for decision-making and the implication of multiple agents would increase participative, more democratic and accepted decisions (Wegner & Pascual, 2011). Andy Stirling wrote that *"A move towards plural and conditional expert advice is not a panacea. It cannot promise escape from the deep intractabilities of uncertainty, the perils of group dynamics or the perturbing effects of power."* (Stirling (2010), page 3). But *"system dynamics helps us expand the boundaries of our mental models so that we become aware of and take responsibility for the feedbacks created by our decisions [...] that shape the world in ways large and small, desired and undesired."* (Sterman (2002), page 505ff).

Getting there however may be a difficult task, because ultimately, *"Recogni[s]ing the limitations of our knowledge, the [. . .] assumptions at the root of all we think we know, is deeply threatening."* (Meadows 1980, cited in Sterman (2002)). *"Much of the misery people inflict on others arises from the arrogant belief that only we know the True Path, and the resulting intolerance and fear of any who profess beliefs different than ours."* (Sterman (2002), page 526).

6.4 Dynamics: changing objectives and contexts

Some authors ask: adaptation or resilience to what? (Nelson, 2011). Similarly, in Chapter 5 the questions posed were *"What is resilience?"* and *"Whose resilience?"*. Usually, policy analysis and research is undertaken along well-defined conceptual definitions and goals and is used to analyse how best to achieve them. In contrast to this predominant approach, a number of observers have also argued that people do not have fixed goals (G. Morgan et al., 1990). It is easy to understand that social values and goals change over time (Nelson, 2011). For some therefore, the objective of policy research and analysis should not only deal with how to achieve goals but examine what goals to achieve, explore existing alternatives and invent new ones (G. Morgan et al., 1990). According to Adger et al. (2009), an approach to adaptation is one that focuses on a wider process of adaptation to improve well-being in societies. Another perception of adaptation seeks to minimise climate risks at tolerable levels and at acceptable costs, thus avoiding system failure (Adger et al., 2009). However, the second vision seeks at securing the business as usual rather than questioning it, by using adaptation as a means to protect development policies for the future (Brown, 2011). By doing this, we may only be able to *"muddle-through"* difficult decisions in times of crisis (Neumann et al., 2015) without addressing fundamental root causes of poverty and climate change such as inequality and power Brown (2011). A combination of quantitative and qualitative as well as deliberative decision-making tools may be useful to investigate such changing objectives and goals.

6.5 Decision-making under uncertainty: insights from psychology, neuroscience and human physiology

The physiological perspective of adaptation (Young et al., 1989) is valuable in that it suggests that humans are not always under full control of their acts: As Solosse (2017) sustains, all living organisms, be they vegetal or animal, depend on other living organisms or microbes that contribute to their nutrition, development, immunity and behaviour. Thus emerged the idea that human beings are influenced in their cognitive behaviour by the human microbiome (Riché, 2021) which may have relevant implications on individual and therefore also social decision-making.

The psychological perspective provides alternative and complementary explanations to the difficulties in taking sound decisions under uncertainty which are linked to the discussion points above and may also represent directions of future research.

The ways we make decisions are rooted in physiological patterns inherited from evolution in which response to stress plays a key role driven by complex, unpredictable, uncontrollable situations. This is even more so as policy-makers and societies convey a false sense of security in a world in which nothing can happen to us (Sureau cited in Riché (2021)). However, potentially threatening events like climate change combined with their complexity and unpredictability embarrass this mistaken appreciation of safeguard and create anxiety (Marchau et al., 2019).

According to Fradin (2008), uncertainty triggers stress mechanisms which call specific human brain functions for decision-making that are automatic and quick as they are programmed for survival. Simple decision options such as neglecting uncertainty and complexity or being averse to novelty are automatic cognitive processes by nature. These processes occur when facing complex decisions such as those involved in climate policy. However, these are not necessarily well thought through, because emerging stress through the confrontation to novelty and unpredictability usually does not enable hindsight (Fradin, 2008). It is usually considered that prefrontal and *rational* approaches predominate in decision-making, which is likely due to the consideration of humans as *rational* beings. However, as J. Fradin suggests, this is rarely the case because constant stress switches our brain functions to automatic decision mechanisms, which, opposite to prefrontal approaches, do not enable wise and sound decision-making (Fradin, 2008). Similarly, in their work on robust decision-making, Marchau et al. (2019)

argue that the *"decision-making process is more prone to anxiety as the number of variables increases thus overwhelming innate abilities to think through the combinatorics of potential influences and outcomes"* (Marchau et al. (2019), pages 9ff). Importantly, evolutionary stress management strategies call upon protection, which usually arises under the form of commonly accepted beliefs and paradigms. These are reassuring because they are shared within a wider community and alleviate the stress associated with decision-making processes (Tinoco et al., 2018) (see Section 6.3). These in turn may lock-in decision patterns that may not be adapted to the dynamic nature of systems and which require flexibility.

Automatic decision skills follow an evolutionary design for *"survival tasks"* but evolution also endowed humans with the possibility of acquiring skills that enable to make sound decisions (Hastie & Dawes, 2010). According to Fradin (2008), the prefrontal attitude can be trained to avoid the progressive *"rigidification"* of thought processes (Fradin (2008), page 130). *"Ordinary skills can thus be modified to cope effectively with situations that would otherwise create pernicious biases"* (Hastie and Dawes (2010), page 150). This may be achieved through a combination of actions that aim at reducing stress (Riché, 2021), for instance implementing various stress management techniques including meditation, ameliorating our health through more adapted diets, physical activities, choosing an appropriate work-life balance and finding sense in what we do as human beings (Tinoco et al., 2018). Because there is a direct physiological response to stress, reducing stress may be valuable strategy to develop our intuitions for good decision-making. By improving our capacity as individuals to make rational rather than stress-driven decisions, social decisions may therefore also be ameliorated even under difficult, uncertain and complex circumstances. This would back-up other interventions and efforts that confer value to complexity, system thinking, integrative and multidisciplinary approaches to increase the knowledge base on the one hand and to accept the unknown on the other hand.

Chapter 7

Conclusions

The objective of this thesis was to explore the cost and benefit decision tool to incorporate more flexibility and complexities that have become ubiquitous in the realm of global environmental change. The "hard" methodologies used included the cost-benefit model, the decision trees and the fuzzy cognitive mapping enabled to explore *"soft"* avenues to decision-making including multidisciplinarity, participatory as well as holistic approaches. The work presented in Chapters 2 – 5 explored this objective in more detail as follows:

- Chapter 2 reported on costs and benefits of sustainable land management practices based on a multidisciplinary literature.
- Chapter 3 developed a cost-benefit model in Zanzibar's clove plantations with the aim to identify optimal investments in face of local climate threats.
- Chapter 4 expands the CBA of Chapter 3 by including more flexibility increasing from one to two the decision-making periods considered in the analysis. It also accounts for more uncertainty using probabilities of occurrence of various climate and clove price scenarios.
- Chapter 5 developed an approach to capture multiple perspectives of resilience by comparing cognitive maps of diverse agents internal and external to a wastewater utility. Chapter 5 complements the previous chapters by illustrating the use of semi-quantitative methods. It also broadens the analysis by investigating climate as one among a multitude of other drivers of vulnerability and by eliciting subjective views on resilience mechanisms with professionals from the wastewater sector in Belfast (Northern, Ireland)

7.1 Synthesis of findings

In this thesis the CBA was used as a starting point to investigate alternative ways to support decision-making, especially in the light of uncertain and complex contexts. Results indicate that cost and benefit assessments of adaptation options related to soil ecosystems such as the sustainable land management practices may hide conflicting information if they are not evaluated in an integrated manner at the source and that they are not comparable. This is because firstly, cost and benefit estimates of such practices remain driven by specific objective and visions of research communities that investigate them. Secondly, they depend on soil metrics that are local specific. The CBA applied to agroforestry systems of clove plantations in a developing country context showed that the model is founded on a considerable set of questionable assumptions. These amplify the complexities of ecosystems such as agroforestry systems and to the uncertainties these are related to, including unknowns brought by climate change. Improving the data availability by data collection in the field does not substantially reduce the existent information gap. This however may also be due to the simple cost-benefit model used in this project which may not enable to provide policy recommendation. Altogether, the complexity of systems such as soil or agroforestry ecosystems herald space for multiple interpretations that distinct research communities usually do not account for *jointly*. Communicating on complexities and uncertainties through their illustration, for example in the form of decision trees or through mental models / cognitive maps may result insightful and complementary. Such methodologies add and complement economic information provided by the cost-benefit model in that they enable to acknowledge and understand assumptions. They also visualise and highlight the inter-linkages between systems, their inherent complexity and mechanism instead of inhibiting them by simplifying models because they may be more tenable and useful to practitioners. They enable to integrate system thinking and democratic participation in more traditional approaches. Eventually, this may enable to identify and address root causes of vulnerability and a more diverse range of interventions.

7.2 Advances on key knowledge gaps

Though tiny in the immense ocean of unknowns, several findings of this thesis help to shed more light into the critical knowledge gaps highlighted at the onset of this project and which inspired the research questions and rationale. Chapter 2 proposed a new multidisciplinary approach to economic assessment of adaptation practices. While many researchers highlighted the value of multidisciplinarity in the past, few have been using it in practice, especially in economic assessments of adaptation. Using such an approach enables on the one hand to connect and bridge gaps between disciplines. On the other hand, it permits to clearly expose the complexity that is hidden in CBAs and cost and benefit estimations of adaptation. In addition, it enables to limit the risk of generating unintended consequences that may arise when addressing problems in silo, dis-considering the porous boundaries between social and ecological domains.

Chapter 3 elucidated some critical mechanisms of the clove sector in Zanzibar, a study area that has been under-investigated in the past decades, though it represents preponderant economic sector and income source for the archipelago. In addition, it provides a case study of adaptation assessments using a CBA in developing country context. Overall, the practical application of the CBA to adaptation options of a clove agroforestry model highlighted the complexity and uncertainty hidden in such frameworks that make them untenable in the realm of complex systems such as socio-ecological and human environment systems.

Building on Chapter 3, Chapter 4 expanded the CBA of clove agroforestry systems to incorporate more flexibility and uncertainty in the analysis. Although probabilistic CBAs have been developed previously, this chapter used two decision periods in which investment choices can be modified within a backward-looking approach. Such approaches are not *new*, however, such user-friendly applications are novel compared to the conventional CBA which considers a *"once-for-all"* decision and a forward-looking, prediction-based framework. This analysis used the rationale that waiting for new information may be useful in decision processes, which is rarely integrated in CBAs. Outcomes are preliminary and highlight that this methodology may complement CBAs to expose complexity and uncertainties that decision-makers need to be aware of when making decisions.

Finally, Chapter 5 proposed a *"novel"* approach to resilience that systematically screens for sources of vulnerability and simultaneously identifies resilience interventions which could not be easily detected with purely quantitative methods. As opposed to usual resilience analysis, it did not develop the framework around a specific definition of resilience or vulnerability. Instead, it was motivated by understanding what resilience actually means for different actors from the sector. By searching to elicit this question using cognitive maps, the study also uncovered vulnerability/resilience propagation mechanisms that provide a more holistic and dynamic view of a sector under study and how it interacts with other domains such as urban governance, consumer behaviour and legal frameworks. This approach was proposed as a new risk screening approach for risk managers that reflect, include and integrate different tenable views and entry points on a same problem. This system approach can address root-causes of vulnerability rather than symptoms in order to improve adaptability and resilience.

Overall, this thesis showed that improving decision-making based on costs and benefits is both necessary and feasible. It may also be more desirable in order to avoid locking-in present and future societies in both built and social infrastructures that have been founded on rigid mental constructs inherited from the past. In order to achieve this, economic assessments may be complemented or transcended by multidisciplinary and participative approaches that enable to expose hidden knowledge, uncertainty and complexity in decision-making while valuing democratic accountability. Exposing and accepting complexity and uncertainties that are inherent in the nature of socio-ecological systems is indispensable. This is more so given their determinant role, according to neuroscientists and psychologists, in individual and social stress management strategies to guide decision-making.

7.3 Main limitations

Though advances of this thesis were tiny, they have not been realized without obstacles and difficulties. Important persisting limitations are important to consider.

Firstly, the inventory of costs and benefits of SLM at farm level developed in Chapter 2 has resulted challenging because few studies provide farm level information. The nature of literature reviews means that the results are dependent on the information available elsewhere in the literature. We found that few of the studies providing costs and benefits of SLMs were able to calculate and provide primary economic data for these practices and that many relied on secondary data extracted from other papers or literature reviews based on applications at other sites and in other regions and countries. This is an extremely important limitation because it implies strong assumptions that are perpetuated throughout the literature. Moreover, this can have major consequences on the biases of policy recommendation as cost transfers are usually used. There are also limitations to our data collection methodology linked to the decisions that had to be made for analytical purposes. For instance, considering costs and benefits provided as averages when not specified otherwise or clustering different soil protection practices under a same category may also lead to erroneous results.

Secondly, the CBA developed in Chapter 3 is an extremely simple model that was constructed for illustration purposes. It does only focus on financial data and does not consider economic costs and benefits that are likely determinant in such an assessment. These can be environmental resource valuations related to agroforestry systems or possible injuries and deaths due to traditional clove harvesting techniques. By nature, the CBA is based on uncertainty measurements which may not be quantifiable, in particular for climate and socio-economic predictions. However, many of those economic costs may be difficult to monetise and some of them may be even overlooked. Model complexities and uncertainties of clove agroforestry systems in face of climate changes are numerous and aggregate to classical weaknesses of CBAs, which altogether render general conclusions difficult to make.

Thirdly, the extension of the CBA in Chapter 4 does not enable to eliminate many of its limitations but moves them to the decision-tree methodology proposed. To these are added new methodological difficulties. The most prominent one is the practical application of several decision-making periods to the cost-benefit model which resulted difficult in practice due to the application of the discount factor and the choice of cost and benefit data decided upon in each period. In addition, the attempt to merge the cost-benefit model with a backward-looking approach remains immature and proved challenging because decision trees become quickly complex and require to simultaneously consider an important number of parameters. Altogether, these limitations point to the weak significance of results that hinder policy recommendations and methodological issues that remain to be clarified.

Finally, there are two main limitations of the resilience assessment developed in Chapter 5 of this project. The first limitation, is that results and cognitive maps were necessarily conditioned by the boundaries set for the study in terms of experts included. Thus, covering other domains such as the health sector could have enlightened us about other potential and easily overlooked risks such as for example epidemics and hygiene risks. The second shortcoming of the study is that cognitive maps are not dynamic and maps represent only a photography of a specific world-vision at one moment in time, while as we saw, judgements and understandings change over space and time.

7.4 Direction for future research and final remarks

Considering the obstacles encountered and new reflections that emerged during this project, following directions for future research are suggested:

- Extending the cost and benefit database of SLM with multidisciplinary approaches and enlarging the data sample. If this is successful, broad soil protection categories could possibly be avoided. Alternatively, categories may be readjusted to be more comprehensive.
- Developing the analysis to identify the factors that determine costs and benefits and testing whether wider geographic transferability to areas where such data does not exist is justifiable given the importance of context specificities of economic data.
- Improving the backward-looking CBA whose attempt has been started in this project to make it more mature. This includes methodological improvements in the application of discount factors and the choice of costs and benefits across decision periods as well as the calculations of the option values of making one decision rather than another given the information available. Alternative approaches to backward-looking assessments may also be explored. More case studies will therefore be necessary for practical illustrations.

- FCM may be used as a precursor of and in conjunction with the conventional CBA to improve the comprehensiveness and include aspects other than costs and benefits. These are for example, human health and well-being and other domains related to governance and ethics which are inexistent in economic assessments. Including multidisciplinarity into CBAs may render the methodology more reflective, inclusive and integrated which appears to be crucial in moving towards system thinking.
- The multidisciplinary analysis of decision-making may also benefit from different insights provided for example by neuroscientists, psychologists and physiologists. In fact, sound decision-making may not come from methodological abstractions alone, but from our own cognitive and physiological capacities to both develop and implement them.

Appendix A

Overview of selected studies for economic inventory of SLMs

This Appendix lists all references used for the literature review-based inventory of costs and benefits of SLMs. For each reference it provides detailed information about the a) economic metrics retrieved and their ranges, b) the number of data points used, c) the region and country of application, d) the hazard considered in the original studies as well as e) the type of soil protection technique investigated and the f) the methodologies used.

Table A.1: Overview of selected studies for the economic inventory of soil protection/SLM techniques. References, location, data points, hazards, soil protection measures, methods and economic metrics assessed.

Nr.	Reference	Region/Country	Data points**	Hazard	Type of soil protection technique	Methodology	Economic metrics and their ranges [min; max]
1	*Kuhlman et al., 2010*	EU	BCR: 4	Soil erosion Compaction Soil Organic Matter (SOM) loss Salinization	Conservation tillage Cover crop Residue management Buffer strips Contour ploughing Conversion of arable land	CBA Cost estimates	**Investment cost (M EUR/ha):** [0; 13.31] **Average cost (EUR/ha/yr):** [5.56; 1329.61] **BCR:** [0.48; 8.42] **Total net benefit for area at risk (Billion EUR):** [-4.7; 1.1]
2	*Brand-Sassen, 2004*	Baden-Württemberg Bayern Hessen Niedersachsen Nordrhein-Westfalen Rheinland Pfalz Sachsen Sachsen Anhalt Schleswig- Holstein East and West Gernany Germany	Average costs and benefits: 445 BCR: 423	Physical soil impact: soil erosion and compaction Chemical soil impact: SOM loss Soil degradation	No-till, strip-till Loosening of lanes Changing direction of cultivation Choice of wheal type Tyre pressure systems Wind break Buffer strip/green belt Cover and catch crops Renouncement to cultivation on low productive land	CBA CEA	**Investment cost (EUR/ha):** [0; 2577.14] **Average cost (EUR/ha/yr):** [0; 1709.48] **Average benefit (EUR/ha/yr):** [0; 968.22] **Average net benefit (EUR/ha/yr):** [-1409.03; 601.08] **NPV (EUR):** [-6649.39; 4875.28] **BCR: [**0.02; 10] **CE: [**-21.37; 54047.34] **Average subsidy (EUR/ha/yr): [**29.84; 140.37]
3	*MacLeod et al., 2010*	UK	0	GHG emissions	Reduced tillage/no-till Improving land drainage	CEA/MACC Optimisation	**CE (€/tCO2e):** [-589.34; 19480.99] **Cost for total abatement potential (M EUR):** [-5.99; 198]
4	*Rickson et al., 2010*	England Wales	Average costs and benefits: 754 BCR: 754	Water erosion Wind erosion Tillage erosion Co-extraction on root vegetables and farm machinery	Cover crop during winter/under sowing maize Geotextiles Mulching In field / riparian buffer strip (6m) High density planting Crop rotation Timeliness Land use change Agroforestry Shelterbelts Subsoiling Drainage Reduced tillage/no/zero tillage Tramline management Coarser seedbeds Contour ploughing Swales/sediment traps Earth banks	CBA financial (without off site costs/benefits) CBA economic (with off-site cost/benefits)	**Investment cost (EUR/ha):** [0; 2518.98] **Average cost (EUR/ha/yr):** [-7.56; 764.51] **Average benefit (EUR/ha/yr):** [0; 264.49] **Average net benefit (EUR/ha/yr):** [-749.40; 114.61] **NPV (EUR):** [-8631.1; 1320.04] **BCR:** [-4.17; 16.67] **Average GM change (EUR/ha/yr):** [-4.41; 59.20]

Nr.	Reference	Region	Data points**	Hazard	Type of soil protection technique	Method	Economic metrics and their ranges [min;max]
5	*Le Garrec et Revel, 2004*	Indre et Loire Côte d'Armor France	0	Soil degradation	Soil conservation No tillage Mulching Rotations	Partial budgeting INDIGO and DELTAMEQ approaches	**Average GM change (EUR/ha/yr):** [-59.15; 106.46]
6	*Van-Camp et al., 2004*	Austria Flanders, Wallonia Bayern Brandenburg Nordrhein- Westfalen Rheinland-Pfalz Norway Portugal Bern England	0	Soil erosion	Recreating waterside grassland Managing arable field margins Overwinter stubbles Bank restoration Buffer and wildlife strips Upland hay meadows and regeneration of heathers	Subsidies	**Total cost area at risk (EUR):** [9191.92; 334073.20] **Average subsidy (EUR/ha/yr):** [0; 8056.43]
7	*Lundekvam et al., 2003*	South East Norway	0	Soil erosion	No autumn tillage depending on erosion risk No autumn tillage with catch crops Light harrowing in autumn with or without sowing of winter wheat Direct drilling of winter wheat	Subsidies	**Average subsidy (EUR/ha/yr) :** [48.89; 241.90]
8	*Chamen et al., 2015*	England	Average costs and benefits: 96 BCR: 80	Soil compaction	Soil compaction alleviation: general subsoiling, targeted subsoiling and ploughing Soil compaction avoidance options: low ground pressure tyres, tracked tractors and controlled traffic farming (CTF)	Partial budgeting	**Average cost (EUR/ha/yr):** [0; 61.17] **Average benefit (EUR/ha/yr):** [5.43; 128.37] **Average net benefit (EUR/ha/yr):** [-48.87; 128.37] **Average GM change/(EUR/ha/yr):** [-48.87; 128.37] **BCR:** [0.10; 22.86] **CE:** [-373.22; 435.28]
9	*HLUG, 2005*	Hessen Bern	0	Climate impact	Irrigation plant for frost and drought control Hagel net protection Roofing with rain protection Reestablishment of soil fertility: deep loosening of soils, filter gravel, extensive meadows and pasture	Cost estimation	**Investment cost (M EUR/ha):** [0.01;1.61] **Total cost for area at risk (M EUR):** [0.58; 185.23]

Nr.	Reference	Region	Data points**	Hazard	Type of soil protection technique	Method	Economic metrics and their ranges [min;max]
10	*Tröltzsch and Görlach, 2012*	Northern Germany Sachsen	Average costs and benefits: 12 BCR: 12	Climate impact	Soil conservation Irrigation systems	Cost estimation	**Investment cost (EUR/ha):** 11562.11 **Average cost (EUR/ha/yr):** [104.06; 346.86] **Average benefit s(EUR/ha/yr):** [85.52; 1208.24] **Average net benefit (EUR/ha/yr):** [-101;1104] **NPV (EUR):** [-12398.69; -2379.08] **BCR:** [0.11; 0.81] **Total net benefit for area at risk (M EUR):** [-439.89; -18.21]
11	*De Groot et al., 2006*	Friesland Zeeland West Brabant Zegveld Nether-lands	Average costs and benefits: 5 BCR: 5	Climate impact	Widening ditches Converting land to water buffer and taking land out of production Increasing ditch water levels Retention polder Subsoil drainage of peatland Structural wetting and increased drainage intensity Periodical wetting Irrigation using brackish water	Cost estimation	**Investment cost (EUR/ha):** [2575.20; 11652.49] **Average cost (EUR/ha/yr):** [227.22; 332.68] **Average benefit (EUR/ha/yr):** [3.5; 3146.17] **Average net benefit (EUR/ha/yr):** [-317.53; 990.46] **BCR:** [0.76; 11.61] **Total cost for area at risk (M EUR):** 679.34 **Total benefit for area at risk (M EUR):** [0.84; 1165.25] **Total net benefit for area at risk (M EUR):** 0.84 **Average GM change (EUR/ha/yr):** -258.69 **Average subsidy (EUR/ha/yr) :** [3.5; 3146.17]
12	*Panagopou-los et al., 2014*	Pinios Catchment Greece	Average costs and benefits: 12 BCR: 12	Water scarcity	Deficit irrigation Conveyance improvement Precision Agriculture Waste water reuse Combination of options	CEA	**Investment cost (EUR/ha):** [0; 6222.08] **Average cost (EUR/ha/yr):** [2.98; 412.81] **Average benefit (EUR/ha/yr):** [7.52; 45.42] **Average net benefit (EUR/ha/yr):** [-398.4; 18.2] **BCR:** [0.03; 7.10] **Total net benefit for area at risk (M EUR):** [-80.47; 3.67] **CE (EUR/m3):** [-0.26; 0.72]
13	*Gonzalez-Sanchez et al., 2015*	Spain	0	Soil degradation	Conservation agriculture measures	Cost estimation	**Total net benefit for area at risk (M EUR):** [0.20; 31.38]

Nr.	Reference	Region	Data points**	Hazard	Type of soil protection technique	Method	Economic metrics and their ranges [min;max]
14	*Riksen et al, 2003*	Barnham site (England) UK Germany	Average costs and benefits: 6 BCR: 6	Soil erosion	Cover crop Plough and press	Cost estimation CBA (without-with)	**Average cost (EUR/ha/yr):** [0; 294.45] **Average benefit (EUR/ha/yr):** [105.95; 3439.84] **Average net benefit (EUR/ha/yr):** [-122; 3330] **BCR:** [0.58; 31.25]
15	*Sieber et al., 2010*	Baden-Württemberg Brandburg, Bayern Sachsen, Thüringen Hessen, Niedersachsen Mecklenburg-Vorpommern, Nordrhein-Westfalen, Rheinland Pfalz, Saarland, Sachsen Anhalt, Schleswig-Holstein, Germany	0	Environmental pollution Pesticide risk	Conversion to riparian buffer zones	CEA Optimisation	**Average cost (EUR/ha/yr):** [20.31; 601.85] **Total cost for area at risk (M EUR):** [0; 408] **CE (M EUR/1% risk reduction):** [0; 71]
16	*Buckley et al., 2012*	Rep. of Ireland	0	Environmental pollution Pesticide risk	Conversion to riparian buffer zones	WTA Subsidies	**Average cost:** [151.11; 2158.68] **Average net benefit (EUR/ha/yr):** [0; 2158.68] **Total cost for area at risk (M EUR):** [0; 0.16] **Average subsidy(EUR/ha/yr):** [475.80; 903.62]
17	*Borin et al., 2010*	Veneto Italy	0	Diffuse water pollution Landscape quality N and P loss	Buffer strips	MCA Optimisation	**Average cost (EUR/ha/yr):** [6.13; 520.63] **CE (EUR/nitrogen loss reduction):** [0.57; 5.19] **CE (EUR/%point landscape quality):** [2.3; 12] **Average GM change/Net benefit (EUR/ha/yr):** [-520.63; -6.13] **Average subsidy (EUR/ha/yr):** [287.99; 488.93]
18	*Van den Born et al., 2000*	Austria, Belgium, Denmark, EU15, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, netherlands, Portugal, Spain, Sweeden, UK	Average costs and benefits: 16 BCR: 10	Soil degradation Climate impact	Soil erosion management	Cost estimation Subsidies	**Average cost (EUR/ha/yr):** [0; 37.40] **Average benefit (EUR/ha/yr):** [45.68; 52.35] **Average net benefit (EUR/ha/yr):** [0; 51.08] **BCR:** [1.39; 1405.30] **Total cost for area at risk (M EUR):** [0; 932] **Total benefit for area at risk (M EUR):** [0; 1304] **Total net benefit for area at risk (M EUR):** [5.07; 372.21]

Nr.	Reference	Region	Data points**	Hazard	Type of soil protection technique	Method	Economic metrics and their ranges [min;max]
19	*Berbel et al., 2010*	Guadalquivir River Basin Spain	Average costs and benefits: 1 BCR: 1	Water scarcity	Modernisation of irrigation systems Volumetric billing Extension services to irrigators Strict groundwater abstraction control	CEA AQUATOOL	**Investment cost (M EUR/ha):** [0;13] **Average cost (EUR/ha/yr):** [0.17; 224.21] **Average benefit (EUR/ha/yr):** 3.58 **BCR:** 1 **Total cost for area at risk (M EUR):** [0.8; 215.92] **CE (EUR/m3 impact reduction):** [0.07; 6.50] **CE (EUR/m3 pressure reduction):** [0.02; 0.7]
20	*Sutton et al., 2013a*	Alpine Continental, Meditarranean AEZ* Macedonia	BCR: 282	Water scarcity Climate impact	Extension programmes for irrigation Improvement of hydro-meteorological capacity Adding new/rehabilitate drainage capacity at farm level Create new/rehabilitate irrigation systems Crop varieties Hail nets	CBA	**NPV (EUR):** [-50936.19; 78960.69] **BCR:** [-0.41; 268.08] **Total cost for area at risk (M EUR):** 0.42
21	*Sutton et al., 2013b*	Central, North, South AEZ*, Moldova	BCR: 294				**NPV (EUR):** [-64700.60; 35176.92] **BCR:** [-3.4; 95.51]
22	*Sutton et al., 2013c*	Intermediate, North, South, Lowlands AEZ*, Albania	BCR: 320				**NPV (EUR):** [-52105.85; 304088.29] **BCR:** [-0.07; 1958.33]
23	*Le Bissonnais, 2003*	Normandie Midi-Pyrénées France	BCR: 8	Soil erosion	Buffer zones Talweg	CBA	**Investment cost (M EUR/ha):** [1477;20774] **BCR: [**0.25; 12.89] **Total cost for area at risk (M EUR): [**0;2077] **Total benefit for area at risk (M EUR): [**125;8565] **Total net benefit for area at risk (M EUR):** [-3383;1729]
24	*García-Torres et al., 2002*	Southern Spain	0	Soil degradation Soil and water quality	Direct sowing	Cost Estimation	**Average benefit (EUR/ha/yr): [**52,56;78.84]
25	*Rodrigues et al., 2013*	Vigia Irrigation District Portugal	0	Water scarcity	Drip, centre pivot and set sprinkler irrigation with: - Full irrigation in all crop development stages - Stress imposed during vegetative stage - Stress imposed during maturation stage - Stress imposed at vegetative and maturation stage	MCA Utility functions	**Average cost (EUR/ha/yr):** [178.66; 1019.28]
26	*Riksen and de Graaf, 2001*	Barnham site (England) UK	0	Soil erosion	Conservation agriculture measures	Cost estimation (without-with)	**Average benefit (EUR/ha/yr):** [0; 111.88]

Appendix B

Average costs and benefits by type of vegetated buffer strips

This Appendix displays the average costs and benefits of different types of vegetated buffer strips that were encountered in the literature review. Figure B.1 shows these data points calculated in the original studies through two different approaches: financial and economic estimates.

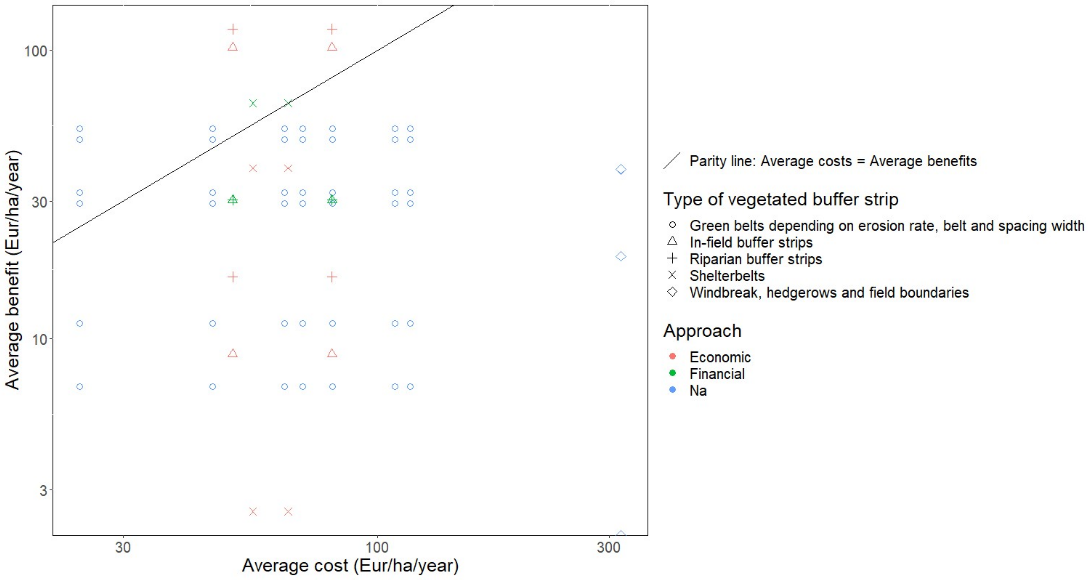

Figure B.1: Average costs and benefits for vegetated buffer strips depending on the type of estimates (financial or economic). The points represent combinations of average costs (x-axis) and average benefits (y-axis) of different practices for economic and financial cost and benefit estimates. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies.

Appendix C

Average costs and benefits by type of tillage practice in Germany and the UK

This Appendix displays average costs and benefits of different types of tillage practices across Germany and the UK.

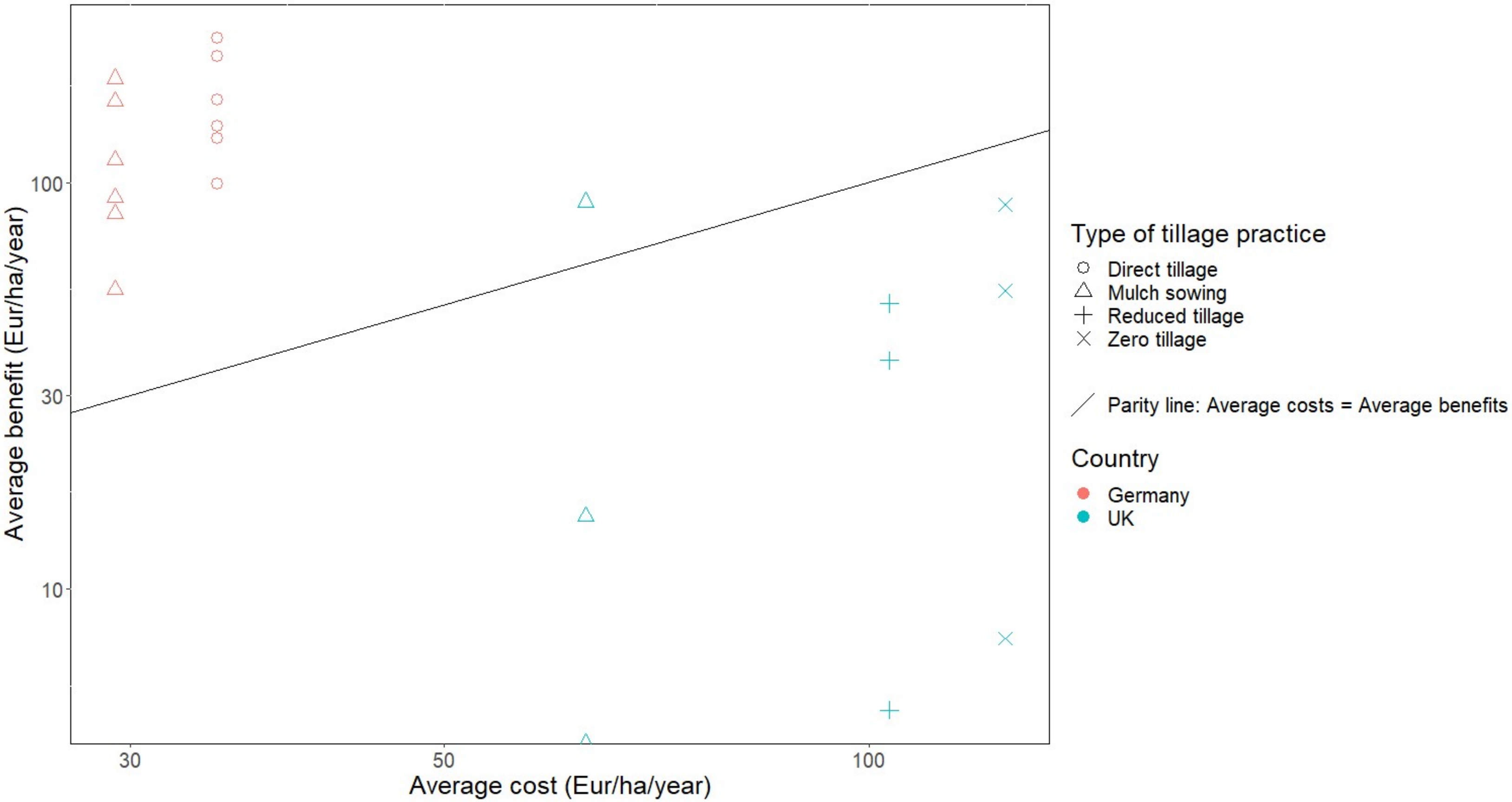

Figure C.1: Average costs and benefits of tillage practices in Germany and the UK. The points represent combinations of average costs (x-axis) and average benefits (y-axis) of different practices provided. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies.

Appendix D

Regional analysis of average costs and benefits

This Appendix displays average costs and benefits across different countries that were grouped in 3 "regions": Figure D.1 for the *"North"*, Figure D.2 for the *"Centre"* and Figure D.3 for the *"South"*.

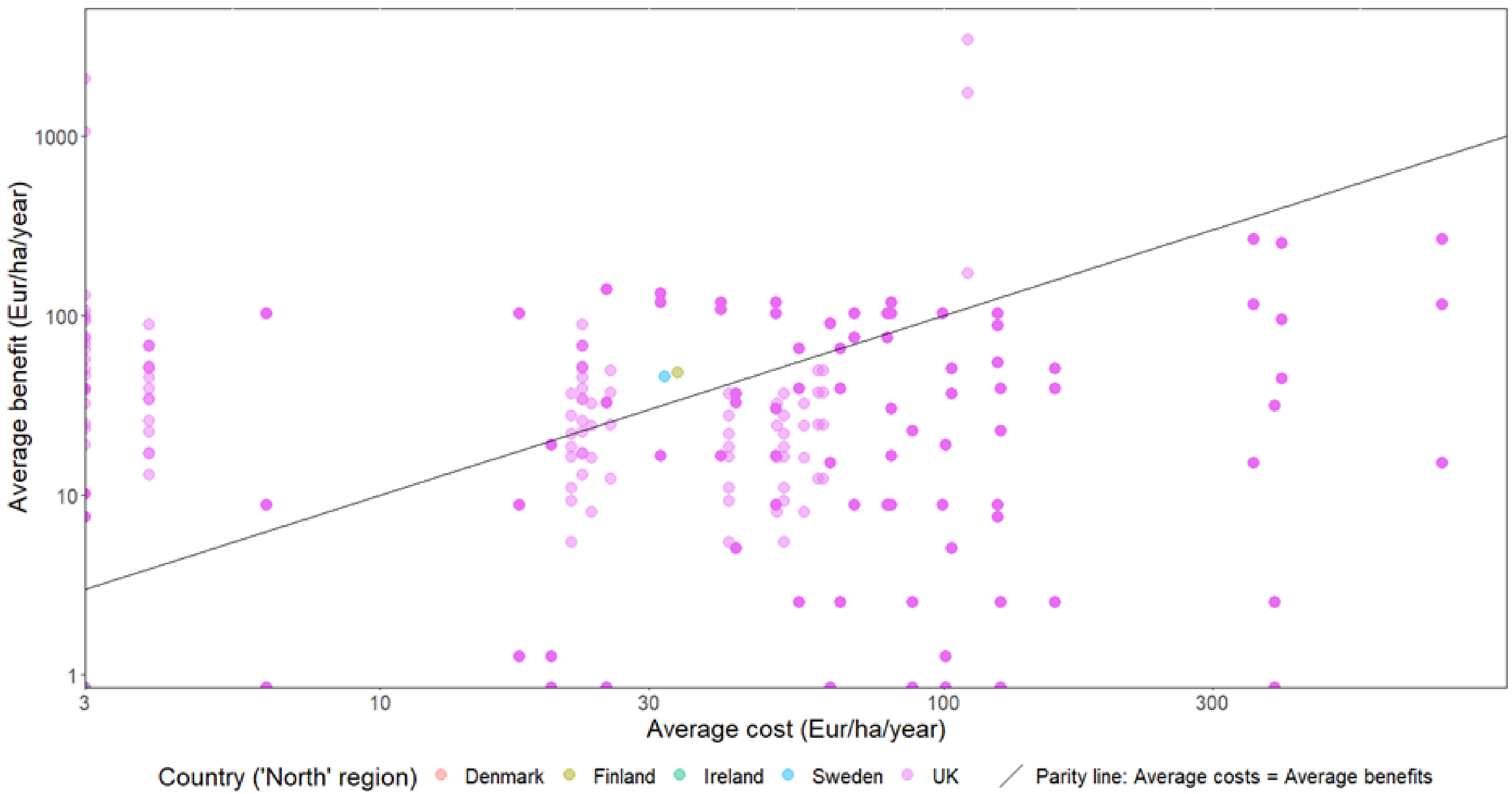

Figure D.1: Regional analysis of average costs and benefits - North region. The points represent combinations of average costs (x-axis) and average benefits (y-axis) of different practices provided. The North region comprises Denmark, Finland, Ireland, Sweden and the UK. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies. Dark dots of the same colour result from overlapping data points.

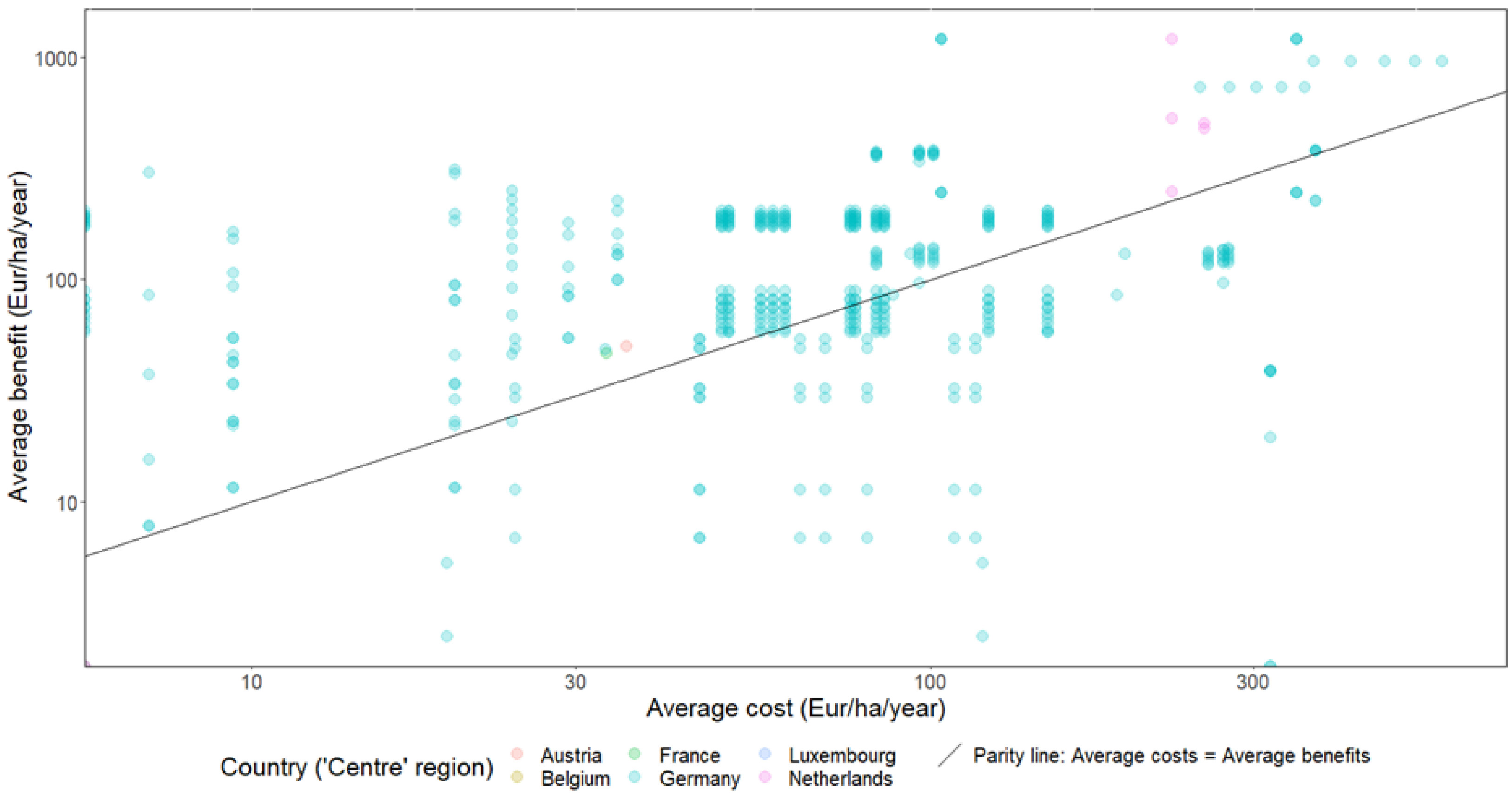

Figure D.2: Regional analysis of average costs and benefits - Centre region. Points represent combinations of average costs (x-axis) and average benefits (y-axis) of different adaptation practices provided. The Centre region comprises Austria, Belgium, France, Germany, Luxemburg and the Netherlands. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies. Dark dots of the same colour result from overlapping data points.

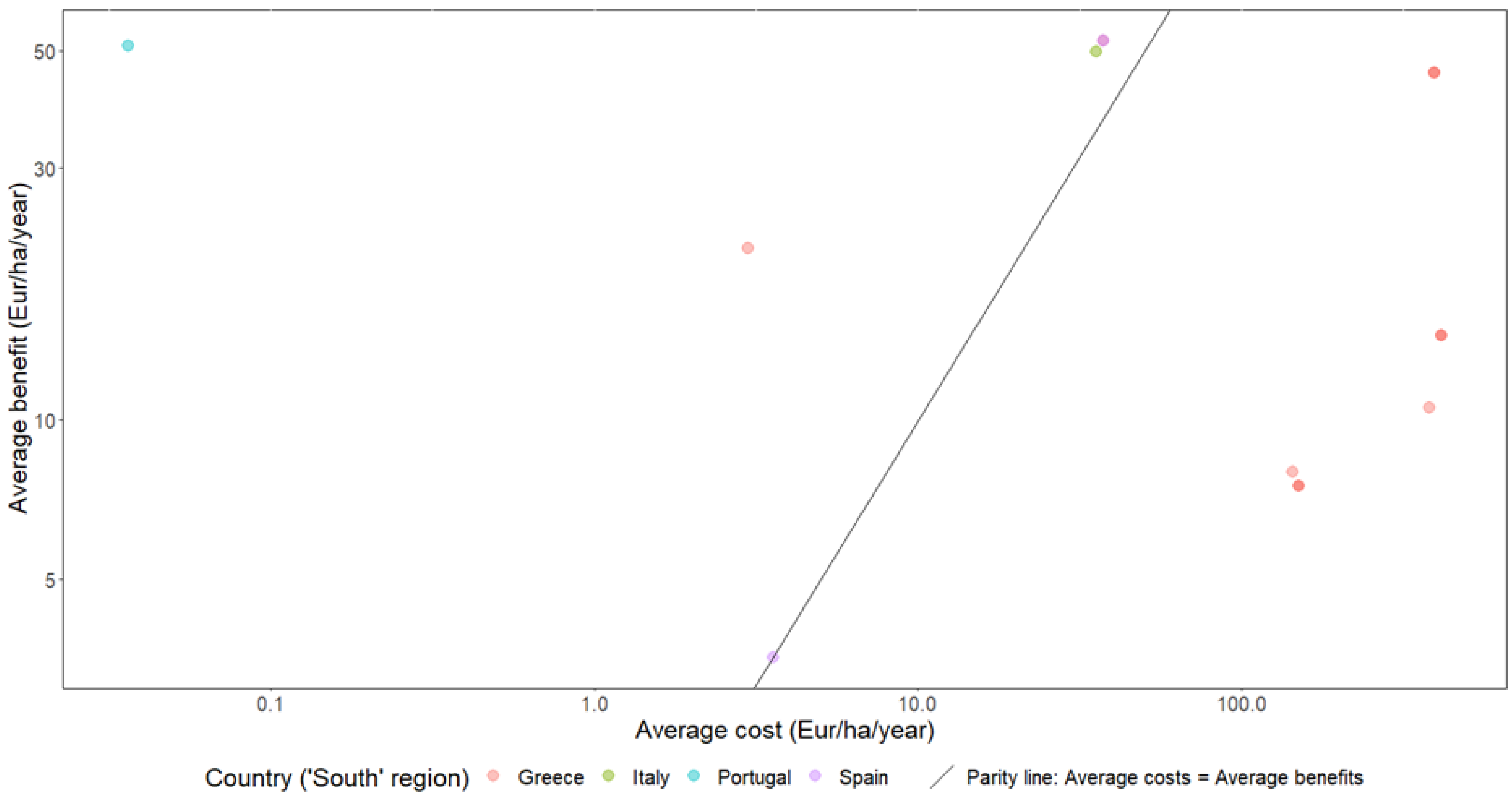

Figure D.3: Regional analysis of average costs and benefits - South region. Points represent combinations of average costs (x-axis) and average benefits (y-axis) of different adaptation practices provided. The South region comprises Greece, Italy, Portugal and Spain. Data are plotted in reference to the parity line on which average costs equal average benefits. Below that line, costs exceed benefits and above it the reverse is true. The figure illustrates costs and benefits on a log scale to accommodate the wide range of estimates reported in the studies. Dark dots of the same colour result from overlapping data points.

Appendix E

BCRs of soil protection practices

This Appendix displays BCRs of different types of soil protection practices in Europe by country (Figure E.1) and by study of origin (Figure E.2).

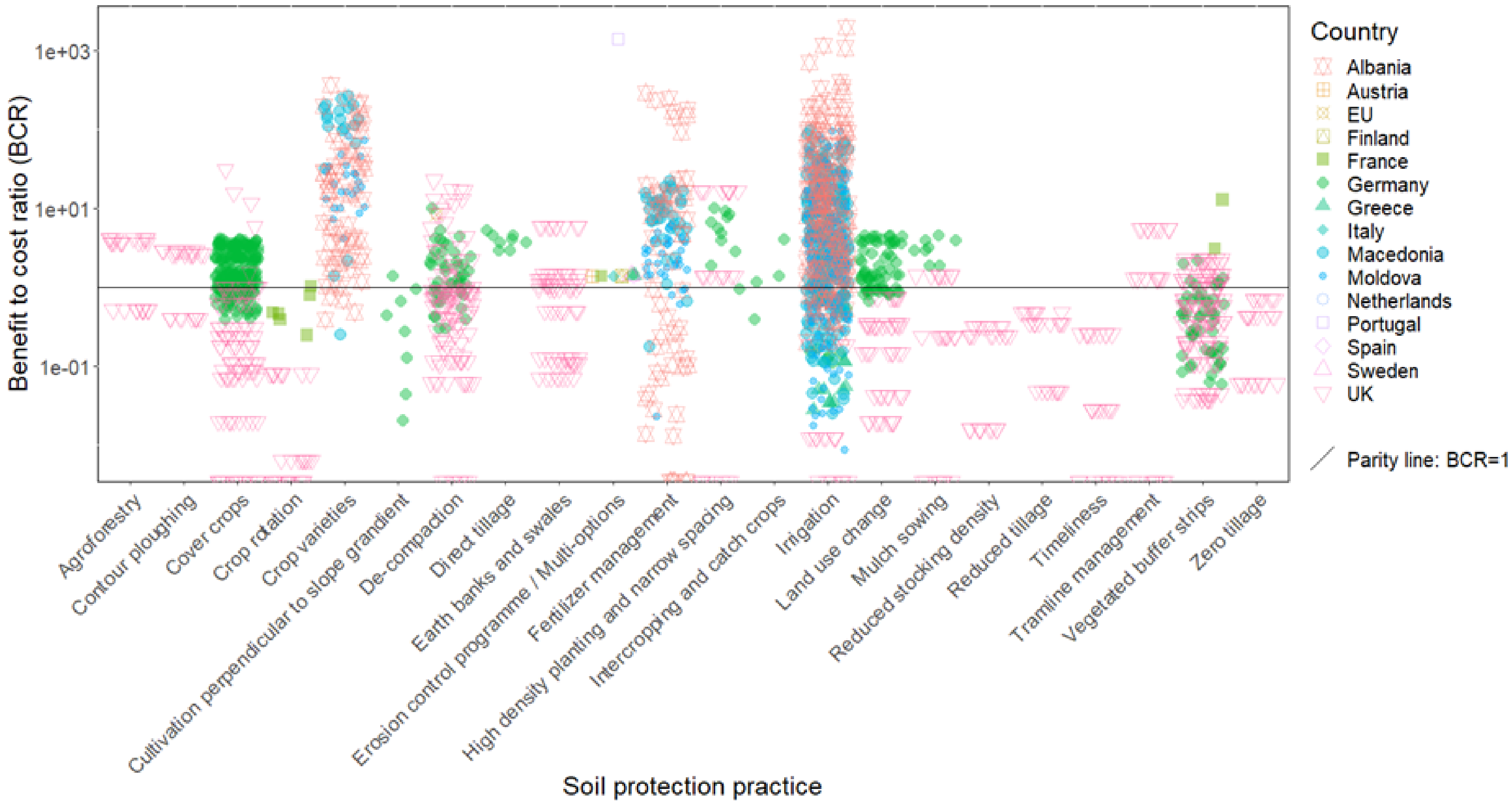

Figure E.1: BCRs of soil protection practices by country. Except figures for Albania, the former Yugoslav Republic (FYR) of Macedonia and the Republic of Moldova which are all provided by a World Bank study, the bulk of data points obtained from the literature review are from the UK and Germany as observed in the analysis of average costs and benefits. Original figures are log transformed to accommodate the wide range of estimates reported in the studies. They are illustrated together with the $BCR = 1$ reference line below which costs exceed benefits. Above this reference line benefits exceed costs, whereas the contrary is true below the reference line. Dark points of the same colour are due to overlapping data points. Graphics are created with *R Studio*. Data for BCRs could only be extracted from the following studies: [1] Kuhlman et al. (2010); [2] Brand-Sassen (2004); [4] Rickson et al. (2010); [8] Tim Chamen et al. (2015); [10]Tröltzsch et al. (2012); [11] de Groot et al. (2006); [12] Panagopoulos et al. (2014); [14] Riksen et al. (2003); [18] van den Born et al. (2000); [19] Berbel et al. (2010); [20] Sutton, Srivastava, Neumann, Iglesias, and Boehlert (2013); [21] Sutton, Srivastava, Neumann, Strzepek, and Boehlert (2013); [22] Sutton, Srivastava, Neumann, Strzepek, and Droogers (2013); [23] Le Bissonnais et al. (2003).

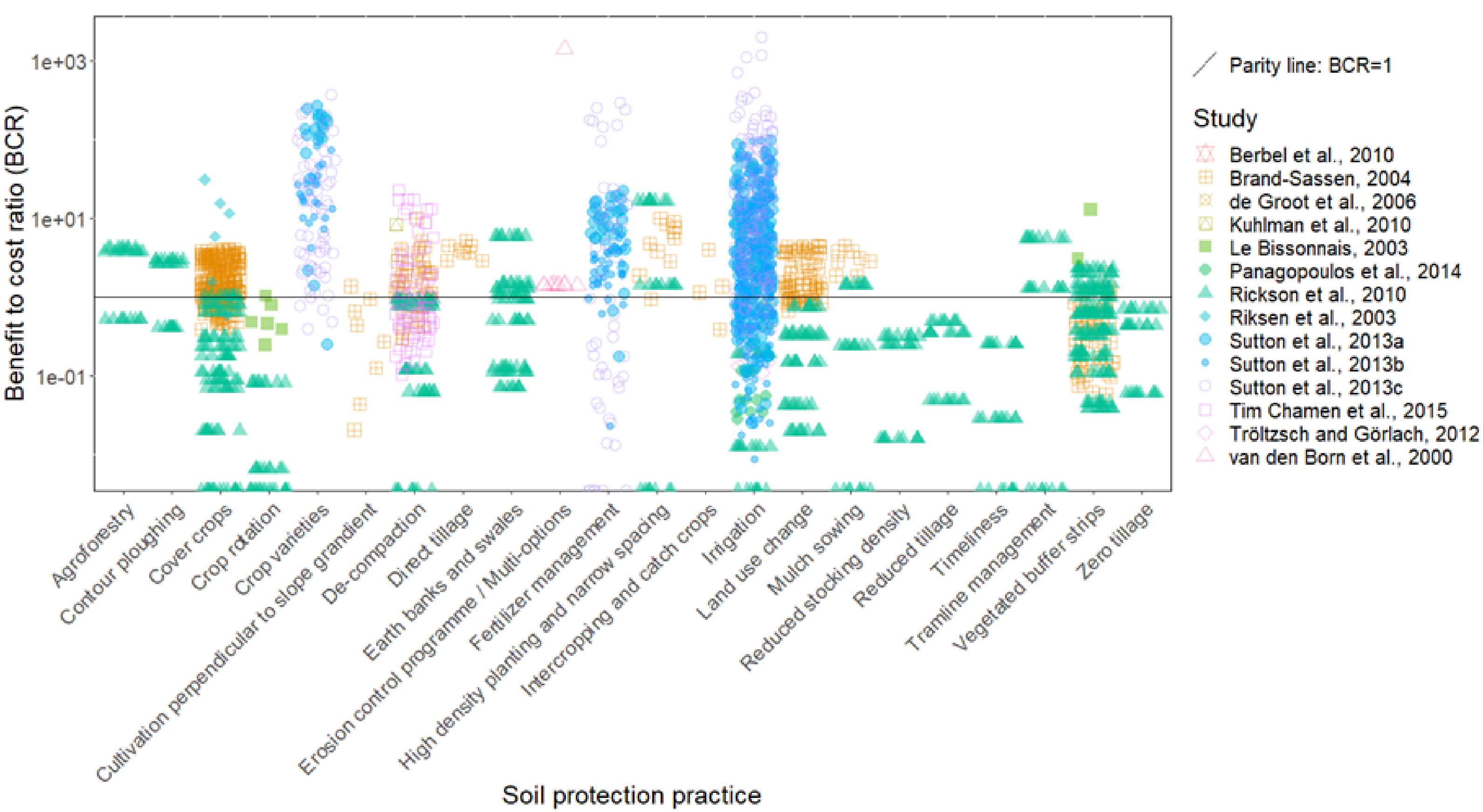

Figure E.2: BCRs of soil protection practices by study. Except figures for Albania, the former Yugoslav Republic (FYR) of Macedonia and the Republic of Moldova which are all provided by a World Bank study, the bulk of data points obtained from the literature review are from the UK and Germany as observed in the analysis of average costs and benefits. Original figures are log transformed to accommodate the wide range of estimates reported in the studies. They are illustrated together with the $BCR = 1$ reference line below which costs exceed benefits. Above this reference line benefits exceed costs, whereas the contrary is true below the reference line. Dark points of the same colour are due to overlapping data points. Graphics are created with *R Studio*.

Appendix F

Smallholder questionnaire - Zanzibar - January and June 2016

This Appendix provides an overview of the type of questions posed during the stakeholder interviews in Zanzibar for the construction of the cost-benefit model.

Table F.1: Smallholder questionnaire - Zanzibar - January and June 2016

Item	Question
Clove production	*What is the area of clove plantation you owe?* *How many trees do you grow on this land - we calculated 220/ha, is this correct?* *What is a typical clove tree density on the plantation?* *What is the survival rate of seedlings?* *What does the survival rate depend on and how can it be optimised?* *What is the annual production of cloves per hectare? What are the min/max/average prodcution?* *What is the average annual production of clove trees per age class?* *Do you have any perspectives of expanding your clove plantation?* *What is the frequency of low/high production cycles?* *What are the main crops you intercrop with cloves? Why?* *What are the most important ones in terms of revenue?* *What is the production of those intercrops/ha (stems/ha)?*
Costs	*What are main investment items and costs?* *Do you owe or rent land?* *What is the value of your plantation/land without clove trees?* *What are main management needs and their costs?* *What are main diseases of clove trees, what are they related to?* *What are the costs of these diseases - are there treatments or production loss?* *How much are farmers paid for clove production - how many days7men and at what wage?* *What are the costs of land preparation, seedlings, planting and weeding?* *What are the costs of additional (adaptation) measures?* *Are there any fertilizer costs?* *What are the costs of felling and replanting clove trees and itnercropping varieties?* *What are the maintenance, drying, sorting, transportation costs of cloves?* *Are there any other costs?*
Benefits	*What are the revenues from clove and itnercrop production?* *Are there other revenues from the plantation for example selling timber from felled trees?* *What are the synergies and benefits from itnercropping with other species?*
Impacts	*Did you experience any impacts from climate anomalies, for example during El Niño 1998 and 2016?* *Has any increase in these impacts been observed in the past 10 years?* *Are clove trees sensitive to weather and climate or environmental indicators?* *Is there any issue of environmental degradation, weather and climate impacts on clove production?* *Did you notice any link between production and weather/climate/rains dry conditions/soils/?* *Do you believe strong winds and potential cyclones can have relevant impacts on clove plantations?*
Adaptation options and their effectiveness	*What are the costs and effectiveness of shadowing with intercrops?* *What are the costs and effectiveness of mini drip (irrigation)?* *How do farmers respond to environmental, weather and climate difficulties?* *What techniques are used to alleviate plantations from these effects?* *To what extent do these measures reduce the impacts on the plantation?* *By how much would the effect be reduced?*
Other	*Is there ongoing research on the agronomy of cloves on the islands?* *What is the investment incentive to grow clove trees?* *Are there available time series for production per regions and prices?*

Appendix G

Actors met during Zanzibar missions

This Appendix gives the list of institutions visited during the field missions in Zanzibar where different actors were met as well as their location.

Table G.1: Actors met during Zanzibar missions - January and June 2016

Institution	Location
First Vice President's Office, Department for Environment	Stone Town, Unguja
Ministry of Agriculture, Forestry and Natural Resources (MANR), Department of Agriculture, Department of Forestry (cash crop and tree crop divisions)	Stone Town, Unguja
Ministry of Agriculture, Forestry and Natural Resources (MANR), Department of Agriculture, Department of Forestry	Wete, Pemba
Ministry of Trade and Industry	Stone Town, Unguja
Zanzibar State Trade Corporation (ZSTC)	Stone Town, Unguja
Zanzibar Clove Producers' Association (ZACPO)	Chake-Chake, Pemba
United Nations Development Programme (UNDP)	Stone Town, Unguja
Matangatuani Agricultural Research Centre	Wete, Pemba
Kizimbani Agricultural Research Centre	Stone Town, Unguja
Various private and Government clove farms as well as private and public nurseries	Unguja and Pemba

Appendix H

CBA assumptions: baseline and adaptations under current climate

This Appendix provides a list of basic assumptions made for the construction of the baseline cost-benefit model and the integration of adaptation options under current climate.

Table H.1: Assumptions for the construction of the baseline and adaptation options under current climate.

	Baseline
Clove tree density	100 trees/ha
Survival rate of clove trees	55%. During the field trip we were given a range of 40%-80% and we chose a survival rate slightly lower than the average to account for the damaged conditions of the average plantation
Seedling plantation	182 seedlings/ha (density/survival rate)
Weeding	Weeding is supposed to be practiced at 50% so costs are considered accordingly to be TZS 100,000/ha.
Mean annual production (Pemba)	389.88 kg dry or 513 pishis of cloves/ha/year
Harvest	513 pishi/ha. The harvest is calculated in pishi as the remuneration of seasonal clove pickers is effectively done in TZS/pishi. We use following measure equivalents: 1 pishi=2.3 kg fresh cloves and 1 kg fresh cloves=1/3 kg dry cloves. Si 1 pishi is equivalent to 0.76 kg of dried cloves.
Felling	20 trees are felled in year 70 and 40 both in years 75 and 80.
Replantation	As for the seedling plantation we replant in each year 70, 75 and 80 the number of tree felled accounting for the survival rate (trees felled/survival rate)
Cassava seedlings	5,000 seedlings/ha
Banana seedlings	160 stems/ha
Revenues	Revenues arise from clove buds (390kg/ha/year at a price of TZS 13,500 –high– and TZS 3,000 – low), from clove timber in years 70,75 and 80 and each tree will generate a revenue of TZS 550,000 in each of those years.
	GMPs - Package of good management practices
Weeding of the clove plantation	Weeding is done at 100% and so the total cost is TZS 200,000/ha (Year 0 to 80).
Organic compost	TZS 50,000/ha (Year 0 to 80).
Timing of transplantation	Zero cost (Year 0 to 80).
Mini drip irrigation	TZS 20,000/ha. Low cost technique using of the top of a closed, funnel-shaped plastic bottle in which cap wholes are drilled to release water drops. It is then filled with water and fixed into the soil at root level of the young tree (Year 0, 1, 2).
Mulching	TZS 10,000/ha. Lemon grass mulching is reported by farmers in the field to be the only to prevent termite nests (Year 0, 1, 2).
Lemon grass against termites	Zero cost (Year 0 to 80).
Removal of parasites	We consider 3% of trees (3 trees) are affected by parasites and each treatment costs TZS 1 500 (Year 0 to 80).
Pruning of damaged branches after harvest	We assume 50% of the plantation (50 clove trees) need to be pruned after harvest at the cost of TZS 1,000/tree (Year 0 to 80).
Additional revenues	We assume 10% additional production resulting from GMPs together with a higher survival rate of 80%.

Table H.2

	Vanilla intercropping
Subplots	3 subplots of $400m^2$ are assumed to be planted with 75 vanilla stands reducing the total number of clove trees by 12 and total clove plantation costs and revenues to 88% of the baseline figures.
Land clearing	Vanilla intercropping is assumed to necessitate additional land clearing at the cost of TZS 494200/ha every 10 years, when the vanilla supporting trees are replanted (Year 0 and every 10 years).
Vanilla seedlings	75 vanilla seedlings are assumed to be planted at the cost of TZS 1,000 each (Year 0 and every 10 years).
Support trees	Vanilla support trees cost TZS 15,000/ha (Year 0 and every 10 years).
Digging and planting	TZS 250/vanilla seedling (Year 0 and every 10 years).
Usual clove weeding	Clove weeding is kept at 50% as in the baseline but additional weeding is necessary for the vanilla plantation (Year 0 to 80).
Additional weeding	TZS 741,000/ha (Year 0 to 80)
Harvesting	TZS 216,000/ha (Year 3 to 80)
Pollination	TZS 150,000/ha (Year 0 to 80)
Processing	TZS 114,000/ha (Year 3 to 80)
Vanilla Revenues	Vanilla production of 62.5 kg/ha is assumed with a price of TZS 126,000/kg (Year 3 to 80).
	Cinnamon intercropping
Intercropping	For intercropping with cinnamon trees, assume 50% cinnamon and 50% clove tree distribution is assumed. As both type of trees imply similar costs, most of the costs remain the same when they do not need to be adapted (see below).
Seedlings	The same number of seedlings are planted (182 seedlings/ha) and cinnamon trees have the same survival rate as clove trees.
Usual clove weeding	It is kept at 50% as in the baseline.
Additional weeding	Additional weeding costs of TZS 62,500/ha need to be applied (Year 0 to 80).
Harvesting	Costs of TZS 22,500/ha (Year 11 to 80) are assumed.
Cinnamon revenues	Cinnamon production is assumed to be TZS 437.5 ton/ha/year between year 5 and 20 and the double afterwards.
	Windbreak (WB)
Usual clove weeding	It is kept at 50% as in the baseline
Teak seedlings	The same amount of seedlings as in the baseline is assumed implicating the survival rate is the same for teak and clove trees.
Others	The same density is required for both species and land area available remains identic: the clove plantation is reduced and replaced by 64 teak trees. The same 80-years lifecycle is assumed for both tree species. Clove and clove timber production decreases to 36% of initial amounts. Cost of plantation and felling are the same for both species therefore the model is kept identic for most items. Felling takes place in years 70, 75 and 80.
Revenues from teak timber	Revenues from teak only arises in year 70, 75 and 80 when trees are felled. Indeed, trees are kept for the protection for the clove plantation. Revenues per teak tree are TZS 2,000,000.

Appendix I

CBA Results for various assumptions

This Appendix displays CBA results under different assumptions of clove prices (Sections I.1 and I.2), the lifetime of the project (30 vs. 80 years), the climate change occurrence (climate change vs.no climate change), and the magnitude of impact regarding dry spells (high vs. low impact) as well as the time of occurrence of cyclones (year 7, 15 and 30).

I.1 High clove prices

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	62 611	21 775	16 704	73 316	24 762	18 714	145 470	49 731	37 195	57 227	19 293	14 911	31 488	12 248	10 276
PV Costs (USD 2016)	28 966	15 369	13 625	29 934	15 913	14 099	43 476	21 338	18 407	21 321	13 315	12 277	17 922	12 287	11 551
NPV (USD 2016)	33 645	6 406	3 079	43 382	8 849	4 615	101 995	28 393	18 787	35 906	5 978	2 635	13 566	(-) 39	(-) 1 275
BCR	2.16	1.42	1.23	2.45	1.56	1.33	3.35	2.33	2.02	2.68	1.45	1.21	1.76	1	0.89

Table I.1: No CC; n=80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	40 636	20 388	16 229	47 318	23 101	18 144	96 032	46 463	36 070	35 277	17 908	14 437	20 900	11 920	10 188
PV Costs (USD 2016)	21 911	14 894	13 461	22 688	15 426	13 931	32 229	20 581	18 147	17 183	13 039	12 181	15 017	12 095	11 485
NPV (USD 2016)	18 725	5 493	2 767	24 630	7 675	4 213	63 802	25 882	17 923	18 094	4 869	2 255	5 883	(-) 174	(-) 1 297
BCR	1.85	1.37	1.21	2.09	1.5	1.3	2.98	2.26	1.99	2.05	1.37	1.19	1.39	0.99	0.89

Table I.2: No CC; n=30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	55 919	19 664	15 228	69 301	23 496	17 828	129 567	44 716	33 687	53 881	18 238	14 173	29 079	11 488	9 745
PV Costs (USD 2016)	30 675	15 906	14 015	29 934	15 913	14 099	44 980	21 810	18 751	22 227	13 628	12 516	18 603	12 537	11 749
NPV (USD 2016)	25 243	3 758	1 213	39 367	7 583	3 729	84 587	22 905	14 937	31 654	4 610	1 657	10 475	(-) 1 049	(-) 2 004
BCR	1.82	1.24	1.09	2.32	1.48	1.26	2.88	2.05	1.8	2.42	1.34	1.13	1.56	0.92	0.83

Table I.3: RCP 4.5; Low impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	36 128	18 415	14 800	44 613	21 918	17 287	85 321	41 776	32 674	33 024	16 922	13 722	17 632	10 994	9 585
PV Costs (USD 2016)	23 002	15 390	13 837	22 688	15 426	13 931	33 189	21 018	18 478	17 773	13 331	12 414	15 467	12 330	11 677
NPV (USD 2016)	25 243	3 758	1 213	21 928	6 492	3 356	52 131	20 759	14 197	15 250	3 590	1 308	2 165	(-) 1 336	(-) 2 093
BCR	1.57	1.2	1.07	1.97	1.42	1.24	2.57	1.99	1.77	1.86	1.27	1.11	1.14	0.89	0.82

Table I.4: RCP 4.5; Low impact; 30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	50 899	18 081	14 121	63 277	21 596	16 500	117 640	40 955	31 057	51 371	17 447	13 620	27 272	10 918	9 346
PV Costs (USD 2016)	30 675	15 906	14 015	29 934	15 913	14 099	44 980	21 810	18 751	22 227	13 628	12 516	18 603	12 537	11 749
NPV (USD 2016)	20 224	2 176	106	33 343	5 683	2 401	72 660	19 144	12 306	29 144	3 819	1 103	8 668	(-) 1 619	(-) 2 402
BCR	1.66	1.14	1.01	2.11	1.36	1.17	2.62	1.88	1.66	2.31	1.28	1.09	1.47	0.87	0.8

Table I.5: RCP 4.5; High impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	32 748	16 936	13 728	40 556	20 143	16 001	77 288	38 261	30 128	31 333	16 182	13 186	16 415	10 461	9 199
PV Costs (USD 2016)	23 002	15 390	13 837	22 688	15 426	13 931	33 189	21 018	18 478	17 773	13 331	12 414	15 467	12 330	11 677
NPV (USD 2016)	9 746	1 546	(-) 109	17 868	4 717	2 070	44 098	17 244	11 650	13 560	2 851	772	948	(-)1 869	(-) 2 479
BCR	1.42	1.1	0.99	1.79	1.31	1.15	2.33	1.82	1.63	1.76	1.21	1.06	1.06	0.85	0.79

Table I.6: RCP 4.5; High impact; 30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	55 026	19 427	15 145	68 765	23 353	17 778	126 190	43 168	32 607	53 434	18 120	14 132	28 757	11 403	9 715
PV Costs (USD 2016)	30 675	15 906	14 015	29 934	15 913	14 099	44 980	21 810	18 751	22 227	13 628	12 516	18 603	12 537	11 749
NPV (USD 2016)	24 350	3 521	1 130	38 831	7 440	3 679	81 210	21 358	13 856	31 207	4 491	1 615	10 154	(-) 1 135	(-) 2 034
BCR	1.79	1.22	1.08	2.3	1.47	1.26	2.81	1.98	1.74	2.4	1.33	1.13	1.55	0.91	0.83

Table I.7: RCP 8.5; Low impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	34 888	18 175	14 717	43 868	21 774	17 237	81 117	40 221	31 595	32 403	16 801	13 681	17 186	10 907	9 555
PV Costs (USD 2016)	23 002	15 390	13 837	22 688	15 426	13 931	33 189	21 018	18 478	17 773	13 331	12 414	15 467	12 330	11 677
NPV (USD 2016)	11 886	2 785	880	21 181	6 348	3 306	47 927	19 203	13 117	14 630	3 470	1 267	1 719	(-) 1 423	(-) 2 122
BCR	1.52	1.18	1.06	1.93	1.41	1.24	2.44	1.91	1.71	1.82	1.26	1.10	1.11	0.88	0.82

Table I.8: RCP 8.5; Low impact; 30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	49 337	17 667	13 976	61 938	21 241	16 375	111 730	38 247	29 166	50 590	17 239	13 547	26 709	10 769	9 294
PV Costs (USD 2016)	30 675	15 906	14 015	29 934	15 913	14 099	44 980	21 810	18 751	22 227	13 628	12 516	18 603	12 537	11 749
NPV (USD 2016)	18 661	1 761	(-) 39	32 004	5 328	2 276	66 750	16 436	10 415	28 363	3 611	1 031	8 106	(-) 1 768	(-) 2 455
BCR	1.61	1.11	1	2.07	1.33	1.16	2.48	1.75	1.56	2.28	1.26	1.08	1.44	0.86	0.79

Table I.9: RCP 8.5; High impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	30 576	16 515	13 584	38 695	19 782	15 877	69 931	35 540	28 239	30 248	15 972	13 114	15 634	10 310	9 147
PV Costs (USD 2016)	23 002	15 390	13 837	22 688	15 426	13 931	33 189	21 018	18 478	17 773	13 331	12 414	15 467	12 330	11 677
NPV (USD 2016)	7 575	1 125	(-) 254	16 007	4 356	1 946	36 741	14 522	9 761	12 474	2 640	700	166	(-) 2 020	(-) 2 531
BCR	1.33	1.07	0.98	1.71	1.28	1.14	2.11	1.69	1.53	1.7	1.2	1.06	1.01	0.84	0.78

Table I.10: RCP 8.5; High impact; 30 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	42 596	13 574	10 889	27 061	10 236	8 813
PV Costs (USD 2016)	29 376	15 635	13 845	15 228	12 487	11 717
NPV (USD 2016)	13 220	(-) 2 061	(-) 2 956	11 833	(-) 2 251	(-) 2 904
BCR	1.45	0.87	0.79	1.78	0.82	0.75

Table I.11: Cyclone; year 7; 80 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	22 048	12 356	10 481	14 828	9 692	8 636
PV Costs (USD 2016)	22 318	15 160	13 682	15 323	12 294	11 650
NPV (USD 2016)	(-) 270	(-) 2 804	(-) 3 201	(-) 495	(-) 2 602	(-) 3 014
BCR	0.99	0.82	0.77	0.97	0.79	0.74

Table I.12: Cyclone; year 7; 30 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	47 412	17 949	14 517	29 798	11 715	9 952
PV Costs (USD 2016)	29 276	15 493	13 708	18 126	12 420	11 661
NPV (USD 2016)	18 136	2 456	809	11 673	(-) 705	(-) 1 709
BCR	1.62	1.16	1.06	1.64	0.94	0.85

Table I.13: Cyclone; year 15; 80 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	28 748	16 922	14 180	17 566	11 171	9 775
PV Costs (USD 2016)	22 220	15 018	13 544	15 221	12 228	11 595
NPV (USD 2016)	6 528	1 904	636	2 344	(-) 1 057	(-) 1 820
BCR	1.29	1.13	1.05	1.15	0.91	0.84

Table I.14: Cyclone; year 15; 30 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	53 539	20 859	16 354	30 925	12 181	10 249
PV Costs (USD 2016)	29 151	15 398	13 638	17 968	12 294	11 554
NPV (USD 2016)	24 388	5 460	2 716	12 957	(-) 114	(-) 1 305
BCR	1.84	1.35	1.20	1.72	0.99	0.89

Table I.15: Cyclone; year 30; 80 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	39 950	20 277	16 179	19 224	11 699	10 097
PV Costs (USD 2016)	22 095	14 924	13 474	15 064	12 102	11 488
NPV (USD 2016)	17 854	5 353	2 705	4 161	(-) 403	(-) 1 392
BCR	1.81	1.36	1.20	1.28	0.97	0.88

Table I.16: Cyclone; year 30; 30 years

I.2 Low clove prices

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	36 839	14 583	11 865	42 390	16 132	12 907	90 115	32 541	25 015	37 215	14 035	11 414	21 130	9 648	8 532
PV Costs (USD 2016)	28 193	15 153	13 480	29 934	15 913	14 099	42 795	21 148	18 280	20 934	13 207	12 204	17 643	12 209	11 499
NPV (USD 2016)	8 647	(-) 570	(-) 1 615	12 456	219	(-) 1 192	47 319	11 393	6 736	16 281	828	(-) 790	3 486	(-) 2 562	(-) 2 966
BCR	1.31	0.96	0.88	1.42	1.01	0.92	2.11	1.54	1.37	1.78	1.06	0.94	1.2	0.79	0.74

Table I.17: No CC; n=80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	24 551	13 855	11 617	28 015	15 262	12 610	60 189	30 600	24 349	23 453	13 207	11 132	13 464	9 352	8 439
PV Costs (USD 2016)	21 428	14 698	13 323	22 688	15 426	13 931	31 805	20 409	18 025	16 942	12 941	12 112	14 844	12 024	11 435
NPV (USD 2016)	3 123	(-) 844	(-) 1 706	5 327	(-) 164	(-) 1 321	28 385	10 191	6 324	6 511	266	(-) 980	(-) 1 379	(-) 2 672	(-) 2 996
BCR	1.15	0.94	0.87	1.23	0.99	0.91	1.89	1.5	1.35	1.38	1.02	0.92	0.91	0.78	0.74

Table I.18: No CC; n=30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	33 369	13 489	11 099	40 308	15 475	12 448	80 703	29 573	22 940	35 480	13 488	11 031	19 880	9 254	8 257
PV Costs (USD 2016)	29 129	15 474	13 725	29 934	15 913	14 099	43 619	21 431	18 495	21 454	13 412	12 371	18 047	12 382	11 644
NPV (USD 2016)	4 240	(-) 1 986	(-) 2 625	10 374	(-) 438	(-) 1 651	37 084	8 142	4 444	14 026	76	(-) 1 340	1 834	(-) 3 128	(-) 3 387
BCR	1.15	0.87	0.81	1.35	0.97	0.88	1.85	1.38	1.24	1.65	1.01	0.89	1.1	0.75	0.71

Table I.19: RCP 4.5; Low impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	22 214	12 832	10 876	26 613	14 648	12 166	53 850	27 826	22 339	22 284	12 695	10 762	12 623	8 984	8 172
PV Costs (USD 2016)	22 037	14 998	13 561	22 688	15 426	13 931	32 340	20 673	18 234	17 291	13 135	12 276	15 120	12 189	11 578
NPV (USD 2016)	177	(-) 2 166	(-) 2 684	3 925	(-) 778	(-) 1 765	21 510	7 154	4 105	4 994	(-) 440	(-) 1 514	(-) 2 497	(-) 3 205	(-) 3 406
BCR	1.01	0.86	0.8	1.17	0.95	0.87	1.67	1.35	1.23	1.29	0.97	0.88	0.83	0.74	0.71

Table I.20: RCP 4.5; Low impact; 30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	30 767	12 668	10 525	37 185	14 491	11 759	73 644	27 347	21 383	34 178	13 078	10 744	18 943	8 958	8 050
PV Costs (USD 2016)	29 129	15 474	13 725	29 934	15 913	14 099	43 619	21 431	18 495	21 454	13 412	12 371	18 047	12 382	11 644
NPV (USD 2016)	1 637	(-) 2 806	(-) 3 199	7 251	(-) 1 422	(-) 2 340	30 025	5 916	2 888	12 725	(-) 335	(-) 1 627	897	(-) 3 424	(-) 3 594
BCR	1.06	0.82	0.77	1.24	0.91	0.83	1.69	1.28	1.16	1.59	0.98	0.87	1.05	0.72	0.69

Table I.21: RCP 4.5; High impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	20 461	12 065	10 321	24 509	13 728	11 499	49 096	25 746	20 832	21 408	12 312	10 484	11 992	8 708	7 972
PV Costs (USD 2016)	22 037	14 998	13 561	22 688	15 426	13 931	32 340	20 673	18 234	17 291	13 135	12 276	15 120	12 189	11 578
NPV (USD 2016)	(-) 1 576	(-) 2 933	(-) 3 240	1 821	(-)1 698	(-)2 432	16 756	5 073	2 598	4 117	(-) 824	(-) 1 792	(-) 3 128	(-) 3 481	(-) 3 606
BCR	0.93	0.8	0.76	1.08	0.89	0.83	1.52	1.25	1.14	1.24	0.94	0.85	0.79	0.71	0.69

Table I.22: RCP 4.5; High impact; 30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	32 906	13 366	11 056	40 030	15 402	12 422	78 650	28 615	22 262	35 248	13 427	11 010	19 714	9 209	8 241
PV Costs (USD 2016)	29 129	15 474	13 725	29 934	15 913	14 099	43 619	21 431	18 495	21 454	13 412	12 371	18 047	12 382	11 644
NPV (USD 2016)	3 777	(-) 2 109	(-) 2 668	10 096	(-) 511	(-) 1 677	35 031	7 184	3 767	13 794	15	(-) 1 361	1 667	(-) 3 172	(-) 3 403
BCR	1.13	0.86	0.81	1.34	0.97	0.88	1.8	1.34	1.2	1.64	1	0.89	1.09	0.74	0.71

Table I.23: RCP 8.5; Low impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	21 570	12 707	10 834	26 227	14 573	12 140	51 308	26 864	21 662	21 963	12 633	10 740	12 391	8 939	8 157
PV Costs (USD 2016)	22 037	14 998	13 561	22 688	15 426	13 931	32 340	20 673	18 234	17 291	13 135	12 276	15 120	12 189	11 578
NPV (USD 2016)	(-) 466	(-) 2 291	(-) 2 727	3 539	(-) 853	(-) 1 791	18 968	6 191	3 428	4 672	(-) 502	(-) 1 535	(-) 2 728	(-) 3 250	(-) 3 421
BCR	0.98	0.85	0.8	1.16	0.94	0.87	1.59	1.3	1.19	1.27	0.96	0.87	0.82	0.73	0.7

Table I.24: RCP 8.5; Low impact; 30 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	29 956	12 453	10 450	36 490	14 306	11 695	70 052	25 670	20 197	33 773	12 970	10 707	18 652	8 881	8 023
PV Costs (USD 2016)	29 129	15 474	13 725	29 934	15 913	14 099	43 619	21 431	18 495	21 454	13 412	12 371	18 047	12 382	11 644
NPV (USD 2016)	827	(-) 3 021	(-) 3 275	6 556	(-) 1 607	(-) 2 404	26 433	4 239	1 702	12 319	(-) 442	(-) 1 664	605	(-) 3 501	(-) 3 621
BCR	1.03	0.8	1	1.22	0.9	0.83	1.61	1.2	1.09	1.57	0.97	0.87	1.03	0.72	0.69

Table I.25: RCP 8.5; High impact; 80 years

	Baseline with shading			GMPs			Vanilla intercropping			Cinnamon intercropping			Wind break		
	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	19 335	11 847	10 246	23 544	13 541	11 435	44 648	24 061	19 647	20 845	12 203	10 446	11 587	8 629	7 945
PV Costs (USD 2016)	22 037	14 998	13 561	22 688	15 426	13 931	32 340	20 673	18 234	17 291	13 135	12 276	15 120	12 189	11 578
NPV (USD 2016)	(-) 2 702	(-) 3 151	(-) 3 315	856	(-) 1 885	(-) 2 496	12 308	3 388	1 413	3 554	(-) 933	(-) 1 829	(-) 3 533	(-) 3 560	(-) 3 633
BCR	0.88	0.79	0.76	1.04	0.88	0.82	1.38	1.16	1.08	1.21	0.93	0.85	0.77	0.71	0.69

Table I.26: RCP 8.5; High impact; 30 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	26 461	10 331	8 850	18 834	8 604	7 774
PV Costs (USD 2016)	28 601	15 419	13 700	17 949	12 409	11 664
NPV (USD 2016)	(-) 2 139	(-) 5 088	(-) 4 850	885	(-) 3 805	(-) 3 890
BCR	0.93	0.67	0.65	1.05	0.69	0.67

Table I.27: Cyclone; year 7; 80 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	14 912	9 690	8 637	11 169	8 309	7 680
PV Costs (USD 2016)	21 836	14 964	13 543	15 150	12 224	11 601
NPV (USD 2016)	(-) 6 923	(-) 5 274	(-) 4 906	(-) 3 981	(-) 3 915	(-) 3 920
BCR	0.68	0.65	0.64	0.74	0.68	0.66

Table I.28: Cyclone; year 7; 30 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	28 958	12 599	10 731	20 254	9 371	8 365
PV Costs (USD 2016)	28 503	15 277	13 563	17 798	12 271	11 540
NPV (USD 2016)	456	(-) 2 678	(-) 2 832	2 455	(-) 2 900	(-) 3 176
BCR	1.02	0.82	0.79	1.14	0.76	0.72

Table I.29: Cyclone; year 15; 80 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	18 387	12 058	10 555	12 588	9 075	8 271
PV Costs (USD 2016)	21 738	14 822	13 406	14 999	12 086	11 477
NPV (USD 2016)	(-) 3 351	(-) 2 765	(-) 2 851	(-) 2 410	(-) 3 011	(-) 3 206
BCR	0.85	0.81	0.79	0.84	0.75	0.72

Table I.30: Cyclone; year 15; 30 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	32 135	14 108	11 683	20 868	9 615	8 519
PV Costs (USD 2016)	28 378	15 183	13 493	17 690	12 217	11 502
NPV (USD 2016)	3 758	(-) 1 075	(-) 1 810	3 179	(-) 2 602	(-) 2 983
BCR	1.13	0.93	0,87	1.18	0.79	0.74

Table I.31: Cyclone; year 30; 80 years

	Baseline with shading			Wind break		
	3.5%	10%	13%	3.5%	10%	13%
PV Revenues (USD 2016)	24 195	13 797	11 592	13 432	9 347	8 437
PV Costs (USD 2016)	21 613	14 728	13 336	14 890	12 031	11 439
NPV (USD 2016)	2 582	(-) 931	(-) 1 744	(-) 1 458	(-) 2 685	(-) 3 002
BCR	1.12	0.94	0.87	0.90	0.78	0.74

Table I.32: Cyclone; year 30; 30 years

Appendix J

Decision trees - GMP application and methodological steps

This Appendix details the steps for the calculation of expected values with option reversibility for one source of uncertainty (Section J.19 and two sources of uncertainty J.2). It also shows how these are transcribed in the decision trees.

J.1 One source of uncertainty: climate change

	P1				P2					
	Costs		Benefits		PV Costs		PV Benefits		Pr_{CC}	Expected Value
	No CC	CC	No CC	CC	No CC	CC	No CC	CC		
B	10 194	/	6 819	/	8 235	8 949	23 793	17 678	10%	11 500.1
WB	10 606	/	6 819	/	8 446	8 446	28 552	23 310	10%	15 794.8
B	10 194	/	6 819	/	8 235	8 949	23 793	17 678	50%	8 678.5
WB	10 606	/	6 819	/	8 446	8 446	28 552	23 310	50%	13 698
B	10 194	/	6 819	/	8 235	8 949	23 793	17 678	90%	6 036.9
WB	10 606	/	6 819	/	8 446	8 446	28 552	23 310	90%	11 601.2

Table J.1: Sum of discounted costs and benefits and expected values for high clove prices over two periods for GMP and Baseline investments without decision reversibility between P1 and P2. High clove prices for two periods and two climate scenarios (No CC and CC). Period 1 includes years Y=0 to Y=5 and period 2 the years Y=6 to Y=30. Both periods, including Y0 and Y6, were discounted with a discount rate of 10%. In both investment years the discount factor is 1. Figures are those for the high price of cloves. For climate change low rainfall projections under RCP 4.5 Model 4 high impact were used. All figures were taken from the CBA and are expressed in 2016 PPP USD. Adapted from Markandya (2016).

	P1		P2		Pr_{CC}	Expected Value
	No CC	CC	No CC	CC		
B	(-) 3 375	/	15 558	8 729	10%	11 500.1
WB	(-) 3 787	/	20 106	14 864	10%	15 794.8
B	(-) 3 375	/	4 446	(-) 3 378	50%	8 678.5
WB	(-) 3 375	/	1 239	3 414	50%	13 698
B	(-) 3 375	/	4 446	(-) 3 378	90%	6 036.9
WB	(-) 3 375	/	1 239	3 414	90%	11 601.2

Table J.2: NPVs and expected values without decision reversibility between p1 and P2 over two periods for the GMP and Baseline investments. High clove prices for two periods and climate scenarios, No CC and CC. This table uses benefit and cost figures from table J.1 to calculate NPVs. NPVs are expressed in 2016 PPP USD.

	Period 1		Period 2	
	B	GMP	B	GMP
No CC	$NPV_{1B}^{No\ CC,H}$ = (-) 3 375	$NPV_{1GMP}^{No\ CC,H}$ = (-) 3 787	$NPV_{2B}^{No\ CC,H}$ = 15 558	$NPV_{2GMP}^{No\ CC,H}$ = 20 106
CC	/	/	$NPV_{2B}^{CC,H}$ = 8 729	$NPV_{2GMP}^{CC,H}$ = 14 864

Table J.3: NPVs for two periods depending on climate uncertainty. NPVs are expressed in 2016 PPP USD.

Expected values over the two periods that allow for decision reversibility are calculated using the results from Table J.3 and $Pr_{noCC} = 0.9$ as follows. Outcomes are summarised in J.4 and illustrated in Figure J.1.

$$\begin{aligned} E_{1B,\ 2B} &= NPV_{1B}^{noCC} + NPV_{2B}^{noCC} \times Pr_{noCC} + NPV_{2B}^{CC} \times Pr_{CC} \\ &= -3375 + 15558 \times 0.9 + 8729 \times 0.1 \\ &= -3375 + 14002.2 + 872.9 \\ &= 11500.1 \end{aligned} \tag{J.1}$$

$$\begin{aligned} E_{1GMP,\ 2GMP} &= NPV_{1GMP}^{noCC} + NPV_{2GMP}^{noCC} \times Pr_{noCC} + NPV_{2GMP}CC \times Pr_{CC} \\ &= -3787 + 20106 \times 0.9 + 14864 \times 0.1 \\ &= -3787 + 18095.4 + 1486.4 \\ &= 15794.8 \end{aligned} \tag{J.2}$$

$$\begin{aligned} E_{1GMP,\ 2B} &= NPV^{noCC}_{1GMP} + NPV^{noCC}_{2B} \times Pr_{noCC} + NPV^{CC}_{2B} \times Pr_{CC} \\ &= -3787 + 15558 \times 0.9 + 8729 \times 0.1 \\ &= -3787 + 14002.2 + 872.9 \\ &= 11088.1 \end{aligned} \tag{J.3}$$

$$\begin{aligned} E_{1B,\ 2GMP} &= NPV^{noCC}_{1B} + NPV^{noCC}_{2GMP} \times Pr_{noCC} + NPV^{CC}_{2GMP} \times Pr_{CC} \\ &= -3375 + 20106 \times 0.9 + 14864 \times 0.1 \\ &= -3375 + 18095.4 + 1486.4 \\ &= 16206.8 \end{aligned} \tag{J.4}$$

		Period 2	
		B	GMP
Period 1	B	$E_{1B,\ 2B}$ = 11 501.1	$E_{1B,\ 2GMP}$ = 16 206.8
	GMP	$E_{1GMP,\ 2B}$ = 11 088.1	$E_{1GMP,\ 2GMP}$ = 15 794.8

Table J.4: Expected values with decision reversibility between P1 and P2 for Pr_{noCC} = 0.9**.** $E_{1B,\ 2B}$ reads *Expected value of not investing in GMP in P1 if not investing in GMP in P2*. Not investing means keeping B. Expected values are expressed in 2016 PPP USD.

Expected values are calculated as above for $Pr_{noCC} = 0.1$. Results are summarised in Table J.5 and illustrated in Figure J.2.

		Period 2	
		B	GMP
Period 1	B	$E_{1B,\ 2B}$ = 6 036.9	$E_{1B,\ 2GMP}$ = 12 013.2
	GMP	$E_{1GMP,\ 2B}$ = 5 624.9	$E_{1GMP,\ 2GMP}$ = 11 601.2

Table J.5: Expected values with decision reversibility between P1 and P2 for Pr_{noCC} = 0.1**.** $E_{1B,\ 2B}$ reads *Expected value of not investing in GMP in P1 if not investing in GMP in P2*. Not investing means keeping B. Expected values are expressed in 2016 PPP USD.

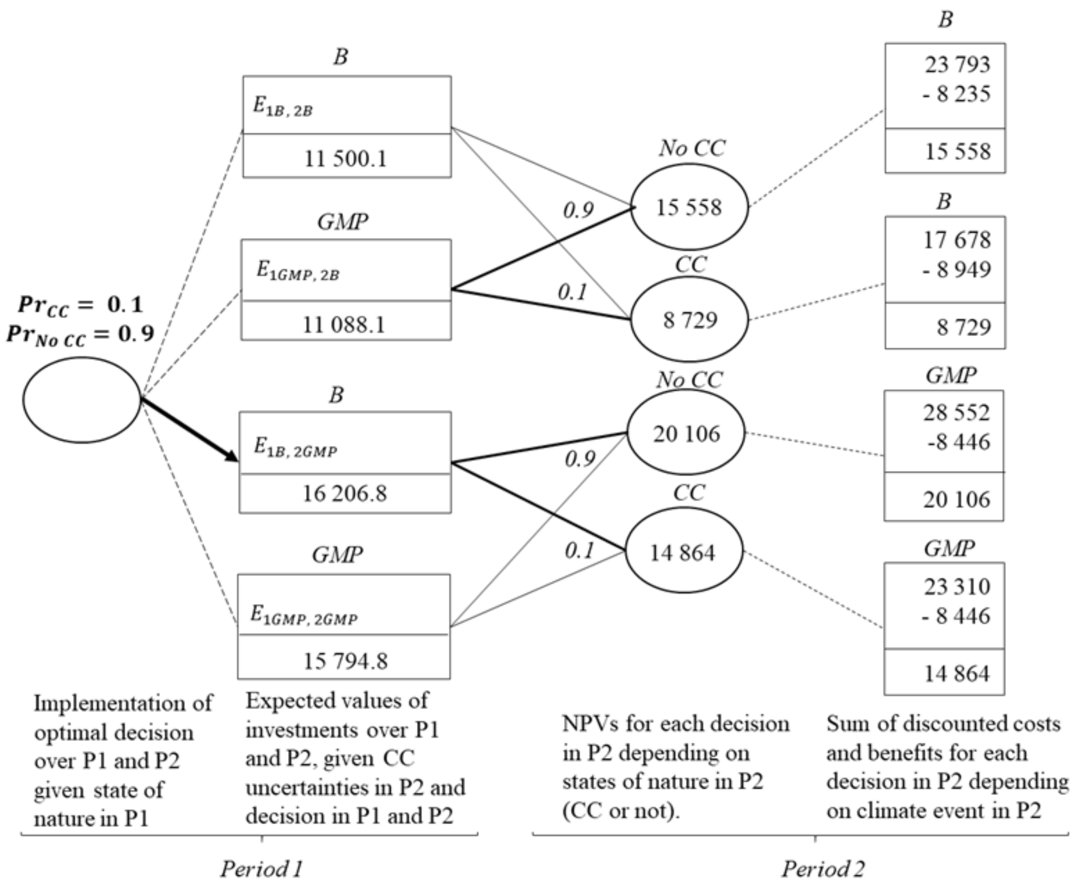

Figure J.1: Decision diagram for optimal investment in P1 given climate uncertainties in P2 for $Pr_{noCC} = 0.9$. Decisions can be taken prior to Y=0 (P1) and Y=6 (P2). Only climate change is a source of uncertainty in P2. In P1, prices are assumed to be high and there is no climate change.

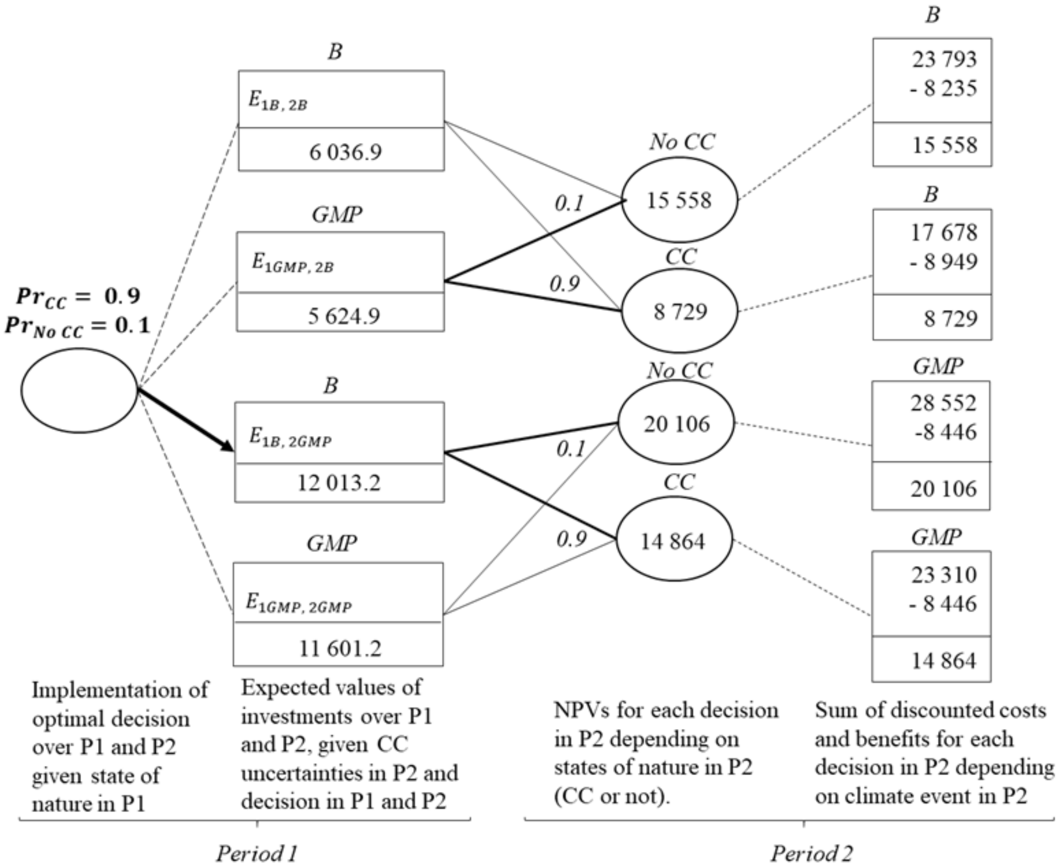

Figure J.2: Decision diagram for optimal investment in P1 given climate uncertainties in P2 for $Pr_{noCC} = 0.1$. Decisions can be taken prior to Y=0 (P1) and Y=6 (P2). Only climate change is a source of uncertainty in P2. In P1, prices are assumed to be high and there is no climate change.

J.2 Two sources of uncertainty: climate change and clove prices

	P1				P2					
	Costs		Benefits		PV Costs		PV Benefits		Pr_{CC}	Expected Value
	No CC	CC	No CC	CC	No CC	CC	No CC	CC		
B	10 194	/	6 819	/	7 891	8 262	12 337	9 166	10%	716.8
WB	10 606	/	6 819	/	8 446	7 859	14 805	11 149	10%	2 265.1
B	10 194	/	6 819	/	7 891	8 262	12 337	9 166	50%	(-) 700
WB	10 606	/	6 819	/	8 446	7 859	14 805	11 149	50%	1 037.5
B	10 194	/	6 819	/	7 891	8 262	12 337	9 166	90%	(-) 2 116.8
WB	10 606	/	6 819	/	8 446	7 859	14 805	11 149	90%	(-) 381.4

Table J.6: Sum of discounted costs and benefits and expected values for low clove prices over two periods for GMP and Baseline investments without decision reversibility between P1 and P2. Low clove prices for two periods and two climate scenarios (No CC and CC). Period 1 includes years Y=0 to Y=5 and period 2 the years Y=6 to Y=30. Both periods, including Y0 and Y6, were discounted with a discount rate of 10%. In both investment years the discount factor is 1. Figures are those for the high price of cloves. For climate change low rainfall projections under RCP 4.5 Model 4 high impact were used. All figures were taken from the CBA and are expressed in 2016 PPP USD. Adapted from Markandya (2016).

	P1		P2		Pr_{CC}	Expected Value
	No CC	CC	No CC	CC		
B	(-) 3 375	/	4 446	904	10%	716.8
WB	(-) 3 787	/	6 359	3 290	10%	2 265.1
B	(-) 3 375	/	4 446	904	50%	(-) 700
WB	(-) 3 375	/	6 359	3 290	50%	1 037.5
B	(-) 3 375	/	4 446	904	90%	(-) 2 116.8
WB	(-) 3 375	/	6 359	3 290	90%	(-) 381.4

Table J.7: NPVs and expected values without decision reversibility between p1 and P2 over two periods for the GMP and Baseline investments. Low clove prices for two periods and climate scenarios, No CC and CC. This table uses benefit and cost figures from table J.6 to calculate NPVs. NPVs are expressed in 2016 PPP USD.

Expected values over the two periods that allow for decision reversibility are calculated using the results from Table J.8 as follows. Probabilities used are: and $Pr_{noCC} = 0.9$ and $Pr_H = 0.8$. Results are summarised in Table J.9:

	Period 1		Period 2	
	B	GMP	B	GMP
No CC	$NPV_{1B}^{No\ CC,H}$ = (-) 3 375	$NPV_{1GMP}^{No\ CC,H}$ = (-) 3 787	$NPV_{2B}^{No\ CC,H}$ = 15 558	$NPV_{2GMP}^{No\ CC,H}$ = 20 106
CC	/	/	$NPV_{2\ B}^{CC,H}$ = 8 729	$NPV_{2GMP}^{CC,H}$ = 14 864
No CC	/	/	$NPV_{2\ B}^{no\ CC,L}$ = 4 446	$NPV_{2\ GMP}^{no\ CC,L}$ = 6359
CC	/	/	$NPV_{2\ B}^{CC,L}$ = 904	$NPV_{2\ GMP}^{CC,L}$ = 3 290

Table J.8: NPVs depending for climate and price uncertainties. NPVs are expressed in 2016 PPP USD.

$$\begin{aligned}
E_{1B,\ 2B} = {} & NPV_{1B}^{noCC,H} + \\
& \left(NPV_{2B}^{noCC,H} \times Pr_H + NPV_{2B}^{noCC,L} \times Pr_L\right) Pr_{noCC} + \\
& \left(NPV_{2B}^{CC,H} \times Pr_H + NPV_{2B}^{CC,L} \times Pr_L\right) Pr_{CC} \\
= {} & -3375 + (15558 \times 0.8 + 4446 \times 0.24)\, 0.1 + (8729 \times 0.8 + 904 \times 0.2)\, 0.9 \\
= {} & -3375 + 1333.56 + 6447.6 \\
= {} & 4406.16
\end{aligned} \tag{J.5}$$

$$\begin{aligned}
E_{1GMP,\ 2B} = {} & NPV_{1GMP}^{noCC,H} + \\
& \left(NPV_{2B}^{noCC,H} \times Pr_H + NPV_{2B}^{noCC,L} \times Pr_L\right) Pr_{noCC} + \\
& \left(NPV_{2B}^{CC,H} \times Pr_H + NPV_{2B}^{CC,L} \times Pr_L\right) Pr_{CC} \\
= {} & -3787 + (15558 \times 0.8 + 4446 \times 0.2)\, 0.1 + (8729 \times 0.8 + 904 \times 0.2)\, 0.9 \\
= {} & -3787 + 1333.56 + 6447.6 \\
= {} & 3994.16
\end{aligned} \tag{J.6}$$

$$
\begin{aligned}
E_{1B,\ 2GMP} = NPV_{1B}^{noCC,H} + & \\
& \left(NPV_{2GMP}^{noCC,H} \times Pr_H + NPV_{2GMP}^{noCC,L} \times Pr_L\right) Pr_{noCC} + \\
& \quad \left(NPV_{2GMP}^{CC,H} \times Pr_H + NPV_{2GMP}^{CC,L} \times Pr_L\right) Pr_{CC} \\
&= -3375 + (20106 \times 0.8 + 6359 \times 0.2)\, 0.1 + (14864 \times 0.8 + 3290 \times 0.2)\, 0.9 \\
&= -3375 + (16084.8 + 1271.8)\, 0.1 + (11891.2 + 658)\, 0.9 \\
&= -3375 + 1735.66 + 11294.28 \\
&= 9654.94
\end{aligned}
\tag{J.7}
$$

$$
\begin{aligned}
E_{1GMP,\ 2GMP} = NPV_{1GMP}^{noCC,H} + & \\
& \left(NPV_{2GMP}^{noCC,H} \times Pr_H + NPV_{2GMP}^{noCC,L} \times Pr_L\right) Pr_{noCC} + \\
& \quad \left(NPV_{2GMP}^{CC,H} \times Pr_H + NPV_{2GMP}^{CC,L} \times Pr_L\right) Pr_{CC} \\
&= -3787 + (20106 \times 0.8 + 6359 \times 0.2)\, 0.1 + (14864 \times 0.8 + 3290 \times 0.2)\, 0.9 \\
&= -3787 + (16084.8 + 1271.8)\, 0.1 + (11891.2 + 658)\, 0.9 \\
&= -3787 + 1735.66 + 11294.28 \\
&= 9242.94
\end{aligned}
\tag{J.8}
$$

		Period 2	
		B	GMP
Period 1	B	$E_{1B,\ 2B} = 4\,406.16$	$E_{1B,\ 2GMP} = 9\,654.94$
	GMP	$E_{1GMP,\ 2B} = 3\,994.16$	$E_{1GMP,\ 2GMP} = 9\,242.94$

Table J.9: Expected values with decision reversibility between P1 and P2 for Pr_{noCC}= 0.9. $E_{1B,\ 2B}$ reads *Expected value of not investing in GMP in P1 if not investing in GMP in P2.* Not investing means keeping B. Expected values are expressed in 2016 PPP USD.

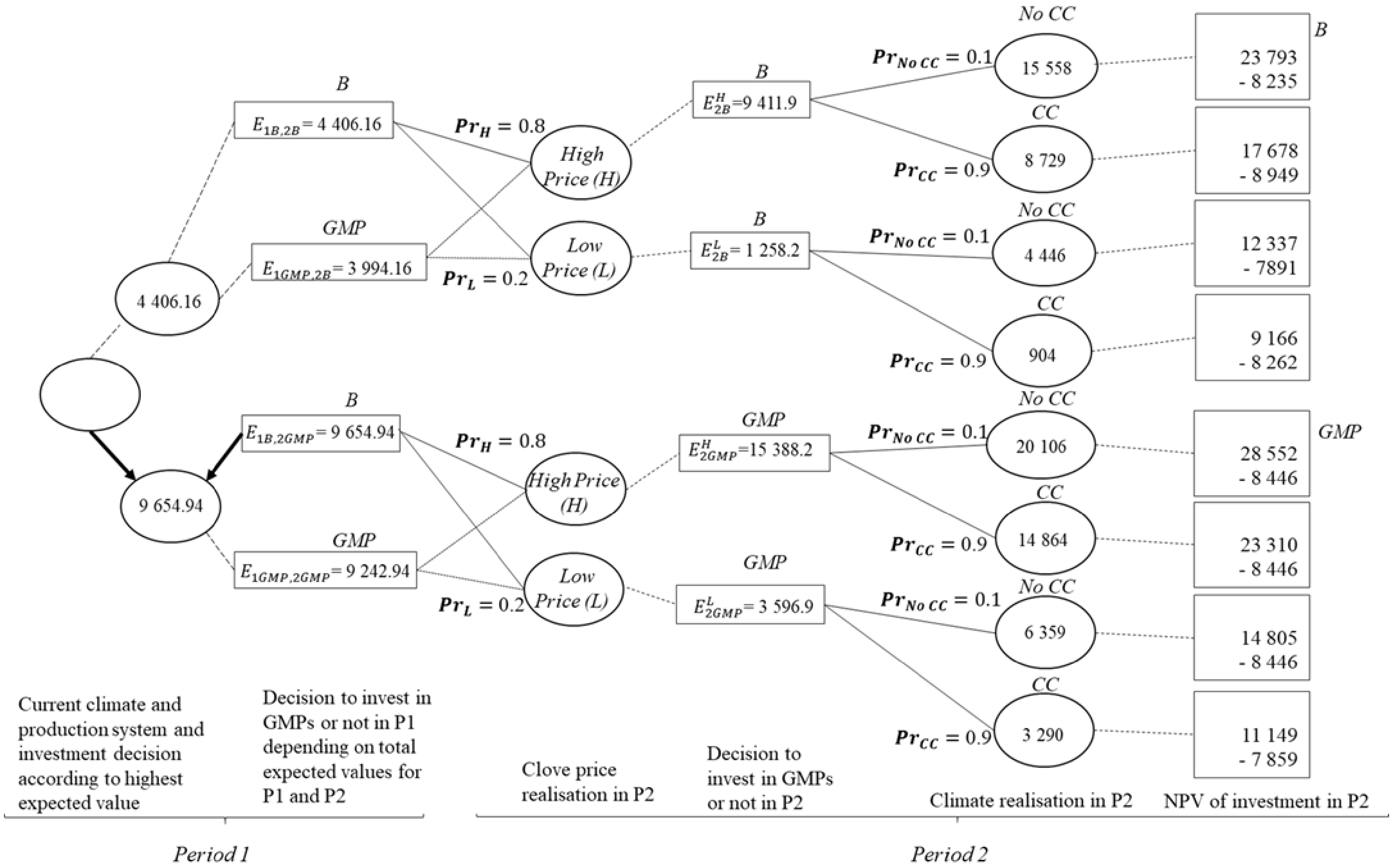

Figure J.3: Decision diagram for optimal investment in P1 given climate and price uncertainties in P2 for $Pr_{CC} = 0.9$ and $Pr_H = 0.8$. Decisions can be taken prior to Y=0 (P1) and Y=6 (P2). Only climate change is a source of uncertainty in P2. In P1, prices are assumed to be high and there is no climate change.

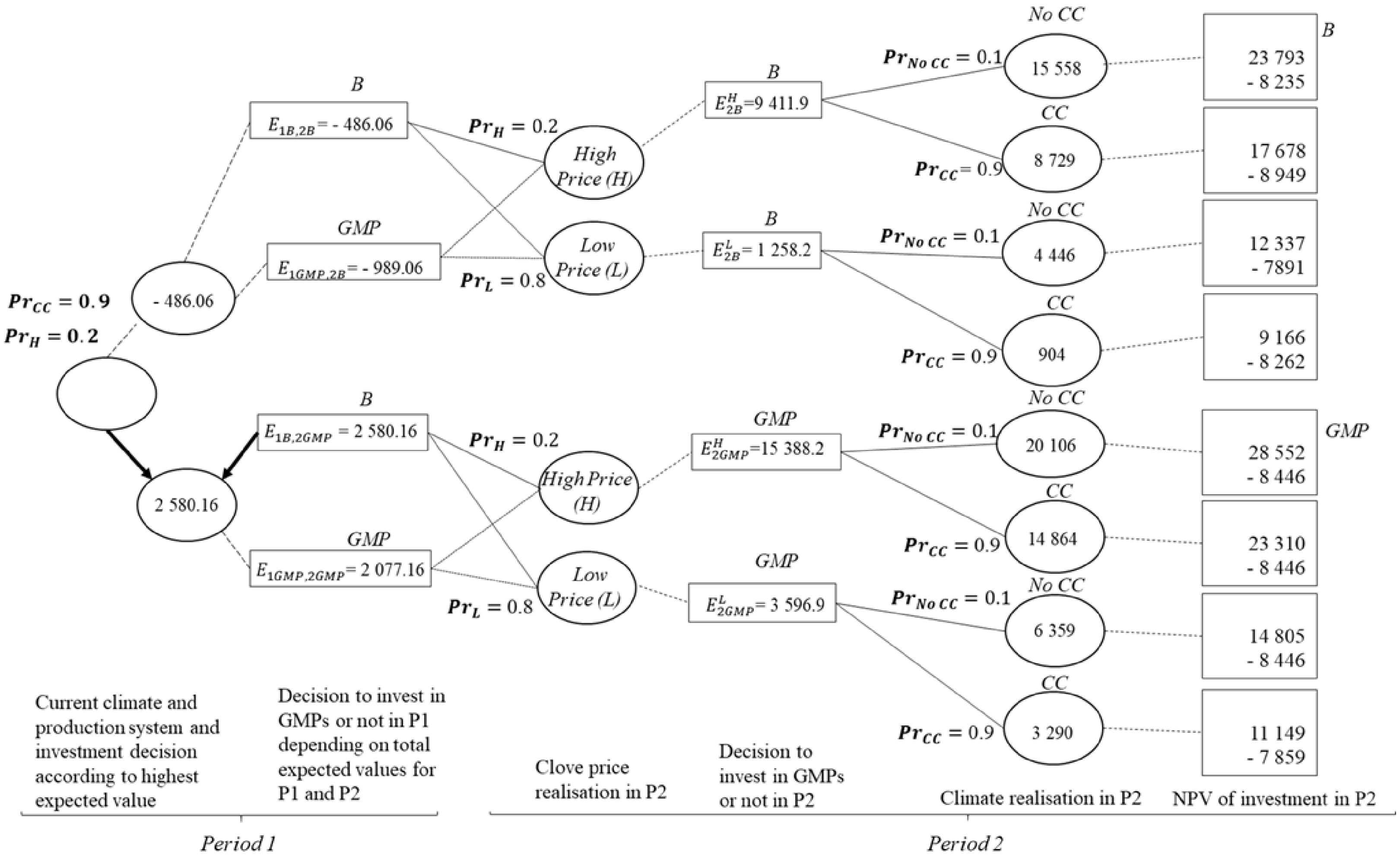

Figure J.4: Decision diagram for optimal investment in P1 given climate and price uncertainties in P2 for Pr_{CC}= 0.9 and Pr_H= 0.2. Decisions can be taken prior to Y=0 (P1) and Y=6 (P2). Only climate change is a source of uncertainty in P2. In P1, prices are assumed to be high and there is no climate change.

Appendix K

FCM - Interview guidelines

This Appendix displays the interview guidelines used for the resilience mapping sessions. These were used as handouts and were provided to all interview participants.

Mapping process – co-production:

Question 1. According to your experience, knowledge and expertise *how are drivers and characteristics of the system affecting resilience* of wastewater management at Northern Ireland Water (NI Water) for the Belfast area in the short, medium and long term?

Question 2. According to your experience, knowledge and expertise *which interventions/changes could increase resilience* of wastewater management at NI Water for the Belfast area in the short, medium and long term?

Create a set of cognitive maps to identify:

1. Different perspectives of resilience.
2. Critical interactions between system components.
3. Unintended consequences.

Applicability

1. Co-production with the end user.
2. Process potentially useful within NI Water: holistic approach to resilience, collect distinctive and complementary points of view by interviewing internal and external agents working on different aspects of wastewater management; broad reflection on the topic of resilience.
3. Methodology transferable to other utilities.
4. Potentially develop an aggregated map.

Question 1. *According to your experience, knowledge and expertise how are drivers and characteristics of the system affecting resilience of wastewater management at Northern Ireland Water (NI Water) for the Belfast area in the short, medium and long term?*

- Write down all concepts and elements that come to mind in relation to drivers or characteristics of the system that affect resilience of wastewater management at NI Water for the Belfast area. Make sure these are quantifiable/scale-dependent (low/high;few/many).
- With all these elements, create a map/network. An illustrative example is provided for micro-plastics in the aquatic environment and human health (below):

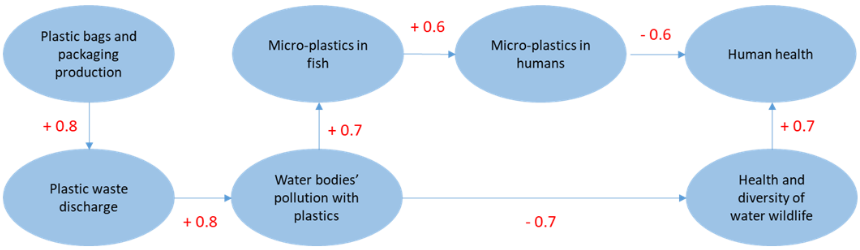

Figure K.1: Example of cause-to-effect relationsips in FCM.

- Place the most important one (from your point of view) at the centre.
- Identify connections between components.
- Identify the sign of each connection positive (+) or negative influence (-) (in red):

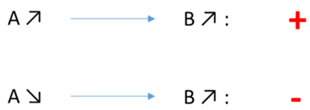

Figure K.2: Allocating signs to connections.

- Set weights for each connection **between 0 and 1** (in red).

  Weights refer to the strength of the cause-effect relation between two elements: on a scale from 0 to 1, how much influence does the first element have over the second?

  Assess weights for each relation independently from the others. However, weights do need to be comparable. For this, identifying one reference connection, and setting the weights of the others comparatively to that one, can be a good choice.

You can assign weights such as:

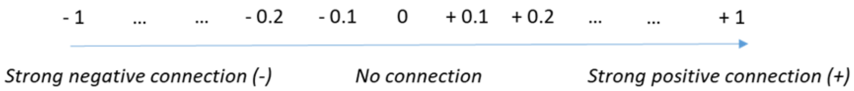

Figure K.3: Assigning weights to connections.

Question 2. *According to your experience, knowledge and expertise which interventions / changes could improve resilience of wastewater management for the Belfast area in the short-, medium- and long term?*

- Write down all potential interventions that come to mind.
- Add these as new concepts to the previous map (in green).
- Connect them to the rest of the elements. An example is provided below:

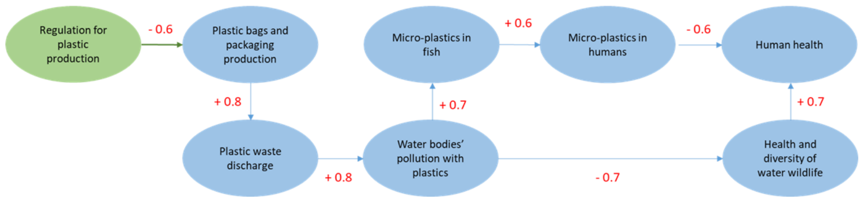

Figure K.4: Example of cause-to-effect relationsips in FCM with interventions.

- If you find that some of the already mentioned concepts could also be conceived as an intervention you can circle them (in green).
- Identify if the connections are positive (+) or negative (-) (in red).
- Set the weights of these connections **between 0 and 1**:

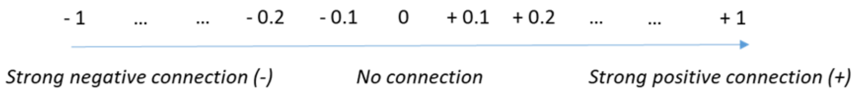

Figure K.5: Allocating signs to connections.

- If you believe these measures can have impacts (positive or negative) on concepts that are not present include as many other elements as necessary. Again, assess if connections are (+) or (-) and set weights between 0 and +1.

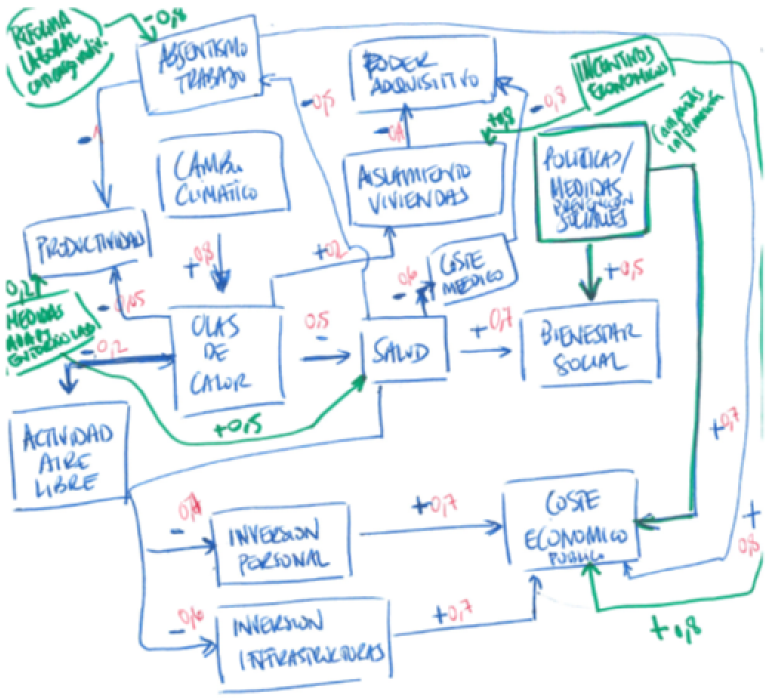

Figure K.6: Example of a map elicited for heatwave impacts in Madrid. Source: Olazabal et al. (2018).

Appendix L

FCM - Participating staff and responsibility

This Appendix lists all 31 participants of the 15 resilience mapping sessions that were done and provides information about their professional responsibility and institution.

# PER	# INT	Responsibility	Department and Division
1	1	Management of wastewater treatment works	NI Water - Operations
2	1	Management of sewerage networks	NI Water - Operations
3	1	Process advice for wastewater treatment works	NI Water - Operations
4	2	Integrating consumers' voice for water management	Northern Ireland Consumer Council
5	3	Base maintenance and quality programme management	NI Water - Life cycle planning
6	4	Human Resource management	NI Water - Human Resources
7	5	Trade effluent management	NI Water - Environmental Regulation
8	5	Compliance reporting	NI Water - Environmental Regulation
9	6	Wastewater capital procurement infrastructure management	NI Water - Asset Delivery - Capital Works
10	6	Wastewater project management - drainage area plans	NI Water - Asset Delivery - Capital Works
11	6	Capital project management - pumping stations	NI Water - Asset Delivery - Capital Works
12	6	Project management - sewerage rehabilitation	NI Water - Asset Delivery - Capital Works
13	7	Regional planning and policy	Department for Infrastructure - Planning
14	8	Governmental policy	Belfast City Council - Planning
15	9	Regulatory analyst - finance and network assets	Northern ireland Utility Regulator
16	9	Regulatory analyst	Northern ireland Utility Regulator
17	10	Research development and innovation management	NI Water - Asset Management - Strategic Planning
18	11	Wastewater capital procurement management - non-infrastructure	NI Water - Asset Delivery - Capital Works
19	11	Wastewater treatment project management - non-infrastructure	NI Water - Asset Delivery - Capital Works
20	11	Wastewater treatment project management - non-infrastructure	NI Water - Asset Delivery - Capital Works
21	12	Flooding and drainage policy management	Department for Infrastructure - Water and Drainage Policy
22	12	Floods directive and climate change engineering	Department for Infrastructure - Water and Drainage Policy
23	13	Interface with Utility Regulator - Price Control submissions	NI Water - Finance and Regulation - Regulation and Business Reporting
24	13	Regulation and finance management - efficiency assessment, tariff setting	NI Water - Finance and Regulation - Regulation and Business Performance
25	14	Project management for supply chain integration - capital efficiency	NI Water - Business Improvement - Capital Efficiency
26	14	Programme Management - Energy	NI Water - Business Improvement - Energy
27	14	Project analysis - Robotics process automation	NI Water - Business Improvement - Customer Experience - Digital
28	14	Efficiency projects, water, wastewater and Customer Service Centre	NI Water - Business Improvement
29	14	Project management, wastewater - achieving OPEX benefits for function	NI Water - Business Improvement
30	15	Regulation to discharges to water and underground stratum	NI Environment Agency
31	15	Scientific analysis - regulation fo NI Water treatment works' discharges	NI Environment Agency

Figure L.1: Participating staff and responsibility.

Appendix M

Resilience maps

This Appendix displays all the 15 resilience maps that were digitised after completion.

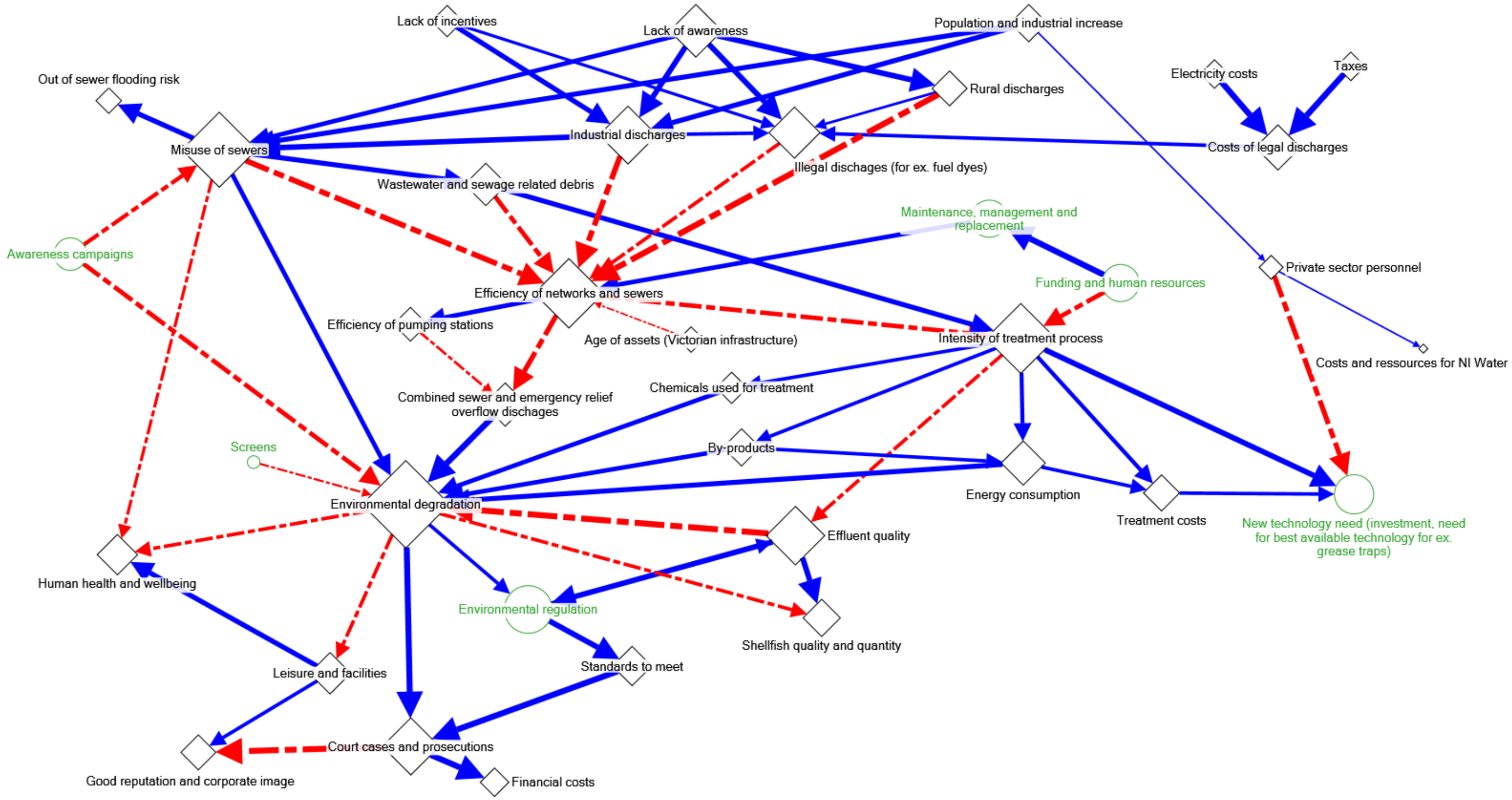

Figure M.1: Resilience map 1.

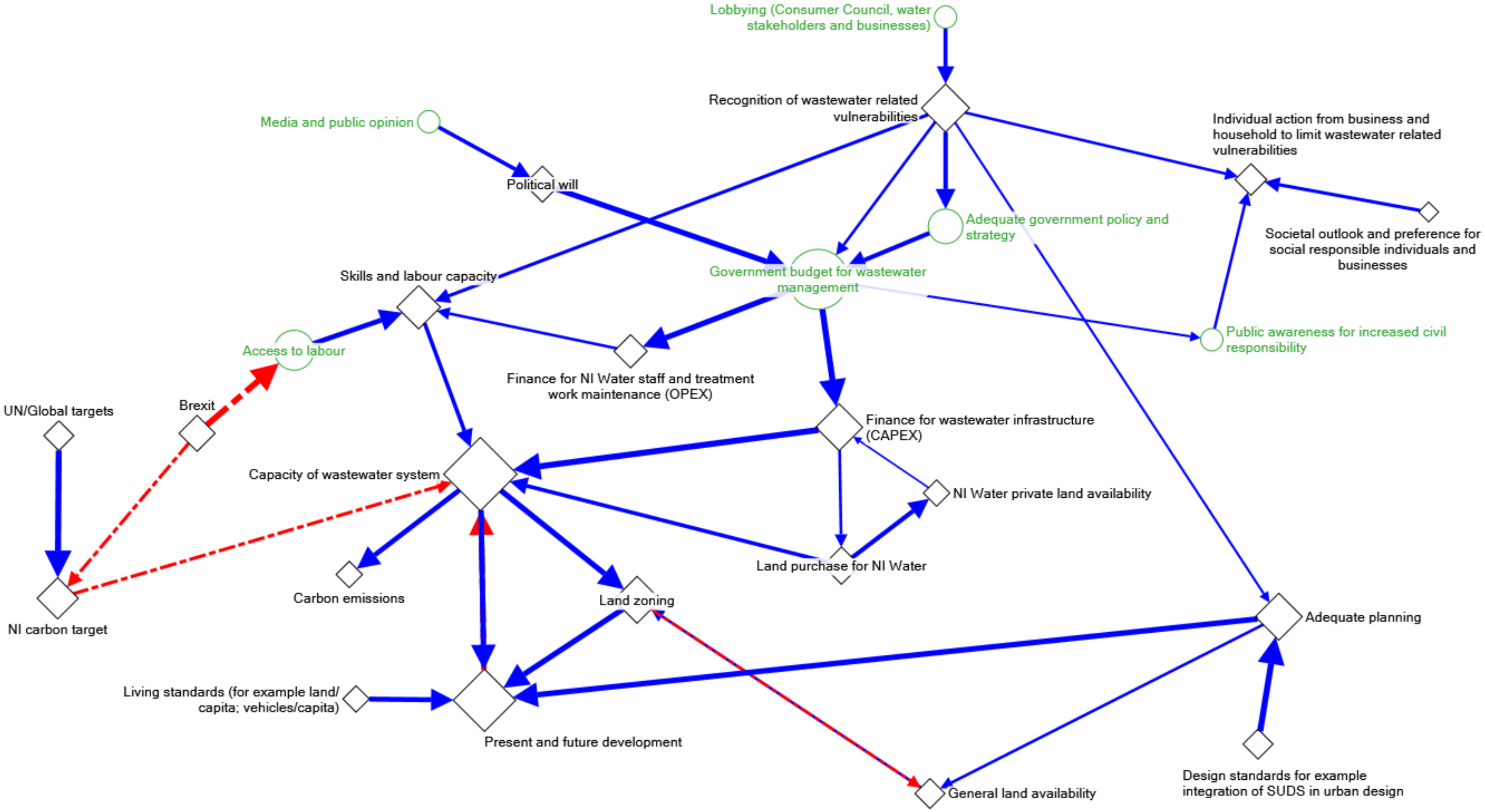

Figure M.2: Resilience map 2.

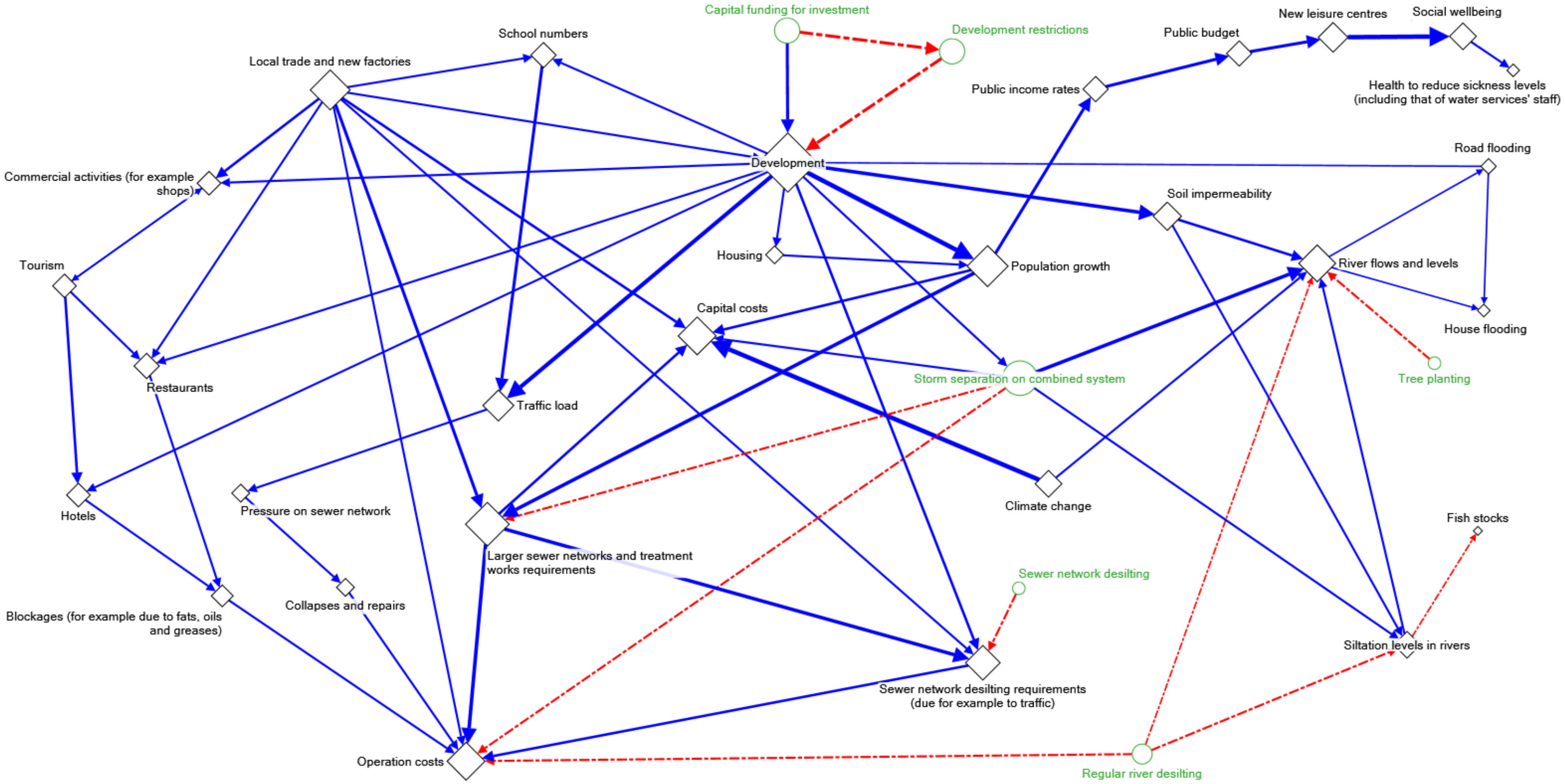

Figure M.3: Resilience map 3.

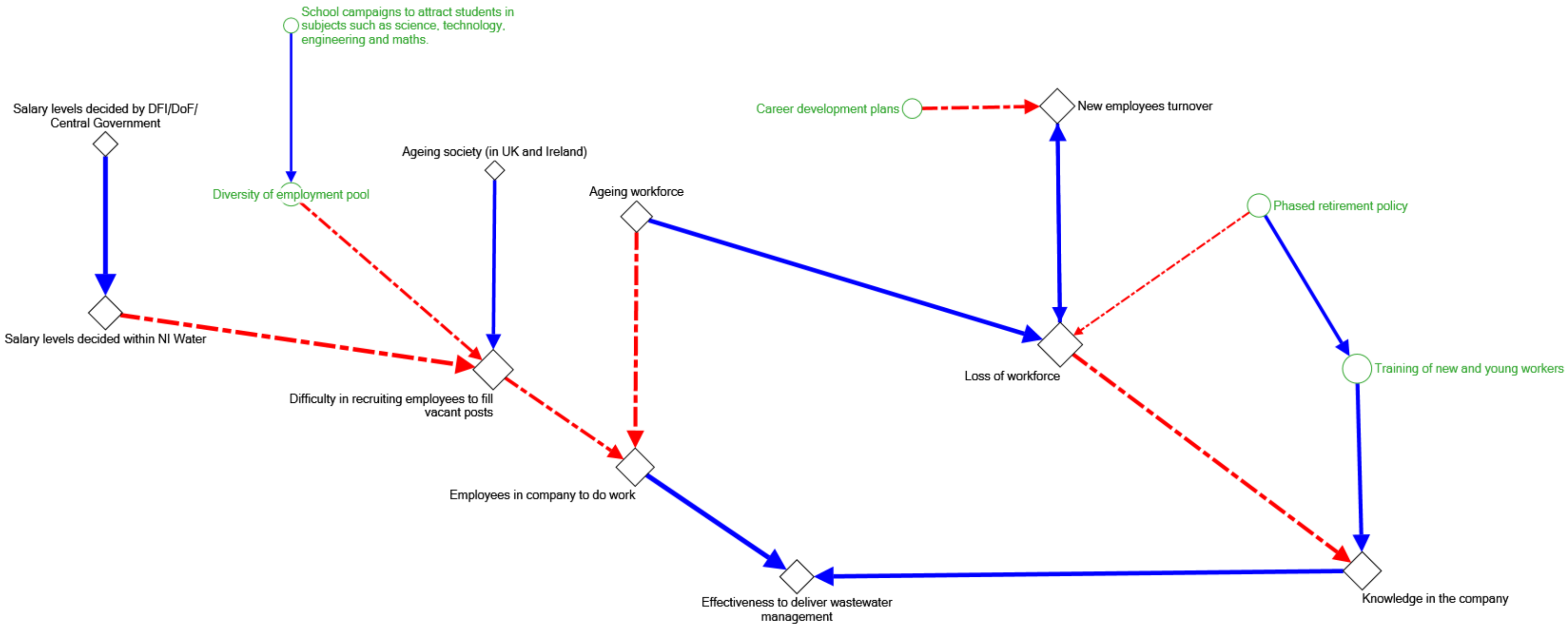

Figure M.4: Resilience map 4.

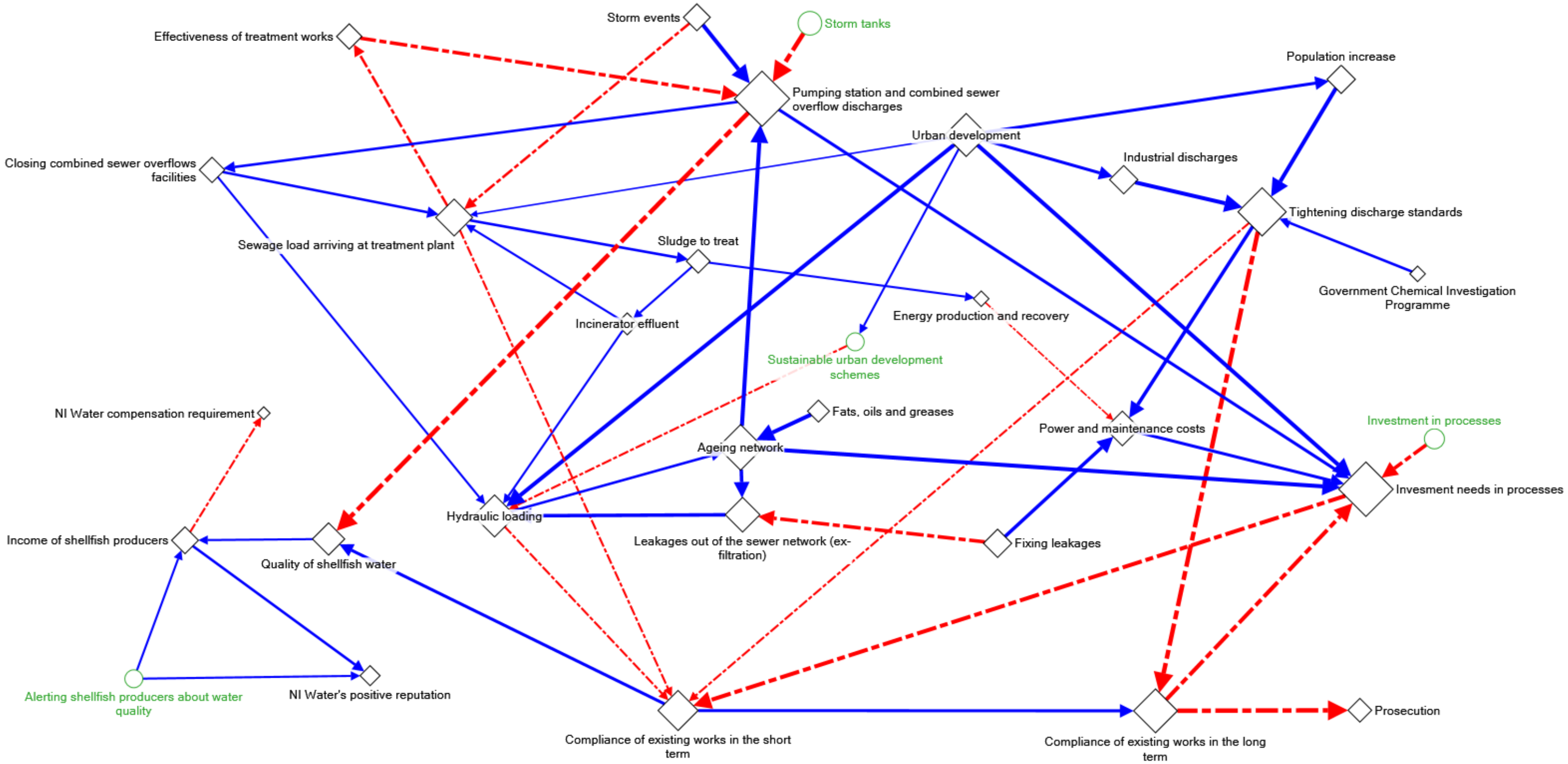

Figure M.5: Resilience map 5.

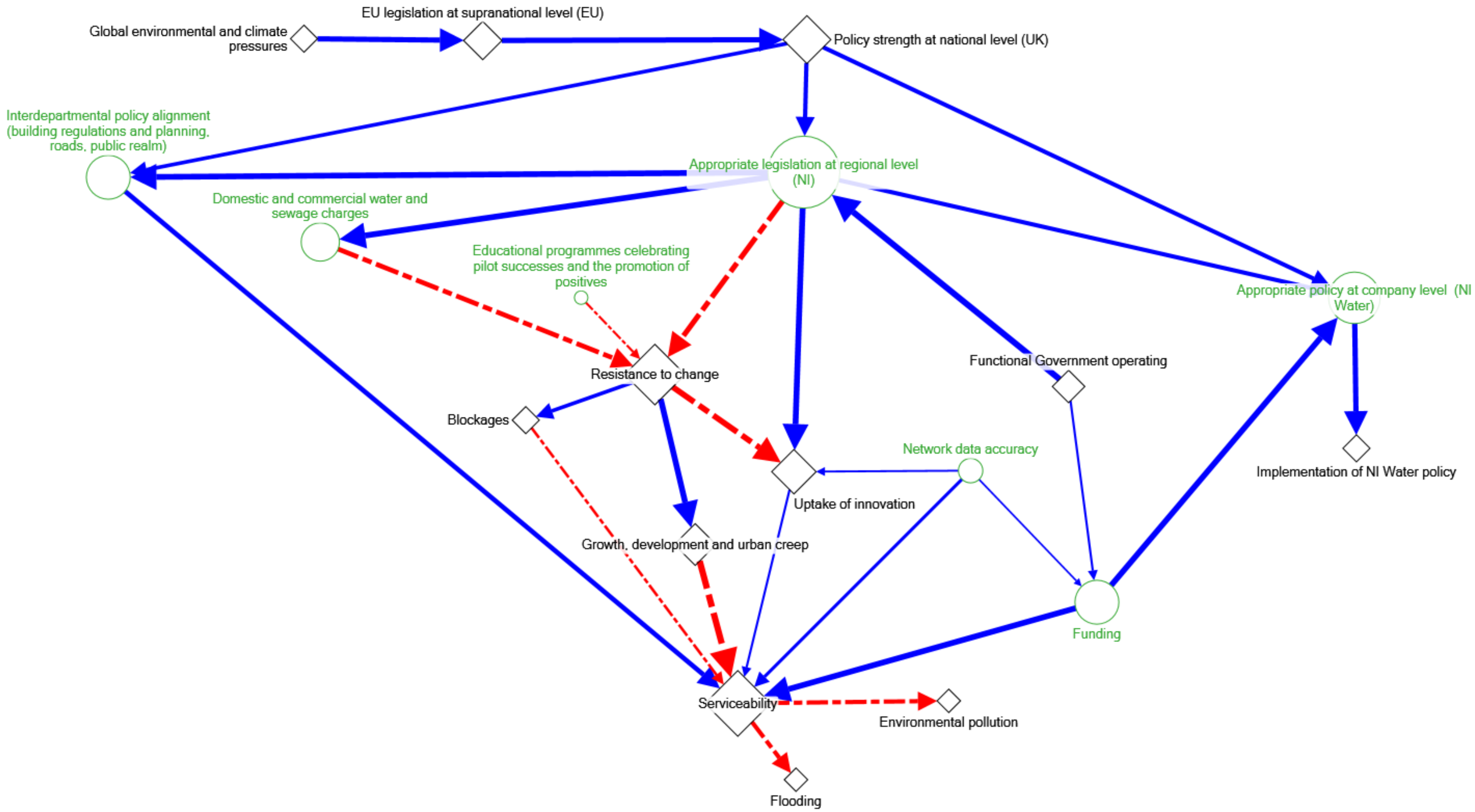

Figure M.6: Resilience map 6.

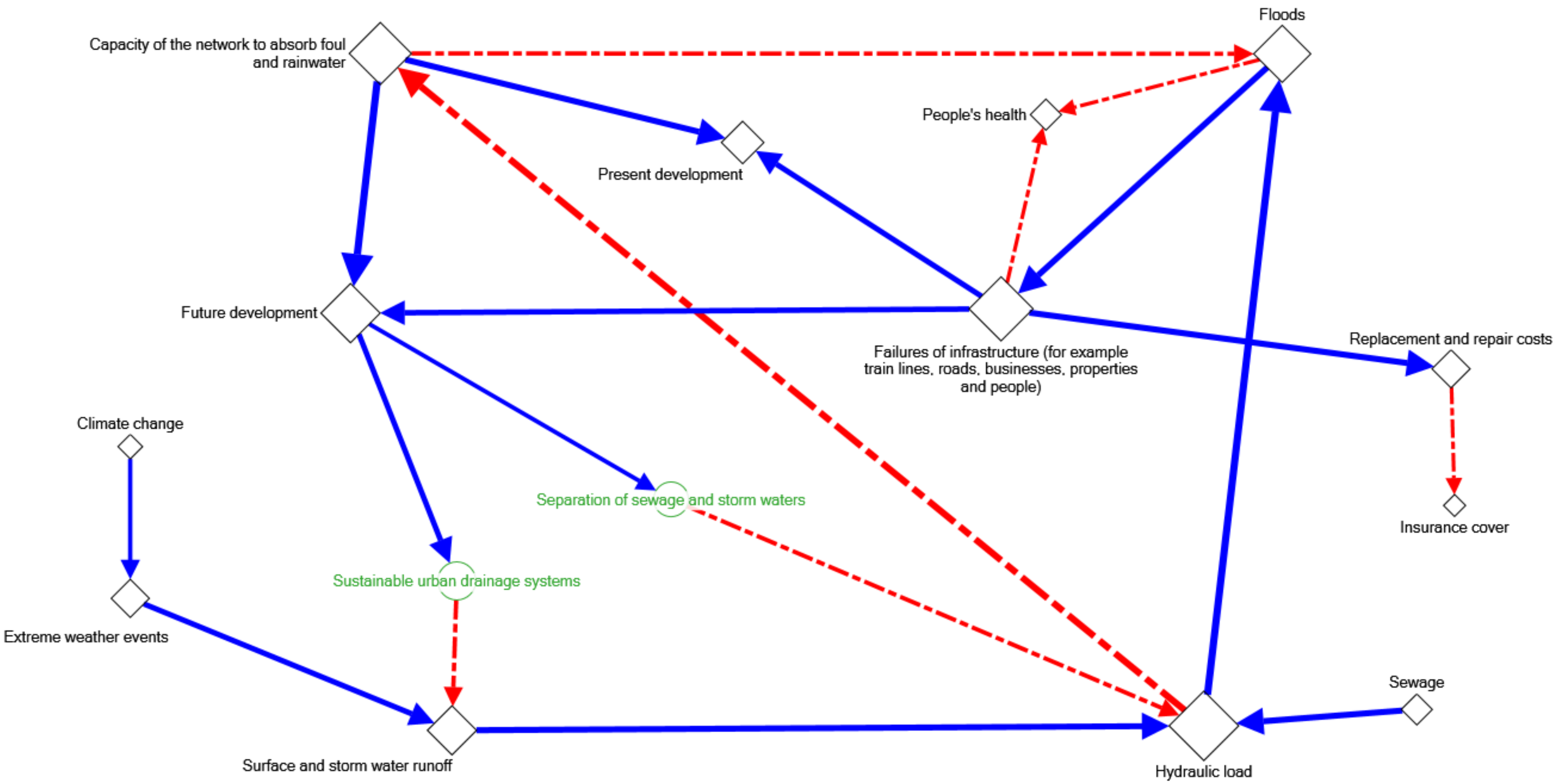

Figure M.7: Resilience map 7.

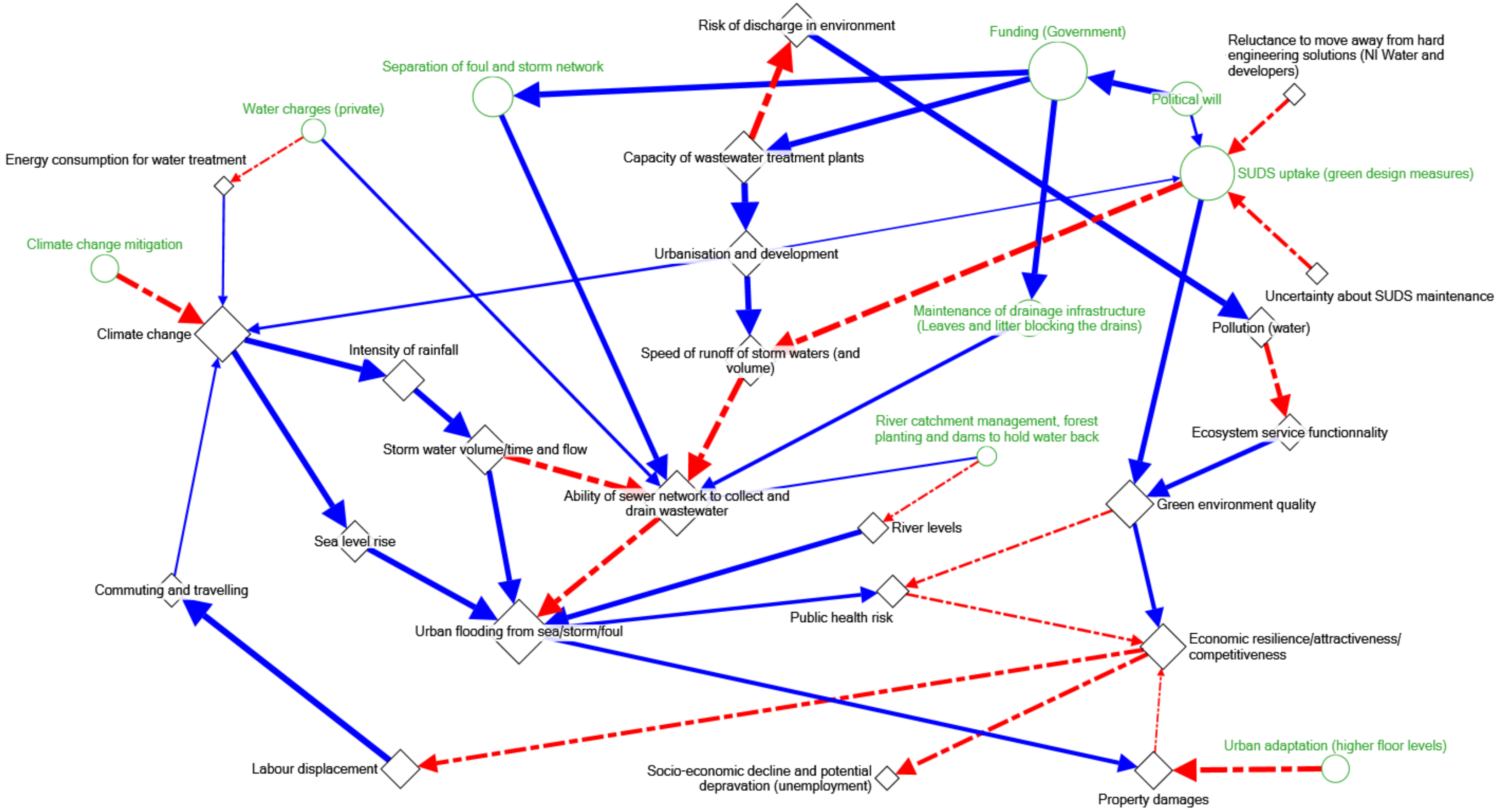

Figure M.8: Resilience map 8.

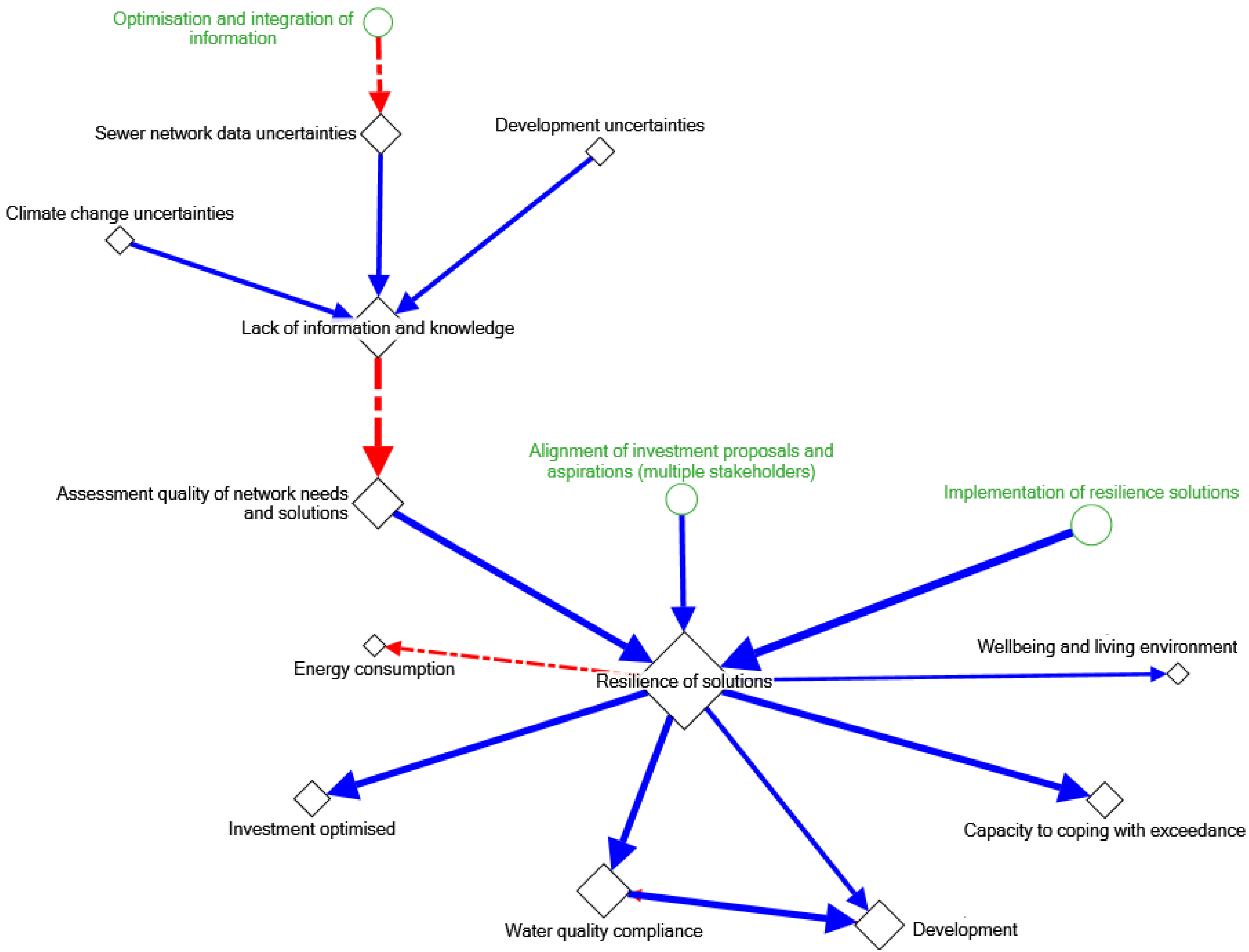

Figure M.9: Resilience map 9.

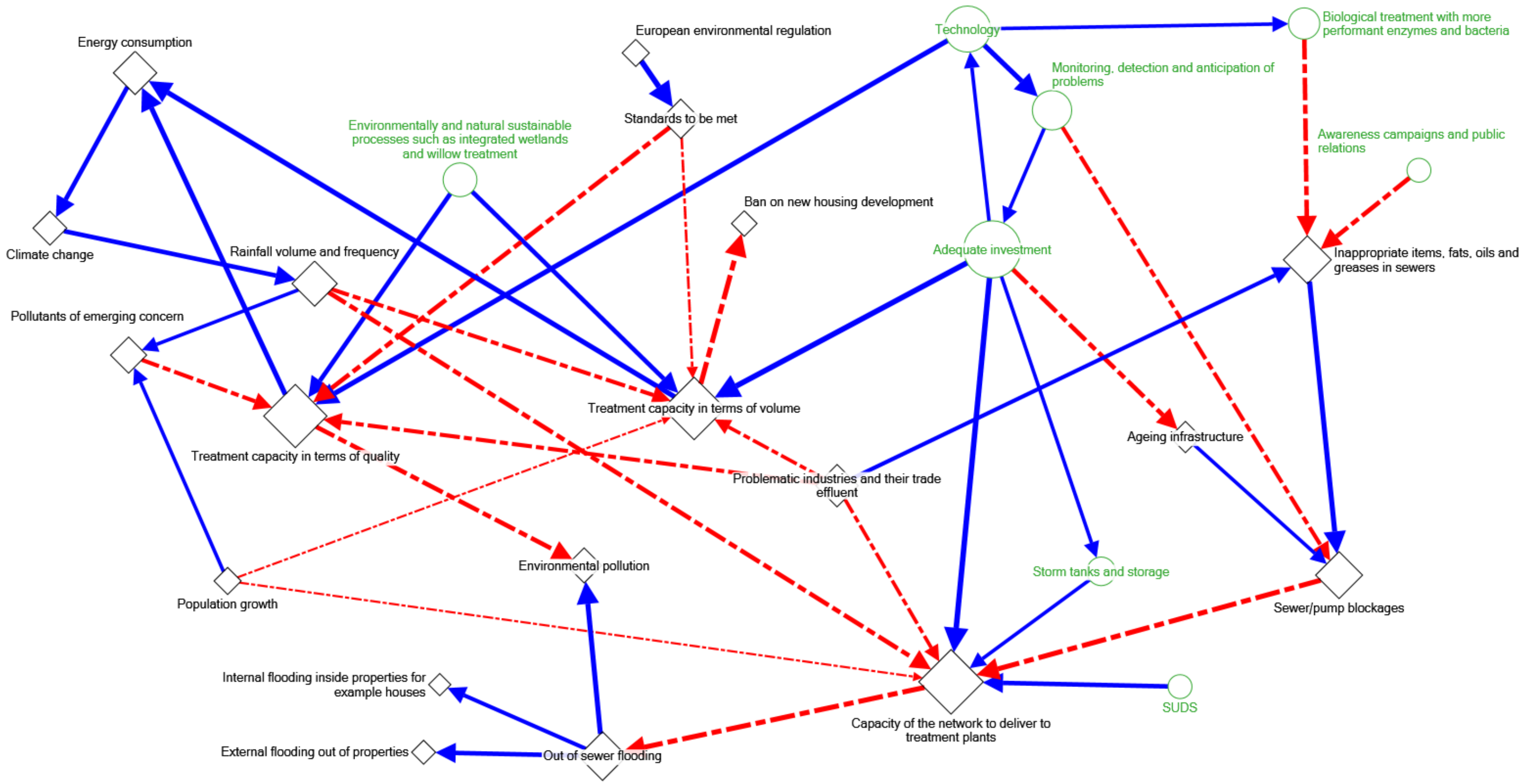

Figure M.10: Resilience map 10.

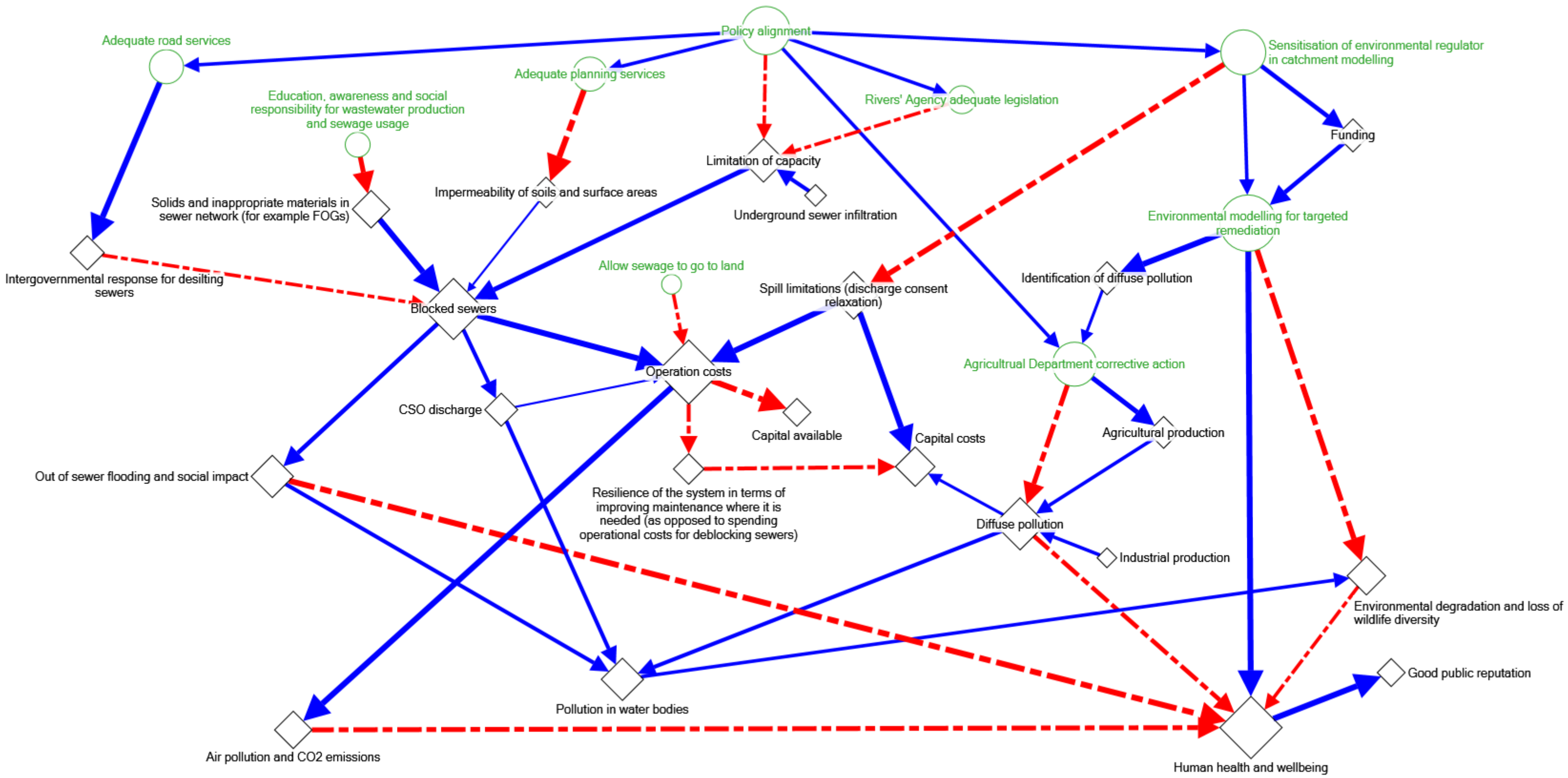

Figure M.11: Resilience map 11.

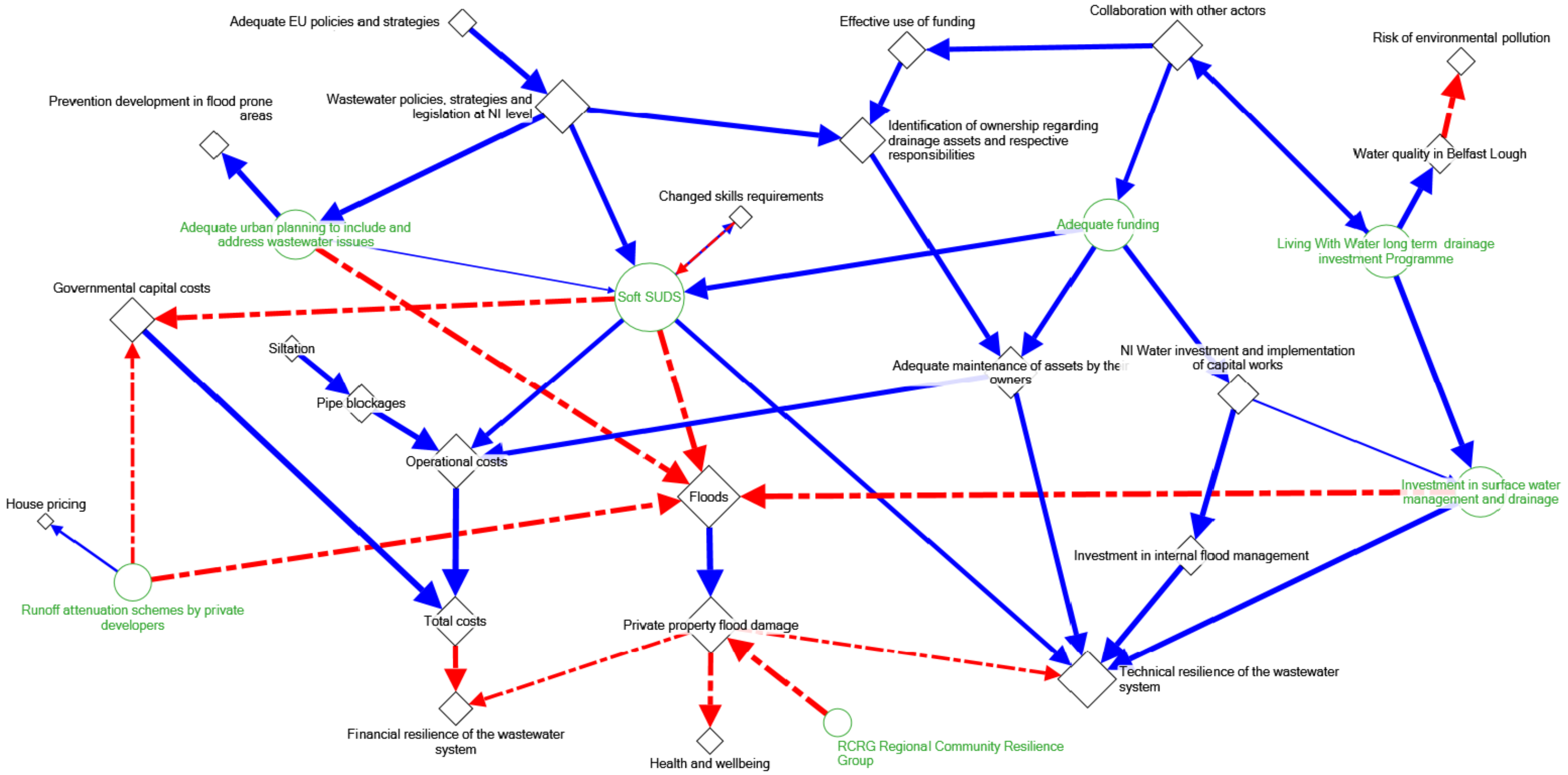

Figure M.12: Resilience map 12.

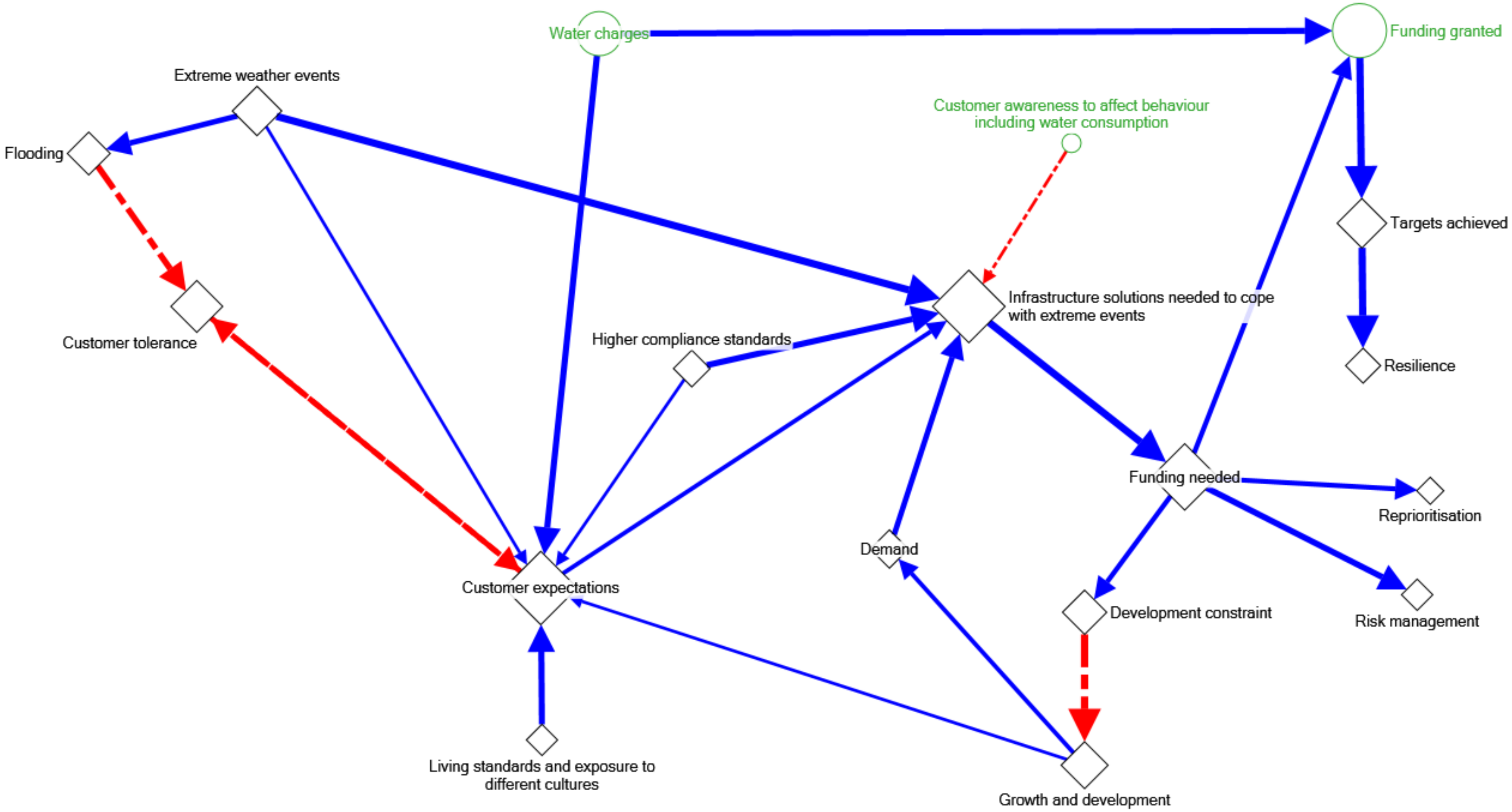

Figure M.13: Resilience map 13.

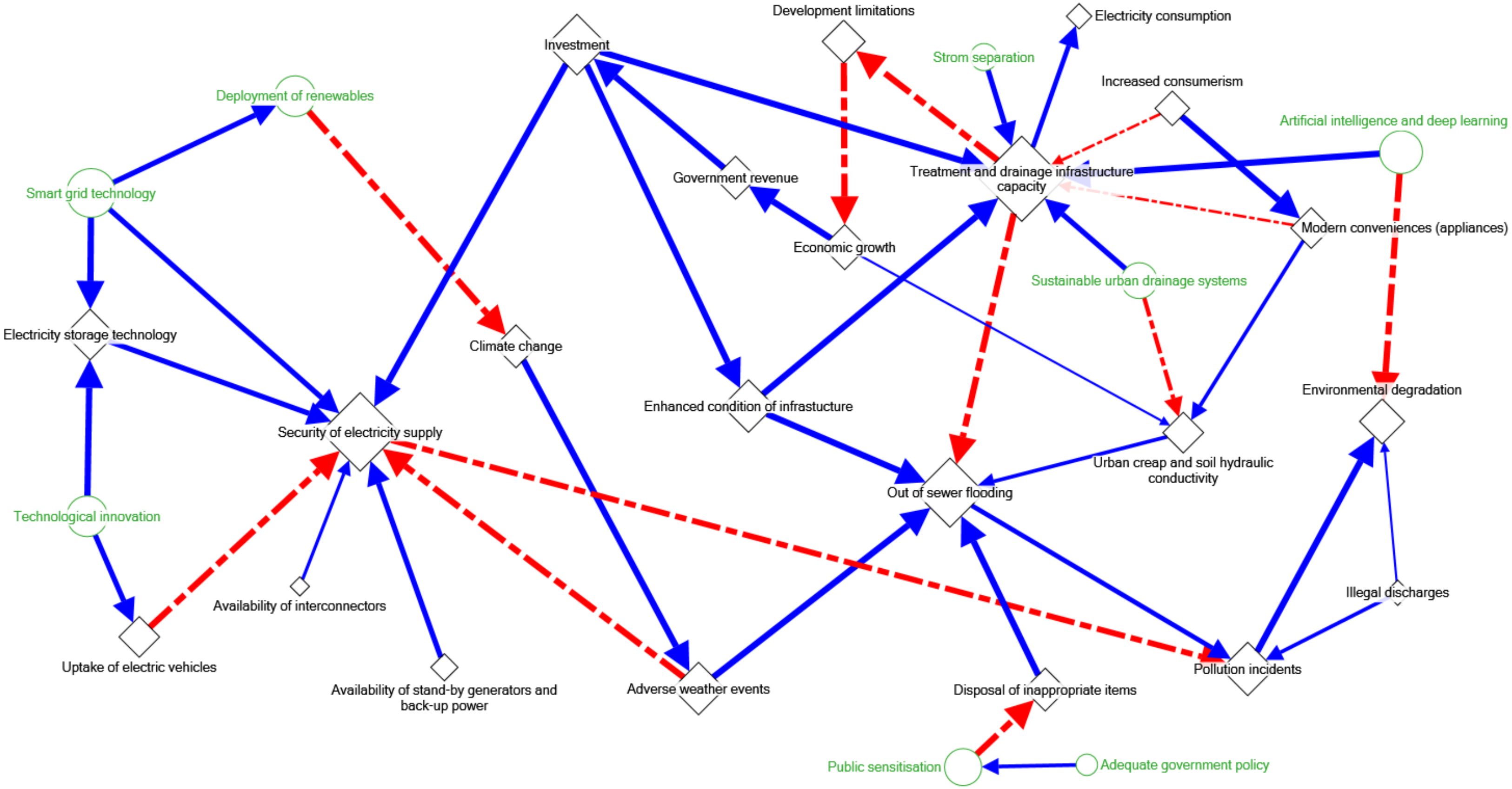

Figure M.14: Resilience map 14.

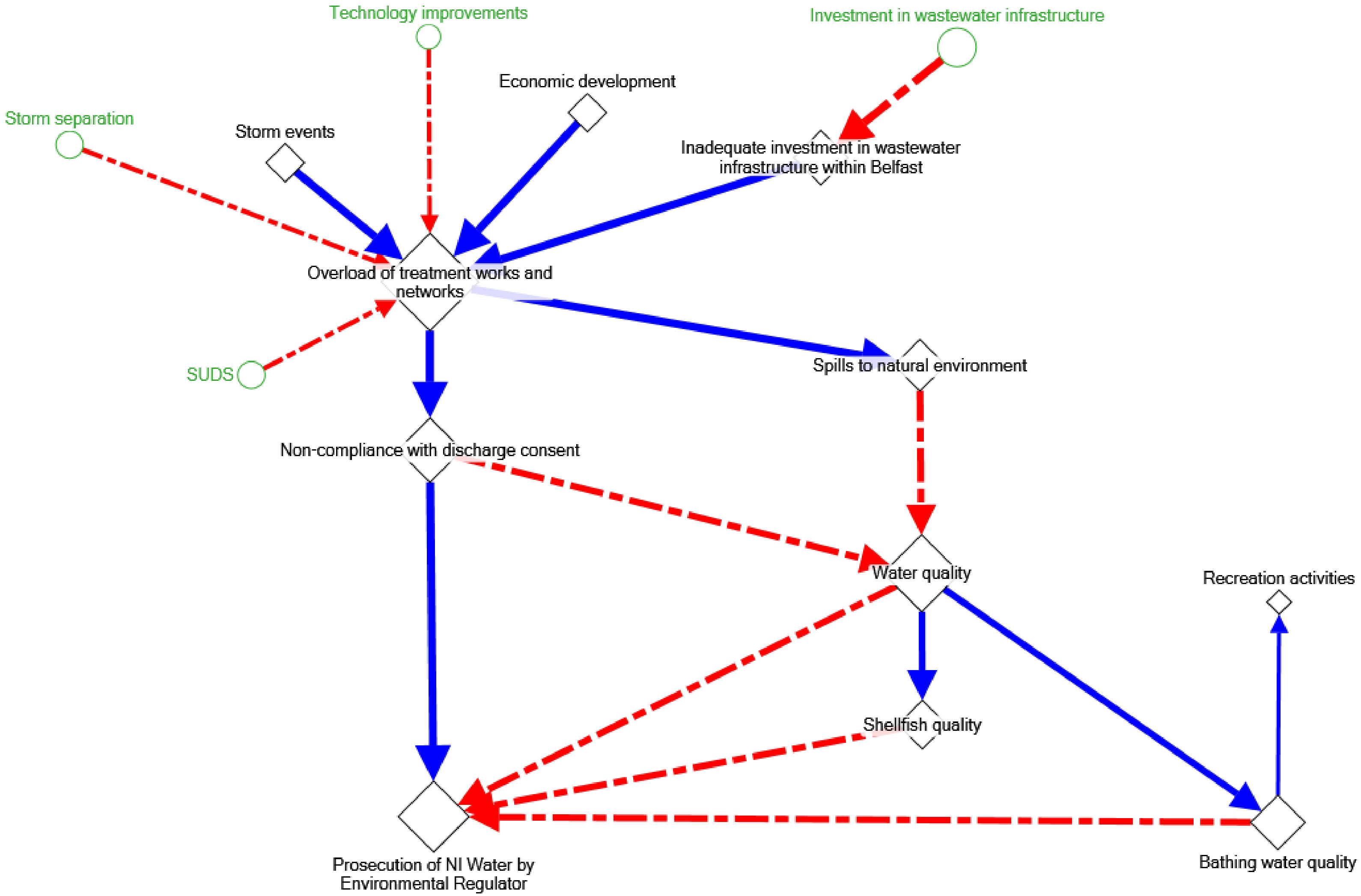

Figure M.15: Resilience map 15.

Appendix N

Storylines and analysis (Narratives)

This Appendix transcribes all detailed inputs that were provided during the (recorded) resilience mapping interviews/sessions by their participants. For each of them, the participants' *story* and/or *mental model* that resulted from the interview questions is reproduced in detail (the *Narratives*). Each is structured in a) a short summary, b) the storyline and c) the analysis, both in terms of content and methodological issues encountered during the interviews.

Resilience map 1

Population- and industrial growth combined with the misuse of sewers are the main drivers of vulnerability that affect the wastewater sector in Belfast. Participants highlighted the importance of wastewater drainage and treatment – which the customer usually takes for granted – for the environment as well as for human health. They emphasised that despite NI Water's legal responsibility for wastewater drainage and treatment, its efforts shall not be enough, without the social responsibility of its customers to control their negative externalities.

Storyline

1. Drivers of insufficient network- and treatment efficiency
   - (a) Population and industry growth.
   - (b) Lack of awareness about the impacts of inappropriate waste discharge into the sewers (not mapped).
   - (c) Lack of public awareness leading to misuse of sewers discharging inappropriate items in the sewers such as wet wipes and related sewage debris. Public awareness is not a quick fix and in addition it may not change the behaviour as regarding illegal discharges.
   - (d) As customers pay wastewater services through general taxes, they are not directly incentivised to reduce water consumption and the resulting wastewater discharges. More generally, taxes are no direct, explicit or transparent incentives that could promote a responsible behaviour in terms of discharge into the sewers (compared for example to the introduction on prices for plastic bags). This situation provides space for "free-riding".
   - (e) Household, rural and industrial activities can lead to illegal discharges through:
     - fats, oils and greases from restaurants, especially fast foods, because of non-maintenance of grease traps
     - waste oils from private car maintenance which could be disposed of free of charge in recycling facilities
     - silt and sand from non-maintenance of roads
     - sewage related debris of all kinds
     - illegal agricultural fuel transformation and trade (fuel laundry) which implies illegal discharges of toxic chemicals.

   (f) Increased electricity costs and taxes augment the cost of legal discharge which encourages the consumer to dispose waste illegally. Higher costs for legal discharges will therefore lead to more illegal discharges.
   (g) Old Victorian wastewater infrastructure in Belfast.
   (h) Climate change is an important threat to Belfast's wastewater infrastructure. In 2017, the Duncrue treatment plant had to deal with inflows from two extreme events with return periods of 1 in 50 years that occurred within two weeks of one another. Higher intensity of rainfall not only leads to higher hydraulic load but also to more suspended solids in the final effluent (not mapped).

2. Consequences of insufficient network- and treatment efficiency
   (a) Increased treatment requirements leading to increase of costs due to higher energy and chemicals consumption; formation of by-products; introduction of processes to break down plastics before entering the plant (in intermediate pumps for example).
   (b) Need for capital investment in new and best available technology, partly addressed by private contractors, yet at higher costs.
   (c) Treating to lower contaminant concentrations – even if required – can have negative technical and financial consequences, in that the regulator further tightens the effluent quality requirements. Ultimately this can lead to higher fines, prosecutions and court cases at high reputational costs for the utility.
   (d) Secondary environmental impacts from intense treatment processes including the use of more chemicals and energy; by-product formation.

3. Interventions that increase resilience or reduce vulnerabilities

   NI Water conducts dissemination and sensitisation campaigns focusing on primary schools. Examples are the "Water Bus" as well as the "Heritage Centre" which aim at educating the youngest. Additional interventions and drivers for improved resilience are:
   (a) Modern treatment technology (for example, NEREDA) with lower footprint is expected to replace the Duncrue treatment plant.
   (b) Resource recycling – sludge could be used for tarmac production for roads or for plaster board insulation material as is done in other countries.
   (c) New technology to meet new standards or new regulations (micro-plastics for example).

(d) Improve companies' social responsibility to contribute to limit inappropriate wastes at source: for example, plastic rings used by companies for packaging of refreshing drinks – not mapped.

Analysis

Content

1. Regulation is a driver that can change on a smaller timescale than infrastructure lifetime. As new regulations appear, wastewater plants need to adapt their infrastructure to respond to such changes. Plastics for example, had been an issue in the past for clogging screens. As a consequence, facilities were equipped with cutters to chop plastics into fine chips so that they could pass the screens allowing for smoother operation. Now, micro-plastics have become an issue of environmental concern. Operators try to extract them but a lot are suspected to escape with the final effluent.
2. What drives the answer to the question as to whether one is socially responsible or disposes waste illegally? How to overcome "freeriding" behaviours that create negative externalities to the wastewater sector and ultimately to the environment?
3. There is a potential mismatch between the missing social responsibility and the environmental regulations that dictate what wastewater treatment plants can discharge. This is because the financial and operational burden of treatment and maintenance falls entirely on the water utility while there is no coercive action or incentives to tackle the source of the problem.
4. Avoiding the production of waste at source may be a sustainable solution to reduce treatment intensity and/or obtain higher effluent quality. The responsibility of manufacturers has been mentioned in the interview through the example of plastic rings that manufacturers use to hold aluminium drink cans before their distribution to the wholesale market. This was an example of solid waste unexpectedly leading to cause operational problems in the treatment works and a pollution source of the final effluent (see point 1).
5. Participants think that leaving the EU will not alter anything in the regulation of wastewater treatment in the UK. There are however a lot of uncertainties as to whether the UK will follow the EU, or have lower or higher ambitions following a Brexit.

Methodology

1. The participants' use of the word "impact" in some concepts such as "environmental impact" was misleading when attributing signs to a connection. A priori it is not clear if the word "impact" refers to a "positive" or "negative" impact. This can create confusion when scoring a cause-to-effect relation. Instead of "environmental impact" the wording "environmental degradation" was chosen to avoid this ambiguity.
2. In this map, the relations were sometimes visualised by participants as ways or tracks that physically connect two concepts (such as a pipe that connects a manhole and a treatment plant).
3. The reference to "Networks and sewers" was unclear and necessitated a discussion and understanding both of participants and analyst, until it was specified to be "Effectiveness of networks and sewers". Similarly, the concept of "Process impact" was accompanied by examples which then led to disaggregation into separate concepts: energy consumption, by-products, chemicals, treatment costs.
4. Some suggested concepts were non-quantifiable and therefore could not be used. An example of this was "Location". By "Location" the participant referred to the Belfast Lough being more regulated for being classified as a protected area. In fact, "Location" as expressed by the participants could have been taken into account through the adjusted concept "Protected areas". Time limitations did not allow the analysts to come up with that suggestion quickly enough.
5. Because of time limitations, important concepts such as climate change, intensity of rainfall and the necessity of hard infrastructure design are not mapped by the analyst. Some connections are lacking too, such as the impact of "Illegal discharges" on "Environmental degradation" or the fact that interventions could also be expected from the private sector and companies that produce waste ("Companies could do more").
6. Another issue which was also identified in other maps is that the scores are sometimes being described as being dynamic in nature. This resulted from comments of participants who mentioned that "at the moment the connection is strong and on an increasing trend" or "It can only get worse".
7. The possibility of "non-unique" relationships makes mapping challenging: high effluent quality compliance can potentially lead either to tightening or relaxing regulation.

Resilience map 2

The central issue in Belfast's wastewater management system is its reliance on governmental budgets for investments in infrastructure (CAPEX) and staff (OPEX). Two aspects of this issue are developed in this map: (a) the fact that future economic development relies on increasing investments into the wastewater sector. Ultimately, the capacity of the sewer system and treatment works determine the possible future development of the city: the connection of new urban sites requires sufficient sewer- and treatment plant capacity. (b) Governmental budget decisions that allow to leverage capital funds for wastewater investments.

Storyline

1. Connections related to the capacity of wastewater systems and future development are
   (a) Spare capacity enables more urban development. Development, in turn, reduces capacity and can lead to upgrade requirements.
   (b) Capital funds make land purchase possible for NI Water in case of needing to expand infrastructure.
   (c) Increasing the capacity of wastewater systems is related to higher energy consumption and an increase in GHG emissions.
   (d) GHG emission targets may limit the capacity of wastewater systems. Brexit might enable to relax these targets freeing up capacity.
   (e) The recognition of wastewater related vulnerabilities can lead to more adequate planning.
2. The rationale around governmental budget decisions is that
   (a) Governmental budgets for wastewater management distinguish between finance for operations (OPEX) - and capital investment (CAPEX). Usually, CAPEX is prioritised in the realm of wastewater management. Access to a larger labour market enables to increase skills within the utility. Brexit may make it harder to employ skilled people from outside the UK.
   (b) To a low extent, the recognition of wastewater related vulnerabilities affects governmental policies and budget decisions – the participant explicitly expresses his low optimism about this.

   (c) Public awareness can promote individual actions from households and businesses to reduce impacts on wastewater systems. This can be accelerated through new trends in society – that reflect responsible behaviours of individuals and businesses.

3. Interventions that increase resilience or reduce vulnerabilities
   (a) Increase the access to the labour market to allow for increased skills and labour capacity within the utility.
   (b) Media and the public opinion can play an important role in altering the political will and have important effect on budget decisions.
   (c) Lobbying to improve the recognition of wastewater related vulnerabilities.
   (d) Adequate government policies and strategies address wastewater vulnerabilities.
   (e) Public awareness can increase individual action of businesses and households.

Analysis

Content

1. The map does not identify all connections: for example, there could be a link between "Media/Public opinion" and "Awareness".
2. "Education" does not influence the system further than individual action of businesses and households. However, as described below, awareness can be narrowly linked to public opinion and influence policy-makers and their political will.
3. The influence of public opinion on political will is an interesting topic to discuss. On the one hand, the public can influence policy-makers to increase resilience: "We work with communities which are at risk of flooding and their collective voice can change the government response to their problem." On the other hand, the reluctance of policy-makers to introduce unpopular water tariffs promote increased vulnerability both by limiting the utility's budget and by losing the opportunity to increase public awareness.

Methodology

1. In some cases, concepts are not sufficiently well specified during the mapping process. This leads the analyst to undertake significant changes to create a consistent map which the reader can easily understand.
   (a) For example, the participant explains to the analyst, he sees two different aspects of "Planning": "There might be two sorts of planning here: I am thinking more of a district level planning permissions, regulations. . . " and the "more planning gets the green light, the less capacity is in the system at current state."
   (b) "Land availability" may refer to general land availability or to private land ownership by NI Water.
2. The mapping process is easily alternating between drawing cause-to-effect relationships or physical processes.
3. The participant writes down concepts on the map and when it comes to scoring she/he sometimes does not remember the rationale. This happened in other maps.
4. Sometimes it is difficult to distinguish between drivers of change and interventions. For example, "Living standards" was identified as an intervention in addition to being a driver.
5. Difficulty of the participant to identify the direction of the influence; sometimes identifying bi-directional connections. In reality, these relationships may occur with time lag and therefore have broader transitory effects and not cancel each other out.
6. Difficulty of the participant to understand the score: does it reflect what it "should be" or "what it is"?
7. The participant identifies some relationships are conditioned by other connections but the conditions are not always mapped.
8. The participant distinguishes between short-, medium- and long term for example for present and future development.

Resilience map 3

Development and population growth are the main drivers of vulnerabilities in the Belfast wastewater system.

Storyline

1. Drivers of vulnerabilities and resilience
   (a) Development increases public income rates and budgets which can result in new leisure centres that increase health and social wellbeing.
   (b) However, urban development entails population growth requiring extension of networks and treatment facilities.
   (c) Development also increases operational costs, for example requiring more desilting of the network due to higher traffic load.
   (d) Increased traffic load increases the pressures on the sewer network and increases the risks of collapses and repairs with higher operation costs.
   (e) More development increases the number of schools, commercial activities (shops), hotels and restaurants leading to more pressure on the sewer system.
   (f) Higher imperviousness increases the risk of road flooding which can lead to house flooding.
   (g) Activities such as local trade, restaurants and hotels increase blockages due to fats, oils and greases and operation costs to address these issues.
   (h) Climate change increases river flows.
   (i) Climate change also considerably increases prospected capital costs.
   (j) New developments are equipped with separate sewer systems. However, this can lead to unintended consequences as silt and contaminants from the roads are directly flushed to the environment without treatment. It also increases river levels which can lead to road and house flooding.
2. Interventions that increase resilience or reduce vulnerabilities
   (a) Development restrictions.
   (b) Increased funding for investment in capacity extensions.
   (c) Regular river desilting to reduce siltation levels in rivers and therefore reduce the risk of flooding and increase fish stocks. Regular river desilting however increases operational costs.

(d) Tree planting to enhance water retention and soil permeability (not mapped through permeability but directly to river levels and flows).

(e) Network desilting increases operation costs but allows more capacity in the sewer (not mapped).

(f) Introduction of storm water separation. It increases capacity in the sewer network and decreases requirements for larger networks and treatment plants. However, it can have unintended environmental and social consequences by draining contaminants and silt directly into the environment and by increasing river flows and levels which potentially leads to more flooding.

Analysis

Methodology

1. Possible double counting can occur in the mapping process, for example in the case of outgoing connections from: development and population growth.
2. Participants sometimes map a process instead of a cause-to-effect relationship, for example in the case of “Development” -> “River flows”, the participant interprets the connection as a pipe transporting material from roads into rivers leading to silt build up.
3. Many relations can be reciprocal for example:
   (a) Development vs. Tourism.
   (b) Trade vs. Development.

Resilience map 4

With about 30% (400 out of 1250) of NI Water personnel expected to leave in the next ten years, the company faces vulnerabilities in terms of human resources and "brain drain" that will be able to keep the high delivery effectiveness of wastewater services: firstly, an ageing workforce will trigger a loss of skills and knowledge within the company. Secondly new recruitment will be more difficult. This is particularly affecting the wastewater side of the company. In the next years, the company needs to prepare for massive shifts in terms of the age of the workforce and the experience and nature of work that goes with generational shifts (for example, in terms of IT).

Storyline

1. Drivers of vulnerabilities and resilience
   (a) The ageing workforce leads to a loss of personnel within NI Water, which leads to a loss of. This is exacerbated by three main factors:
      i. The length of service tends to be shorter for new employees. As more people leave there will be more people entering the short service bracket exacerbating the turnover problem.
      ii. The profile of the UK society is also ageing making it more difficult to match vacant positions.
      iii. NI Water's risk of decreasing attractiveness as an employer, as its budgets and salary regulations depend on governance decisions at higher levels (Central Government, Department of Finance and the Department of Infrastructure). NI Water is limited by the public sector pay agreement. For example, NI Water had difficulty attracting electricians as the company was not paying salaries high enough to be able to recruit them. There are some limits to the flexibility of the company regarding pay progression schemes. There is scope to leverage capital from other savings within the company for example energy saving, but this needs to be achieved first.
2. Interventions that increase resilience or reduce vulnerabilities
   There are a number of HR interventions NI Water is planning around improving employee's development and career plans, building succession plans and ensure knowledge transfer to the next workforce generation:

(a) Phased retirement policies which would enable more experienced staff to extend their employment ensuring a transition period for training of and knowledge transfer to junior staff.

(b) Career development plans to attract new employees and to retain employees.

(c) School campaigns, for example in subjects such as science, technology and mathematics to attract future students in a potential recruitment pool for NI Water in the medium- to long term.

(d) Promote the diversity of recruitment pool. NI Water encourages people of different profiles to apply and expand the recruitment pool (including women, disabled and diversity of ethnicity).

Analysis

Content

1. Technical solutions in the wastewater sector rely on the human capital available at NI Water. Human resource policy is therefore determinant for future resilience of the company. Resilience of wastewater management most often deals with technical knowledge of wastewater systems. However, it is human capital and therefore the human capital management which creates the foundations for the development of this technical knowledge and its successful implementation.
2. The quality of the human capital depends on a combination of financial affordability within the company as well as on external factors that make it more or less easy to hire skilled and semi-skilled professionals such as the competitiveness of the labour market which are very difficult to control.

Resilience map 5

Vulnerabilities of the wastewater management system for the Belfast area (a) are related to a. tightening environmental standards and to b. causes and c. consequences of discharges into the environment.

Storyline

1. Drivers of vulnerability and resilience
   (a) Environmental regulations
      i. Threshold of given parameters such as biochemical oxygen demand, suspended solids and ammonia are exceeded as a result of higher population and development.
      ii. Tightening discharge standards leads to more frequent non-compliance. Following a non-compliance event, the utility is given time to identify the source of the problem and/or to review pollutant limits. Continued non-compliance can lead to prosecution.
      iii. Tightening of standards imply increase of operational cost.
      iv. The Chemical Investigation Programme of the Government will monitor more chemicals in sewer discharge and it will be at the responsibility of the water utilities to find identify these, track them down in the network and address them.
   (b) Causes of discharges into the environment can be due to different factors
      i. Sewage networks and treatment plants are reaching maximum design capacity and experiencing reduction of effectiveness of treatment. This is accelerated by ageing infrastructure, increased population and development.
      ii. In addition to more wastewater production from households and industries, urban development increases imperviousness which increases the hydraulic loads and puts pressure on pumping stations and combined sewer overflows.
      iii. Population increase and movements (for example new student accommodations in York Street) affects network load and hydraulic capacity.
      iv. Increase of fats, oils and greases accelerates the ageing of the network.

   v. Storm events potentially reduce (dilute) the sewage load but increase CSO discharges.
   vi. On the one side, the more sludge to treat, the more energy costs can be recovered. On the other side, more sludge leads to more incinerator effluents that increase the load on the treatment plant.
 (c) Consequences of discharges into the environment
   i. The high sewage and hydraulic loads can potentially lead to non-compliance.
   ii. Closing CSOs because they spill too frequently. There are however unintended consequences of such interventions: they increase the hydraulic load in a system that is already close to maximal capacity and puts more pressure on the downstream network and treatment works, thus reducing their effectiveness.

2. Interventions to increase resilience in the system are:
   (a) Investments for base maintenance.
   (b) Alerting shellfish producers about the water quality of the effluent.
   (c) Closing of Combined Sewer Overflow facilities (with unintended consequences).
   (d) SUDS
   (e) Storm tanks help to reduce overflows.

Analysis

Content

1. If the standards tighten for the Belfast Lough, NI Water may have to spend a disproportionate amount of money in the Belfast area which then would not be available for the rest of the country. Participants explained that if two or three treatment works that serve a large fraction of the population are compliant, there are still 270 smaller works that need to comply and that need to be financed through the same global budget.
2. As a consequence, it is important to analyse the system globally. Also, it would be important to broaden the scope beyond urban wastewater.
3. Existing processes cannot remove emerging contaminants in Northern Ireland's treatment works. The possibilities are to either invest into new treatment processes which would be expensive, or try to manage them at source.

4. One of the participant thinks the impact for shellfish producers is low as businesses are assumed to be small so costs are easier to absorb. The other participant thinks that if businesses are small and non-diversified, then the cost should be more difficult to absorb.
5. It is understood that standards tighten as a result of more polluting industry discharges. It is not clear however, whether tightening standards will lead industries to pollute less. This is because NI Water is considered to be responsible of the quality of the final effluent. The question therefore arises about whether NI Water is going to continue taking over the costs of tighter standards in the future.
6. The Chemical Investigation Programme (CIP) of the Government may result in such higher costs for companies: it has the objective of monitoring more chemicals in sewer discharge; it will be at the responsibility of the water utilities however to monitor and identify chemicals in sewers.

Methodology

1. Non-linearity of mapped links between shellfish producer, income decrease and NI Water's reputation: the participant intervenes to say that "If discharge of NI Water goes out and causes an impact, NI Water will be talked about. If discharges are good however, nobody will talk about it." "One's reputation is never positive", the participant added.
2. Another example of using a concept for different interpretations
   (a) Investment needs: In the connection "Ageing network" -> "investment needs", the concept is used correctly. In the connection "Investment needs" -> "compliance of existing works" the concept is used in the sense of "effective investment", not as "investment needs".
3. The strengths of relationships are not always straightforward: for example, participants do not know how strong the impact of alerting shellfish producers shall be, on the water quality, on their income and on NI Water's reputation.

Resilience map 6

Vulnerability is perceived to be a by-product of a society-wide problem that reaches beyond the borders of wastewater management. It is the result of social resistance to change accompanied by a governance model that does not keep pace with change, thus further accentuating the barriers of society to prepare for and accept change. This has cascading effects on various aspects of the wastewater system:

Storyline

1. Drivers of vulnerability and resilience
   (a) Policy at national level (UK) is not strong enough and legislation at regional level (NI) is not appropriate to enable and facilitate
      i. A coherent approach through interdepartmental policy alignment
      ii. Appropriate NI Water policy and implementation
      iii. Adequate funding and the possibility to levy water and sewage charges
      iv. Acceptance of change, for example, in terms of implementation of SUDS, behaviour and sewage use, development and growth
      v. Innovation uptake, for example SUDS uptake
      vi. Network data accuracy that includes accurate records of NI Water and third party assets, CSO spill frequency, pumping station performance, siltation levels and general sewer condition assessments
      vii. Serviceability in terms of functional infrastructure to benefit the customers (effective household or commercial wastewater discharge) and therefore the society as a whole, through development and the protection of the environment.

   (b) Driven by social resistance to change and the unwillingness to accept responsibilities.

   Despite environmental and climate pressures there is a slow adaptation towards new thinking. There is a general absence of appetite both in society and in institutions. This propagates to higher authority levels: there are gaps in policies and strategies at various levels and a lack to keep up with change. Where such policies are in place, there is either insufficient alignment among different policies or weak implementation of these policies in practice, for example concerning the mainstreaming of climate change. The governance architecture does not leave the water utility much flexibility, including on funding, which makes it reliant on central authorities that may take decisions at their own discretion. Therefore, there are uncertainties about the positive or negative impacts a functional government may have on the NI society including on wastewater systems and a confidence crisis as regarding ruling parties. This contributes to keeping the adversity to change well anchored in the society.

i. Innovation uptake is limited and
ii. The current growth model struggles to move towards a sustainable model that would put less pressure on wastewater assets.

2. Interventions that increase resilience or reduce vulnerabilities

Proposed interventions and drivers for improved resilience are all either directly or indirectly tackling the cultural aspect of resistance to change

(a) Appropriate regional legislation (NI level) that would facilitate implementation of NI water policy.
(b) Appropriate NI Water policy (NI Water level) for example in terms of a quicker SUDS uptake.
(c) Interdepartmental policy alignment that would allow
    i. A coherent overall policy and
    ii. The minimisation of detrimental consequences, impediments that arise in one sector as a result of decisions taken in another Governmental department.
(d) Increased funding to address obsolete infrastructure and insufficient serviceability through appropriate NI Water policy.
(e) Domestic and commercial water and sewerage charges which would facilitate cultural adaptation and reduce the aversion to change.
(f) Educational programmes to celebrate pilot-scale schemes and successes through the promotion of positive experiences such as the rainwater harvesting system recently launched in a primary school in Clandeboy near Belfast.

Analysis

Content

1. Social resistance to change and the lack of social responsibility.
2. Society-wide characteristic and to what extent each individual plays a role in making the change.
3. Confidence crisis in ruling parties and central authorities.
4. The idea that is repeated by participants throughout several maps (mapping processes) and which is worth discussing is that of the necessity of a strong command-based system such as a strong central authority to make things work. Examples of citations that inspire the analyst such thoughts are:
   (a) "I think the blockages for collaboration is that there is nothing saying "you have to do this" and the legislation is weak."
   (b) Participants do not know how strong the relationship is between "appropriate legislation (at NI level) and the "uptake of innovation".
   (c) "Paying for water rates will definitely change our culture. The big thing that is going to change culture is to force people to do something and pay for it."
   (d) "Regulation is all part of the educational and cultural change cycle."

Throughout maps the analyst also realised the importance in the distinction between the existence of policies and their implementation. An example for this differentiation is shown by the weak score in the relation between raising awareness and education towards adequate use of sewers and the actual behaviour that results – or not from such education campaign. This shows that the self-regulating social order that the resilience theory is based on is at least time consuming and may not self-regulate at all. Social issues and tensions need to be considered because they are shaping vulnerability.

Methodology

1. It was not clear to the participants as to whether to score according to the current situation or to the ideal thrived for.

2. There are uncertainties about the sign of some relationships which are determined by the confidence of the interviewee for example in policy and or ruling parties. It was for example difficult to determine the sign of the relation between an operational executive Government in NI and potential funding received by NI Water. In principle, the interviewee would expect more funding to be available in case an executive would be in place in NI. However, this depends on the executive in place and the confidence one has in the same authority.
3. This led to difficulties in some cases to translate the complexity of interactions and intricacies between causes and effects into simple one-by-one cause-to-effect relations. As mentioned in other interview outcomes, the maps do not reflect all the intricacies and complexities that are touched upon in the interview.

Resilience map 7

The lack of capacity to absorb additional wastewater, be it foul- or storm water, as well as the flooding which can result from it are the main vulnerabilities in Belfast's wastewater system.

Storyline

1. Drivers of vulnerability and resilience
   (a) The hydraulic load in the combined sewer system is increased by additional sewage from households and industries that result from more development, as well as by additional surface and storm waters that increase with climate change and more frequent and intense storm events.
   (b) Increased hydraulic load drastically reduces the existing capacity of wastewater infrastructure to absorb additional foul- and rain-water.
   (c) Limited network and treatment capacity increases flood risks as well as failures of critical infrastructure such as train lines, roads, businesses, properties.
   (d) People's health is impacted directly by a) floods through contamination of sewage waters and indirectly by b) damaged infrastructure that lead to potential road closures, collapsed bridges. This could prevent the public and vulnerable people from accessing key medical treatment, doctors, surgeries, hospitals or receiving medical services at their homes.
   (e) Damaged infrastructure increase repair and reconstruction costs but also lead to more jobs and potentially more development.
   (f) On the one hand, limited capacity of the network and inadequate infrastructure can limit present and future economic development in Belfast. On the other hand, infrastructure rehabilitation and renewal can lead to increased development.
   (g) Higher replacement and repair costs potentially decrease insurance covers that insurance companies would grant to subscribers.
   (h) New development is increasing the implementation of Sustainable Urban Drainage Systems and the separation of storm waters in Belfast sewage network, thus releasing the pressures on the hydraulic load and the overall wastewater drainage and treatment capacity.
2. Interventions that should result from new development

(a) SUDS and
(b) The separation of storm waters from the combined sewer system of the city.

Analysis

Content

1. The participant specified that single interventions will not improve resilience, but in conjunction they can reduce the loads significantly.
2. The idea that failures and damages can ultimately lead to increased development was not clear from the discussion with the participant. If that would be the case, the conclusion of the map would be to develop poor systems because their failures increase economic activity. If this may be true in the short term, it is likely that reconstruction also entails opportunity costs in terms of creating development and progress. Here again, the concept "development" might hide various different aspects and interpretations of economic activities.

Methodology

1. The interviewee did not understand he could use decimals to score the strengths of the connections and started to rate all connections with "1" before we went through each relationship once again.
2. The interviewee did not feel comfortable throughout the interview, he repeated not being an expert within the field (of wastewater, for example regarding the combined sewer system). He said he was talking to the analyst from his personal point of view.
3. There is a certain contradiction and difficulty in viewing relations independently when scoring them. Scoring therefore may sometimes imply hidden conditionality.
4. Interviewees usually (in this interview included) do not understand that for example (reduced) capacity of the network -> (reduced) present development is a positive connection. This is usually seen as a negative connection, because the lack of capacity is a limiting factor for development. Hence, the importance of precise concept definitions (capacity vs. lack of capacity).

Resilience map 8

The limits of the sewer network to collect and drain wastewater loads due to a largely combined system and the related capacity limits of its wastewater treatment works (WWTW) to process that influent are the main vulnerabilities of Belfast's wastewater system (a). These vulnerabilities are exacerbated by their consequences (b). In Belfast, drivers and characteristics of the system affecting resilience in wastewater management are all important for different reasons. Some of the present drivers can be dealt with straightforwardly such as by providing increased capacity others such as climate change are more difficult to address.

Storyline

1. Drivers related to the ability of the sewer network to collect and drain wastewater loads and of wastewater plants to treat.
   (a) Climate change risks in the region with more intense rainfall and Sea Level Rise (SLR) are direct threats to the combined sewer network which can become rapidly overwhelmed by large surface water flows.
   (b) This is exacerbated by urbanisation and development of Belfast leading to more impermeable surfaces which increase the speed and volume of storm water runoff and thus further limit the ability of the sewer network to operate effectively.
   (c) The lack of water charges in Northern Ireland to provide private finance for investment.
   (d) The topography of a low-lying city in the estuary of the Lagan River.
   (e) The absence of political buy-in to further invest in system upgrade, including maintenance of drainage infrastructure and Sustainable Urban Drainage Systems.
2. Consequences
   (a) Storm events and sewer overflows can result in external and internal property damages due to urban flooding caused by storm waters and coastal waters. They can also result in foul water flooding, posing a risk to public health, safety and wellbeing including mental health impacts.

(b) The limited capacity of WWTW is also of concern in view of higher discharge risks into the environment that may lead to polluted water bodies, the degradation of ecosystem service functionality, biodiversity and the quality of Belfast's green environment.

(c) Belfast's limited treatment capacity is a major barrier to further development of the city. There are already moratoriums in place that limit developers' construction permits.

(d) Lower economic attractiveness of the city and be a precursor of socio-economic decline.

3. Interventions

   (a) Separation of storm and foul water
   (b) Introduction of water charges
   (c) Climate mitigation
   (d) Urban adaptation (for example higher floor levels)
   (e) Increased funding
   (f) Political will for increased priority of wastewater management in the political agenda
   (g) SUDS uptake
   (h) Maintenance of drainage infrastructure
   (i) River catchment management and nature-based solutions

Analysis

Content

1. During the discussion, it became clear that there are unknowns about:

   (a) What factors drive economic attractiveness at present and in the future and what is the importance of wastewater management with respect to this.
   (b) Insurance responses to potential damages due to flood events related to climate change and more intense rainfall.

(c) Extent of pollution impacts on human health. Due to uncertainties in the magnitude of pollution impacts on human health, there were contradictory statements as to the importance of an unpolluted green environment for human health and wellbeing: according to the interviewee, reconnection to nature is essential on the one hand, and on the other hand pollution in the Belfast Lough is deemed negligible for human health and primarily affects biodiversity and environmental quality.

(d) SUDS

i. Who is responsible for maintaining SUDS?

ii. The effectiveness of SUDS in engineering solutions.

iii. The quality of SUDS implementation and in making them effective.

iv. The uncertainties related to responsibility, and effectiveness of SUDS may explain why SUDS have not been widely implemented to date and why NI Water may have been hesitant to move away from better known hard engineering solutions. However, SUDS should ultimately be one of the major solutions according to the interviewee. This is because they are nature-based solutions which by enhancing the green environment provide multiple benefits to human health in terms of reducing air pollution, promoting biodiversity and reducing stress. Although there have only been small schemes up to know, there is a window of opportunity through the proposals of the LWWP.

2. Government funding is a political matter, and it has not been mentioned during the interview that NI has no executive Government at the moment.
3. According to the interviewee there is a lack of political will to mandate the implementation of SUDS.
4. We found the importance of inviting the interviewees to contemplate connections between systems and drivers in other domains outside the boundaries of the wastewater system. A straightforward link is that to potable water systems. For example, clean water charges are expected to reduce water consumption and therefore to reduce the amount of wastewater. There are also clean water reservoirs that are affected by diffuse pollution for example from agriculture as well as from human activities through wastewater discharges. Lough Neagh is an example of such a reservoir located in an agricultural area and which provides

Belfast with clean water through two treatment plants while it is also a discharge reservoir for three wastewater treatment works. The interview highlighted the possibility of viewing wastewater treatment as a nested system within water management at the catchment level.

5. There are other interconnections for example between baby-wipe manufacturers and the wastewater industry. The idea of interconnection and interdependence between systems is important in that drivers of either vulnerability or resilience in one system can easily propagate to other systems without necessarily being expected. For instance, a resilience measure in one system may simultaneously improve resilience in another or reversely increase vulnerability as an unintended consequence.

Methodology

1. Concepts related to vulnerability are often worded positively which may be misleading by linking vulnerabilities to strengths of the wastewater management as opposed to its current weaknesses. For example, the capacity limitations of wastewater treatment works (WWTW) is referred to as "Capacity of WWTW" and that of the sewer network to function adequately is worded as the "Ability of sewer network to collect and drain". Their vulnerable aspect is then accounted for by adjusting the signs of the connections between concepts. For example, the map shows that "Capacity of WWTW" reduces "Risk of discharge in the environment". However, during the interview this is often expressed as "limited capacity in WWTW" increases this risk. This points towards the necessity of accompanying the map with the narrative of the interview.
2. As regarding time dynamics, pressures due to intense rainfall are a reality in Belfast at the present, whereas sea level rise is an ongoing and a slow- and long term process. Standard use of FCM do not allow to account for dynamics.
3. Difficulty to account for conditionality in the occurrence of events. For example, the consequences of water pollution on the ecosystem service functionality depend on the magnitude of the polluting event. Similarly, the effectiveness of water charges on reducing energy consumption for water treatment depends on the

adequacy of policy design and the water consumption response to that policy. That is, there may be thresholds at which the relationship between two concepts can change, with the current methodology this can only be accounted for by adding additional variables.

4. Time constraints of the interview may potentially limit the accuracy in the definitions of concepts entailing the risk missing important vulnerability and resilience mechanisms.
5. Active engagement of the analyst in the interview (for example asking clarifying questions) allows to identify more concepts and cause-to-effect relationships.
6. In light of these methodological limitations, especially the difficulty to account for dynamics and conditionality, a valuable amount of information and core issues related to the resilience of wastewater management is lost when only contemplating the final map. Therefore, it seems essential to capture the narrative that enfolds in the discussion, for example by transcribing the interview.

Resilience map 9

Vulnerability in Belfast's wastewater is strongly associated to various sources of uncertainty. These include lack of information and knowledge about the network which can lead to an unsatisfactory assessment of system-states and of solutions for the city.

Storyline

1. These uncertainties are related to the lack of information and knowledge about:
   (a) Climate change and what impacts it may have on the network capacity. Investments need to be done continuously based on incomplete knowledge. This may lead the city to have an issue with climate change if it is different to what it is anticipated to be.
   (b) The sewer network data and modelling to properly understand the dynamics and identify appropriate interventions. This is because solutions need to be prioritised rather than developed for all problems. “We have a network which is possibly on the limit of its capacity. We do not know yet because we have not got the information...”.
   (c) Where and how much capacity to create in the network to allow for development.
   (d) Complex interactions and trade-offs. For example, there is a trade-off between drainage and treatment in optimal investment decision-making on storm separation vs. treatment capacities: if more water is captured in the catchment, then less water can be drained and treated. This implies higher expenditures on discharge arrangements into the catchment because of longer outfall or different discharge points but less into treatment capacity. If more treatment is needed, then expenses would be reduced for discharge arrangements and will need to increase for drainage capacity and treatment.
   (e) Diffuse pollution: in the Belfast Lough, roads and potential agricultural drainage cause pollution. Trying to find the right solution is currently hampered by the lack of drainage area studies and models which inform all decisions that wastewater stakeholders need to make. This is to avoid spending on treatment to later find out the problem may be diffuse pollution from agriculture.
2. Interventions to increase resilience are:

(a) An integrated approach trough alignment of multiple stakeholders directly or indirectly responsible for wastewater to:
   i. Identify the common problem
   ii. Find the best solutions together.

(b) Optimise and integrate information.

(c) Implement resilient solutions such as:
   i. Local storm separation and SUDS to limit contamination of the environment
   ii. Allow for capacity exceedance with the example of the LWWP without impacting people and infrastructure
   iii. Maximise/optimise investments
   iv. Minimise energy consumption
   v. Provide flexibility for future development.

Analysis

Content

1. The complexity of the system as each concept itself could be seen as a placeholder for another map. For example, the sustainable urban drainage systems and their health benefits: “Because it is about biodiversity, it is about the general living space, the living environment – phrase I like to use – which touches on health and wellbeing, you are almost into mental health and wellbeing in terms of the impact it has on people living in a green space rather than a concrete jungle. Those are huge maps that need to be thought through quite carefully.”
2. Uncertainty is considered to be the main vulnerability. However, there are uncertainties which may be reduced and others not. For example, a better understanding of the network might be feasible through the development of more performant sewer network models. Climate change instead might be more difficult to predict. Meanwhile, decisions still need to be taken. As the participant puts it, “We may also essentially come up with the wrong solutions.” This points to the fact that solutions may only be resilient if able to cope with uncertainty rather than assuming or expecting uncertainties to be solved.
3. Participants highlighted that the methodology would work better for binary or yes/no issues. This raises the question of whether resilience is a “macro” problem.

Methodology

The participant does not understand the mapping process well and finds this mapping would work much better for small binary problems not for macro problems like "resilience". Wastewater is a complex topic and the analyst was asked how she intended to account for this complexity in the limited time given. Participants have not done this before and "simply do not know how this is done" and "We do not understand what we are doing at the moment". Therefore, they do not feel comfortable in the mapping process.

1. Participants felt that the FCM method imposes "too much rigor for something which is quite vague". This refers to uncertainties which are identified as the main vulnerability in Belfast's wastewater system. Participants struggled as to how to map their complex narrative and the mapping process started twice.
2. Question 1 and 2 were addressed simultaneously by viewing question 1 as a positive conditionality: "If there was more information and knowledge about climate change, network assets (etc.) we would be able to take resilient decisions." The concept of "vulnerability" is usually better understood than "resilience".
3. The direct use of resilience in the map creates quite a generic map which may allow for less interactions. This means that many concepts are in-degree concepts which do not cause other out-degree connections, ending the cause-to-effect cascading and interrelating effects.
4. Participants said the scores were subjective and approximate: "The scores cannot be improved they are very subjective scores."
5. Out-degree connections from "resilient solution" can be examples or drivers of that concept instead of consequences from it. For example, optimised investment and the capacity to cope with exceedance can drive resilience. Another example is the participant's statement that "[. . .] if you take resilient decisions, something like minimising energy consumption is part of that decision-making.". This means that reducing energy consumption is one of the interventions to increase resilience.
6. The positive or the negative approach to concepts may provide a different picture than the reality: for example, both "mis-investment" and "optimisation of investment" was used for the same idea. The analyst feels there is a need of defining concepts in a positive way in order to not to introduce bias towards a negative narrative that may deteriorate the image of the sector/company.

Resilience map 10

The three main vulnerabilities in Belfast's wastewater system are the capacity of the network to deliver to the treatment works, the capacity to treat higher volumes and the capacity to treat specific wastewater loads.

Storyline

1. Drivers of these vulnerabilities are
   - (a) Climate change and more intense and frequent rainfall.
   - (b) Population growth.
   - (c) Problematic industries and their trade effluent which can bring positive changes but is thought to result in a negative impact overall.
   - (d) Ageing of the infrastructure.
   - (e) Inappropriate items and sewer or pump blockages.
   - (f) Change of trade effluents as a result of industry changes in a specific area.
   - (g) Environmental regulation.
   - (h) Increased or tighter standards to be met.
   - (i) Pollutants of emerging concern (PECs) many of which are still unknown and which reduce the capacity of a treatment plant to treat, should these be included in new standards. These include micro plastics or for example tire particles that are washed off from the streets. Population growth and climate change through rainfall increases the risk of contamination with PECs.
2. Consequences
   - (a) Sewer and pump blockages.
   - (b) Out of sewer flooding including internal and external flooding to properties.
   - (c) Environmental pollution.
   - (d) Higher energy consumption.
   - (e) Increased climate change effects.
   - (f) Bans on new housing development.
3. Interventions
   - (a) Investment in technology to better monitor, detect and anticipate problems in the network which in turn facilitates adequate investment decisions through a better knowledge of failures and necessities.

(b) Investment in technology for more performant biological treatment with more efficient enzymes and bacteria.
(c) Technology is mentioned to link to many other concepts in the map.
(d) Investments are also required in storm tanks and storages.
(e) Sustainable drainage systems.
(f) Awareness campaigns to reduce inappropriate items in the sewer system.
(g) Environmentally sustainable processes such as integrated wetlands or willow treatment.

Analysis

Content

1. The importance of the pollutants of emerging concern and the lack of knowledge about them are highlighted by the participant. This is one of the very few maps if not the only one mentioning this concern.
2. Technology might be a positive input but can also be a source of new unknown by-products that may become a concern in the future.

Methodology

1. First, the participant felt unsure about the process and the map started with the keyword “resilience” before restarting with more specific “micro elements” that make up “resilience”.
2. Technology is explicitly identified as probably linking to a lot of the concepts in the map.
3. So does “investment”, especially after separation by the analyst from the initial concept “Storm tanks/investment in storage”.
4. A lack of consistency is identified in the relationship between environmental regulation and pollution: in absolute terms, environmental regulation is meant to reduce environmental pollution. However, in this map environmental regulation increases environmental pollution “relatively”, due to higher risk of non-compliance.

Resilience map 11

Vulnerabilities in the Belfast wastewater management system are driven by the misuse of sewers by NI Water's customers. The lack of a holistic vision and policy alignment between different governmental bodies from the past has left traces which the Living With Water Programme aims to address.

Storyline

1. Drivers of vulnerabilities
   (a) Diffuse pollution not accounted for in standards set by the environmental regulator.
   (b) Underfunding combined with
      i. High operational costs involved in sewage blockages that result from sewer misuse,
      ii. Lack of overall system maintenance due to prioritisation of blockage interventions,
      iii. High capital costs due to upgrades required to comply with environmental regulation.
   (c) Lack of policy alignment between different governmental departments.
   (d) The geology of Belfast with infrastructure built under the water table resulting in high substructure costs due to high ingress and a high rate of infiltration of storm water in the sewer network.
   (e) Impermeable soils.
   (f) Combined sewer network.
   (g) Underground sewer infiltrations.
   (h) Non-permeability of soils.
   (i) Siltation of sewers.
   (j) Lack of a holistic vision in the past (including about diffuse pollution).
2. Consequences
   (a) Blocked network due to inadequate amounts of solids in the network.
   (b) High opportunity cost in terms of reduced maintenance on other sites.
   (c) Environmental costs are generated accompanied by higher base maintenance and capital costs to replace equipment that is not maintained adequately.
   (d) Street or out-of-sewer flooding.

   (e) CSO discharges.
   (f) Pollution of water bodies.
   (g) Human health either directly through out of sewer flooding or indirectly through broader environmental pollution.
   (h) Degrading reputation for NI Water.

3. Interventions and drivers for improved resilience
   (a) Promoting socially responsible behaviour for both private (inappropriate items in sewers and social habits such as limiting fast food consumption to limit FOG discharge) and commercial customers (maintaining grease traps and limit FOG discharge).
   (b) Training the Environmental Regulator as well as the Agricultural Department on environmental catchment modelling of diffuse pollution to ultimately optimise the expenditure profile of the company and corrective action against pollution (sustainable agriculture to limit environmental footprint).
   (c) Department of Finance to ensure policy alignment and joined up thinking for a common vision for environmental and human health, between, the Department of Agriculture, the Environmental Regulator, the Economic Regulator, Rivers Agency, Planning and Road Services.

Analysis

Content

1. Unknowns about the effective change that will result from environmental and catchment modelling: even if NI Water invests in the identification of sources of diffuse pollution, this needs to obtain different Governmental departments buy-in and ownership to make the change effective. In addition, results heavily depend on the behaviour and practice of farmer communities, which have become to be the most important source of diffuse pollution. However, the same would apply for other polluters such as industry or forestry.
2. Unknowns about the cause-to-effect relationships between and relative consequences of water pollution on environmental degradation and human health.

3. The dynamic aspect of diffuse pollution and the fact that the onus of water pollution has historically been entirely put on NI Water. This is currently changing however because there is a certain acknowledgement about downsides of intensive agriculture on the one hand and improved wastewater standards on the other hand.

Methodology

1. This map draws processes instead of cause-to-effect relations. For example, Governmental bodies are used as vulnerability and resilience concepts in the original map. In the cleaned map, each Governmental body marked as a concept is then removed and accounted for in the narratives of the "policy alignment".
2. The difficulty to account for trade-offs. For example, the analyst found it difficult to account for the negation of what is usually seen as a trade-off between diffuse pollution and agricultural production.
3. The difficulty to account for time dynamics in the system, for example the historical trends of the Environmental Regulator to consider NI Water as the main polluter of water bodies, where more recent developments have been game changing especially regarding intensive agriculture.
4. As was also found for example in map 8, concepts related to vulnerability are often worded positively which may be misleading by linking vulnerabilities to strengths of the wastewater management as opposed to its current weaknesses. Their vulnerable aspect is then accounted for by adjusting the signs of the connections between concepts. This wording issue can result counter-intuitive, especially to the unfamiliar reader. For example, "Education, awareness and social responsibility for the management of wastewater sewers" is expected to lead to less solids in the sewer network whereas the reality in Belfast is an unsatisfactory "Education, awareness and social responsibility" around sewer use which puts a strain on NI Waters efforts to increase resilience in the system. Analogically, we find the concept "funding ", where it actually reads "under-funding" or "Government's low priority in wastewater related expenses", leading to higher vulnerability of the system.

Resilience map 12

The main vulnerabilities of Belfast's wastewater system are related to unidentified ownership of wastewater assets. This is due to the lack of reporting on underground infrastructure in the past. This situation results in the lack of responsibility for the maintenance of this infrastructure, the low prioritisation of surface water management and insufficient collaborative action among regional and local authorities.

Storyline

1. Drivers of vulnerability
   (a) Unidentified ownership of wastewater assets is due to the lack of reporting on underground infrastructure in the past. This results in the lack of responsibility for their maintenance.
   (b) Increased responsibility of asset owners to maintain their systems should reduce the operational costs for NI Water.
   (c) Increased responsibility increases resilient systems if it goes hand in hand with adequate funding.
   (d) SUDS can increase or decrease financial resilience depending on the net effect on operational and capital cost of NI Water.
   (e) Increased resilience is driven by investments in both in-sewer flood protection as well as surface water management for effective drainage. This second option is currently less prioritised at NI Water.
   (f) Collaboration creates synergies and economies of scale. For example, within the Flood Investment Planning Group (FIPG) collaborative work enables a more effective use of funding. Unsatisfactory collaboration is a source of vulnerability at the moment. However, the LWWP intends to address this issue by multiple stakeholder engagement.
   (g) Responsibility and collaboration are a result of wastewater policies, strategies and legislation at regional level. These define and pave the way to more responsibility of single owners and collaboration among stakeholders. For example, under the LWWP, the Department for infrastructure (DfI) and NI Water currently develop policies to enable NI Water taking over private drainage infrastructure where feasible.

(h) The regional policy also determines local authorities' adequate urban planning and development policies that may address sewer problems which should prevent further development in flood prone areas.

(i) The regional policy is also shaped by policy at European level.

(j) SUDS should increase resilience but may require a change in skill set at NI Water.

(k) SUDS should reduce governmental capital costs.

(l) Siltation increases risk of pipe blockages and increases maintenance costs thus reducing resilience.

2. Interventions

   (a) LWWP to enable investment in surface water management and drainage (for example, storm separation). The LWWP has linkages to many other concepts in the map and beyond this map.

   (b) Adequate urban planning to avoid development in flood prone areas (in place).

   (c) Attenuation of runoff in new urban development to be equal of that of green fields. This reduces capital costs of government but may increase housing price because the higher capital costs of developers are reflected in rent or selling prices. This goes hand in hand with adequate development planning to avoid flooding. The participant however noted that the increase in house pricing would be adjusted in time through market mechanisms.

   (d) SUDS.

   (e) Regional Community Resilience Group (RCRG) is an example of a surface water management initiative to reduce flood risk and damage in communities that live in flood prone areas and increase their well-being and health.

Analysis

Content

1. The importance of unidentified assets and or unknown ownership about assets which leads to low responsibility about maintenance and investment.

2. “It is not clear whether SUDS increase resilience at the moment but it should”, said a participant: SUDS may increase resilience from a capital expenditure and technical point of view but it may also reduce it by increasing maintenance costs. Higher maintenance of SUDS however, do not necessarily imply higher costs but different types of costs and maintenance as well as a change in skill set at NI Water. “NI Water have been amenable to hard SUDS but they do not like soft SUDS because of maintenance implications. But this is to be implemented through policy and legislation.”. “The change in skills required by SUDS and the reluctance of NI Water due to higher maintenance (costs) is also a problem for developers: it is a barrier to developers because they do not want to be responsible of soft SUDS either”.
3. Adequate funding may increase financial resilience depending on the magnitude of the operational costs increase.
4. A participant referred to storm tanks as SUDS. However, storm tanks are hard infrastructure which is not what is usually understood by SUDS.
5. At the moment, the prioritisation of surface water management is not very high at NI Water though it is their responsibility by legislation. NI Water leads a customer-based approach and therefore everything related directly to the customer is prioritised first. “NI Water’s outlook and how they prioritise is a big issue.”.
6. “Collaboration is a vulnerability at the minute because the funds are possibly not used as effectively as it could be.”
7. Climate change is mentioned at the end of the interview as an important issue that has not been mapped.

Methodology

1. As in map 5, two concepts go hand in hand and relations cannot be seen in isolation: increased responsibility increases resilient systems if it goes hand in hand with adequate funding. Attenuation of runoff also goes hand in hand with adequate development regulations and policies to reduce flooding. The same is valid for policies that need to go hand in hand with adequate funding.
2. The scores of the connections reflect the prioritisation of investments in internal vs. external flooding at NI Water. This involves that scores (priorities at NI Water) would change with increased adequate funding.

3. The scoring poses the question about scoring “how things are or how things should be”.

Resilience map 13

Main vulnerabilities of Belfast's wastewater system are related to the need of adequate solutions to cope with extreme events, increasing customer expectations driven by higher living standards, increasing compliance standards and demand as well as the funding needed for it.

Storyline

1. Drivers of vulnerability
   (a) "Infrastructure solutions needed" refer for example to increased capacity of the network for drainage, treatment plants, separation of storm waters and sustainable urban drainage systems.
   (b) "Solutions needed" are triggered by:
      i. Extreme events
      ii. Higher demand due to growth, development
      iii. Higher compliance standards
      iv. Customer expectations that are accelerated by higher living.
   (c) Funding requirements lead to either more funding granted, or, as funding is usually scarce, reprioritisation and risk management or the activation of development constraints.
   (d) Only received funding leads to achieving targets and increased resilience.
   (e) Customer expectations: people see more, travel more. It happens natural in our generation that we expect more than the previous generation.
2. Interventions
   (a) Funding granted: if a business plan that has all solutions included was fully funded (fully funded Price Control) all solutions could be delivered.
   (b) Customer education: for example, reduced water consumption would increase capacity and reduce the infrastructure solutions needed.
   (c) Water charges would provide more funds and make NI Water more resilient.

Analysis

Content

1. Risk management vs. infrastructure solutions needed: if funding is not sufficient to spend on all priorities then risk management is an alternative to building infrastructure. Risk management can include an effective focus on demand management, community resilience programmes which are about how to live with the risk and prevent damages. These can be viewed as soft solutions as opposed to hard infrastructure interventions. Risk assessments including the development and application sewer models could be useful to this end. If the wastewater system is well understood solutions can be proposed to manage risks. In case risk management is not appropriate then limitations on development need to be introduced.
2. "Funding granted compared to funding needed is quite low. NI Water does not get what it plans for in its Price Control periods. However, it might be sufficient to meet most of the needs except the LWWP." The participant thinks that NI Water does not get all the funds it requests but that overall it receives sufficient funding.
3. Water charges increase the availability of funding but also increase customers' expectations which increases infrastructure solutions needed. However, supposing the right solutions are provided, the costumer might expect higher quality or better services rather than the increase in actual infrastructure.

Methodology

1. Risk management vs. infrastructure solutions needed: if funding is not sufficient to spend on all priorities then risk management is an alternative to building infrastructure. Risk management can include an effective focus on demand management, community resilience programmes which are about how to live with the risk and prevent damages. These can be viewed as soft solutions as opposed to hard infrastructure interventions. Risk assessments including the development and application sewer models could be useful to this end. If the wastewater system is well understood solutions can be proposed to manage risks. In case risk management is not appropriate then limitations on development need to be introduced.

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3. Water charges increase the availability of funding but also increase customers' expectations which increases infrastructure solutions needed. However, supposing the right solutions are provided, the costumer might expect higher quality or better services rather than the increase in actual infrastructure.

Resilience map 14

Main vulnerabilities of Belfast's wastewater system are related to the lack of infrastructure capacity for treatment and drainage as well as to the security of energy supply.

Storyline

1. Drivers of vulnerability
   (a) Limited infrastructure capacity due to development, urban creep and limited size of sewers and treatment plants. Combined to the lack of incentives for an appropriate use of the sewers including trade effluent or illegal commercial dumping.
   (b) Insufficient capacity leads to development limitations but also increased number of blockages that result of inappropriate items in the sewers, out of sewer flooding, pollution incidents triggering fish stock depletion, flora-, fauna- and environmental degradation in general.
   (c) Out of sewer flooding has more important consequences in terms of reputation, if impacting private properties as compared to impacting water bodies.
   (d) By increasing the capacity, more strain is put on the energy network as more energy is needed to treat the wastewater.
   (e) Constructions will also expand in low lying areas and will rely more on pumping which puts pressure on electricity supply.
   (f) In adverse weather conditions you may have the requirement of standby or backup power and the changeover between the two can cause problems. Changing from grid power to backup diesel generator can cause problems because of the outage period. For example, this is an issue for pumping stations.
   (g) The security of supply is reduced by extreme weather events, the costs of external electricity providers and their vulnerabilities, and the increase of renewables and of electric vehicles on the grid.
   (h) The power capacity market is limited by the availability of grid interconnectors (power lines between electricity markets that help to provide resilience to the electricity system).
   (i) There are unknown impacts of the Brexit "deal" on the energy market.
   (j) Energy storage technology increases the security of energy supply.

   (k) Increased consumerism leads to increased "conveniences" per capita that can increase urban creep (parking lots per capita for example). It can also lead to reduced infrastructure capacity.

2. Interventions
   (a) Storm separation and incentives for private rain water harvesting that separate storm waters from household wastewaters to allow for more drainage capacity.
   (b) Technological innovation that increases energy storage technologies but can also accelerate the uptake of electric vehicles leading to potential unintended consequences on the reduction of the security of electricity supply.
   (c) Smart grid technology increases the security of electricity supply and the uptake of renewables thus reducing climate change impacts and extreme weather events.
   (d) Sustainable drainage increases the soil hydraulic conductivity reducing urban creep.
   (e) Artificial intelligence and deep learning reduce the environmental impacts through for example focused monitoring.
   (f) Adequate government policy accelerates sensitisation of the population, for example. to reduce inappropriate items in the sewer.
   (g) Investments increase the security of electricity supply.

Analysis

Content

1. Interconnectivity of markets and the impact that the electricity market and the security of electricity supply can have on pollution incidents created by the wastewater sector as described in the map.
2. The uncertainties related to Brexit, although no split in electricity market is expected.
3. Potential unintended consequences created by technological innovation: for example, a participant highlighted that the uptake of electric vehicles without an adequate development of capacity and smart grids can reduce the security of electricity supply.

Methodology

1. Cause-to-effect relations are not exclusive to one connection especially because this depends on how concepts are "worded". The impact can be conditioned by the contribution of another connection: for example, technological innovation leads to the uptake of electric vehicles but not necessarily without the simultaneous development of the smart grid.
2. Use of the word "energy" instead of "electricity".

Resilience map 15

Main vulnerabilities of Belfast's wastewater system are related to the historically inadequate investment in wastewater infrastructure within Belfast that trigger spills and potential environmental pollution as well as reduced quality of water bodies.

Storyline

1. Drivers of vulnerability
   (a) Inadequate investment in wastewater infrastructure within Belfast lead to overload in wastewater treatment works and networks as well as to spilling and higher risks of non-compliance with its discharge consent conditions.
   (b) Part of the reason the works are overloaded is due to high volumes of storm water entering the combined sewer system – possibly aggravated by climate change – and rapid economic development.
   (c) There are litigation risks of not complying with discharge consents: non-compliance on the one hand would affect water quality, shellfish and bathing waters leading to a reduction of recreational activities. On the other hand, non-compliance increases the risk of NI Water being prosecuted by the Environmental Agency (NIEA) and the risk of EU infraction for the Department of Agriculture and Environmental Affairs (DAERA).
   (d) DAERA would be infracted on by the EU under the urban wastewater framework directive for not implementing the EU legislation and in turn NIEA would prosecute NI Water for non-compliance.
   (e) There can be air emissions and increased odour problems which are regulated by the City Council.
2. Interventions
   (a) Disconnecting storm water would increase the capacity to treat sewage.
   (b) New sewage technologies and treatment technologies like NEREDA can treat more with a smaller footprint, increase the capacity and reduce overload, spills and water quality degradation.
   (c) Both participants think that the only solution to current problems is to provide new treatment facilities. Operational changes will not succeed in tackling the problems.
   (d) It all depends on investing more money: investment feeds into everything.

Analysis

Content

1. Participants said that "If NIEA identifies a reduction of water quality that [is] directly link[ed] to NI Water [and] having an impact on shellfish or bathing water quality, then NIEA would prosecute NI Water: the degradation of water quality and non-compliance with discharge consents lead to prosecution of NI Water." This seems contrary to the necessity of integrating other sources of pollution into the analysis as mentioned in several other maps.
2. Uncertainties about the Brexit "deal" and whether EU water and wastewater framework directives will still be followed by the UK despite the Brexit. In theory, there could be a "deal" in which NI could still be subject to EU infraction for non-implementation of the directives if leaving the EU.

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