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S.S.D: SECS P/02

A portfolio analysis of climate change adaptation measures in the agriculture sector in Rwanda

Tesi di Dottorato di: Dott. Filippo Fraschini

Matricola: 4611779

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Introduction

Climate change emerged as a significant topic in the global scenario at the turn of the XXI century and it has been included among the 17 Sustainable Development Goals of the United Nations 2015 - 2030 (UN, 2015), with a dedicated target: "*Take urgent action to combat climate change and its impact*". The Paris Agreement, which entered into force on the 4th November 2016, gathers together the commitments of 185 parties, in an unprecedented collective political effort by the global community toward the implementation of climate policies. In the text of the agreement, it is stated that there is a "*need for an effective and progressive response to the urgent threat of climate change*" and that there is an "*intrinsic relationship that climate change actions, responses and impacts have with equitable access to sustainable development and eradication of poverty*". Climate change is a pillar and a cross-cutting topic also of the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), where it is stated that "*disasters, many of which are exacerbated by climate change and which are increasing in frequency and intensity, significantly impede progress towards sustainable development*". The New UN Urban Agenda, Habitat III (UN, 2017), imagines future urban developments that "*adopt and implement disaster risk reduction and management, reduce vulnerability, build resilience and responsiveness to natural and human-made hazards and foster mitigation of and adaptation to climate change*".

Climate change is a rising challenge for our society, requiring modifications in decision-makers' perspectives and political strategies. It requires a balanced effort both in the reduction of greenhouse gas emissions, i.e. mitigation, and in adjusting economies and societies to the climate changing framework, i.e. adaptation.

This research work is focused on the adaptation policies, defined by the IPCC (AR5, 2014) as "*the process of adjustment to actual or expected climate and its effects*". In the light of the rising impacts of climate change and the problems that have emerged in finding a global deal for the reduction of greenhouse gas emissions, adaptation has become a key policy on the global agenda. The local communities, especially the ones in the coastal areas, and the developing states have emphasized the importance and the urgency of the adaptation interventions, also requiring an increase of the financial resources available and the improvement of their accessibility.

In spite of the increased relevance of the adaptation policies and the diffusion of several policy briefs, adaptation strategies and adaptation plans (all the EU countries have produced an adaptation strategy and 17 of them an adaptation plan), the implementation of concrete measures has been uneven. This is basically connected to three main issues, which will be presented in the following chapters of this dissertation: i) the lack of a properly defined theoretical framework; ii) the presence of barriers and limits to the implementation of the adaptation policies (e.g. the lack of dedicated economic resources, the presence of conflicting values or the failures in the functioning of the public administrations due to the lack of effective dialogue between the different level of governments); iii) a multi-faceted uncertainty about the costs and benefits of the adaptation policies (uncertainty, as the impossibility to describe an unknown event with objective probabilities – Knight, 1933).

The climate change uncertainty is the fundamental challenge to the design of adaptation policies and it can be divided into four main dimensions: i) the impossibility to exactly forecast the expected greenhouse gas emissions which are the driver of the anthropogenic climate changes; ii) the affordability of the scientific models in identifying the effect of the increasing concentration of CO_2 and equivalent gasses in the atmosphere; iii) the economic estimate of the local impacts of climate change; iv) the effectiveness and the economic evaluation of the adaptation policies. These uncertainties hamper the choice of adequate adaptation measures. Most of these policies are indeed usually referred to the actual climate risk, in the attempt to generically improve the resilience of the communities. But, when long-term policies or investments are needed and the future climate scenarios have to be considered in the planning phase, the decision-making process struggle in identify appropriate solutions, robust to the numerous possible climate futures (generally, there is a significant discrepancy between the possible futures, e.g. in the case study discussed in this dissertation, located in Rwanda, the average temperature might progressively increase until between approximately +0.6°C, in the RCP 2.6 scenario, to +4°C, in the RCP 8.5, by the 2070).

In this complex and challenging context, the common decision-making processes and methods (e.g. the cost benefit analysis or the multi-criteria analysis) are no longer effective for the identification of the adaptation policies, mainly because of their limitations in dealing with the high and pervasive level of uncertainty. Therefore, the application of different methodologies and decision tools is emerging in the attempt to help the decision-makers to find adaptation solutions also in the presence of climate change uncertainty. However, even though the presence of various examples of these methods, their practice is still uneven and there is a need of further developments, in the attempt to understand their potential and to make their use more widespread. This is why, in this dissertation, I tried to test one of these methodologies, the Modern Portfolio Theory (MPT), in the attempt to find helpful insights for the diffusion of these tools, in order to foster the implementation of climate change adaptation measures.

This research work tries also to answer real world needs: i) the urgency of climate change adaptation measures in the agricultural sector in the developing countries; and ii) the necessity of MPT methodology assessments in the climate change framework to enlarge the set of options available to farmers for responding to the expected effects of climate change.

Agriculture is indeed an essential asset for the development of the most deprived countries and, at the same time, it will be severely hit by climate changes. Specifically, the case study discussed in the dissertation refers to tea plantations investments in Rwanda. Tea is particularly sensitive to changes in the average temperatures and in the amount of the precipitations. Furthermore, in the developing countries, the agriculture sector employs large part of the population and it produces key assets for the socio-economic growth of the local communities and for the increase of the foreign trades. As indicated in the SDG 1 “End poverty in all its forms everywhere” and SDG 2 “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”, agriculture is essential for the satisfaction of the basic needs of the population. However, climate change is already having a dramatic impact on this sector. The Paris Agreement (2015) recognizes in its Preamble “*the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse effects of climate change*”. Climate change might compromise the efforts made by poor countries in pursuing a sustainable development, worsening the key meteorological components needed for productive crops investments. The link between agriculture, development and climate change is the central issue also of the FAO Strategy on Climate Change (2017), and a new panel has been created inside the UNFCCC, i.e. the Koronivia Joint Work on Agriculture (2017), with the aim to accurately assess the effects of climate change on agriculture, finding solutions to guarantee the food security. In the Rwanda case study, both in the scenarios with a low increase of the average temperature and in the ones with the strongest modifications, climate change will provoke damages to this pivotal sector, hampering the sustainable development of the country. This is why the agricultural investments and measures must therefore consider the climate change issue, the expected future scenarios and the possible impacts on both the quality and quantity of the crops yields.

Even though there is an urgency of adaptation measures in the agriculture sector, the new decision support tools used in the climate change decisions has been rarely applied in this field. The Modern Portfolio Theory has been used several times for the assessment of the benefits of the crop diversification in the agricultural economics literature, but it has never been applied to agricultural investments in a climate change framework and, in general, few examples of the use of this tool for the design of climate change adaptation measures have been found in the literature. These are the reasons why this dissertation develops this particular economic analysis. It aims at producing some helpful recommendations for the implementation of effective adaptation measures, especially in the developing countries context, particularly exposed and unprepared to the impacts of climate change.

The thesis works is structured in four chapters, in the attempt to design a coherent pathway, from the presentation of the most significant problems emerging with adaptation policies, to the description of the methodology used and the development of the case study:

i) In the first chapter, the theoretical framework of the adaptation measures is extensively analysed, presenting the fragmented conceptualization of the issue and describing the multi-faceted uncertainties characterising this topic;

ii) The second chapter is focused on the rising practice of the new decision processes and decision support tools for the analysis and the identification of effective and successful adaptation measures;

iii) The third chapter presents the key elements of the portfolio analysis, the tool used in this dissertation, with a review of the most interesting works developed with this methodology in the natural resource management sector and in the climate change field; strengths, weaknesses and developments needed for this tool are presented in the chapter;

iv) In the fourth chapter, the portfolio analysis is applied to the assessment of adaptation investments in the tea sector in Rwanda, trying to identify relevant insights from a scientific point of view and to highlight the possible advantages and limitations of this approach in real-world adaptation strategies.

1 Climate change adaptation policies: An uneven theoretical framework and the uncertainty issue

Introduction

Climate change is a key issue of our society. It started as dynamics affecting the availability and quality of the natural resources, but then became a more general problem of sustainable development.

Despite there has been a proliferation of commitments and supporting statements by the global community and the local governments, the implementation of concrete measures is still uneven. If mitigation policies can be more easily defined, i.e. the measures which reduce the greenhouse gas emissions, and their outcome measured, the adaptation policies create a more complex framework. Although, during the last thirty years, the Intergovernmental Panel on Climate Change reports have organised the knowledge in a coherent and comprehensive structure, made by the contribution of hundreds of scientists, there has been a multiplication of definitions and conceptualizations for the adaptation topic and there is still a confusing framework when the adaptation policies have to be planned.

Although the conceptual framework has become clearer in the last years, some problems remain. The most important challenge for the adaptation policies is the estimate of the costs of the climate change impacts and the connected benefits of the adaptation measures. Unfortunately, this assessment is particularly complex, because of a pervasive uncertainty connected to various key dimensions of climate change, limiting the capacity of the public government to define successful and adequate policies.

This initial chapter of the dissertation will present the climate change adaptation analytical framework, focusing on four essential pillars: i) the key concepts that characterise the adaptation policies; ii) a brief analysis of the adaptation efforts made by the global community, the local governments and the private sector; iii) a rapid introduction of the elements which characterise the barriers and the limits to the implementation of effective adaptation policies; iv) a literature review about the uncertainty issue in the climate change environment, focusing on the four most recognised sources of uncertainty in the definition of adaptation measures.

1.1 Adaptation to climate change: Urgency and uneven implementation

1.1.1 The urgent need of the adaptation policies

The Intergovernmental Panel on Climate Change in its Fifth Assessment Report (IPCC, 2014) defines adaptation as *"the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harms or exploit beneficial opportunities. In some natural systems, human measure may facilitate adjustment to expected climate and its effects*" (IPCC, 2014). The practice and the capacity to adapt is a constitutive skill of the human being. People have continuously adapted to the harmful changing of their environment, trying to find solutions to face those challenges. Irrigation, insurance and weather forecasting are just some examples of this natural capacity to adapt (Adger et al., 2009; Adger, 2003). Adaptation is in the self-interest of people; therefore, the human race has adapted to different climate conditions during its history (Fankhauser and Soare, 2013). Fankhauser (2017) reviewed the economic literature on this theme and found that there is a strong presence of self-adaptive behaviours, especially in some sectors, e.g. agriculture.

However, the scientific research (IPCC, 2014; IPCC, 2018) has highlighted the rapidity and the magnitude of these climate changes, which might considerably modify the current natural and socio-economic equilibria. These challenges are in some cases new and they cannot be easily forecasted by traditional meteorology. Complex scientific models have thus been developed for the analyses of the climate changes and the forecast of the possible future scenarios. The information generated by these models is however uncertain and difficult to be managed by people and common private investors. Adaptation decisions are thus particularly complex, requiring a good understanding of the climate principles and the inclusion of these future scenarios in the planning phase. Furthermore, the scientific literature has identified a series of barriers, limits, constrains which can hamper the adaptation process, leading to ineffective measures and short-sighted interventions. The limits in the adaptive capacity of the population are connected both with exogenous problems like the lack of funding or updated climate information or with endogenous ones, as poor social relations between the members of a neighbourhood. Therefore, even if the adaptation practice is something inborn in the private sector, the magnitude, the speed and the nature of the climate changes require a strong commitment from the public sector too. Fankhauser and Soare (2013) highlight three main adaptation areas where the public has to be involved. First of all, public administrations should supply climate-resilient public goods, such as better sea defences, storm warning systems, community-level flood protection or introducing climate change dynamics in the classic public goods like transport infrastructure and the water supply network. Secondly, the barriers to adaptation should be removed, creating an environment that is conducive to effective adaptation. Lastly, there is a need for assistance to vulnerable groups, which cannot sufficiently adapt by themselves.

The need for adaptation measures has also been emphasised by the scientific literature, first of all presenting the sizeable and dangerous amount of ongoing and expected climate change impacts. The most important source of scientific information on climate change is the Intergovernmental Panel on Climate Change, which recently presented the Special Report "Global warming of 1.5°C" (IPCC, 2018). This is a milestone and the most recent step in climate change scientific research, presenting the effects of reaching the key thresholds of +1.5°C and +2°C. Some key insights are demonstrated in this fundamental work:

i) human activities are estimated to have caused approximately +1.0°C of global warming above pre-industrial levels, with a likely range of +0.8°C to +1.2°C

ii) with high confidence, the global warming provoked by anthropogenic emissions since the pre-industrial era will persist from centuries to millennia and will cause further changes in the environment, e.g. sea level rise and connected impacts. Moreover, an estimated increase of +0.2°C per decade connected to the past and current emissions has been forecasted (meaning that there will be a need for adaptation policies also in the remote possibility where the emissions are going to be drastically reduced in the next few years);

iii) if the emission path continues its present trajectory, the global warming will likely reach +1.5°C between 2030 and 2052;

iv) climate related risks to health, livelihoods, food security, water supply, human security, and economic growth are expected to increase in a +1.5°C scenario; this depends on the geographic locations, the levels of development and vulnerability, and on the upscaling and the acceleration of both incremental and transformational adaptation.

These statements basically emphasise the need for and the urgency of adaptation measures, showing that adaptation is going to be necessary also in the presence of massive mitigation efforts and that, continuing on the current emission pathway, the dangerous threshold of +1.5°C will be reached, bringing severe impacts which require a further commitment to adaptation policies.

Besides these new findings specifically focused on the +1.5°C and +2°C futures, there are the analyses carried out by the IPCC in the AR 5 (2014) regarding the current impacts of climate change, effects that are no longer avoidable through any virtuous mitigation measure. In many regions the melting of the glaciers and the changing of the precipitations have altered the hydrological systems, affecting the water resources in terms of quantity and quality. Many plants and animal species have changed their usual geographic ranges, seasonal activities, migration patterns and species interactions. Crop yields have been affected by climate change and negative impacts (mainly concentrated in wheat and maize) have been more frequent than positive ones, which principally exists in the high latitude regions. There are worldwide impacts on human health, even if they are unevenly spread. There has been a general increase in heat-related mortality and a decrease in cold related mortality, where poor people are the most affected. Climate related hazards exacerbate other stressors, with negative outcomes for livelihoods, and cause both direct impacts (food disruption and destruction of homes) and indirect impacts (increases in the food prices and violent conflicts). Besides this analysis about the current impacts of climate change, the IPCC AR 5 (2014) also presented considerations about the future, describing the expected future effects of climate change and the possible impacts on human and nature according to four possible greenhouse-gas emission scenarios, the Representative Concentration Pathways 2.6, 4.5, 6 and 8.5. Some key processes such as the reduction of the Artic sea ice, the global sea level rise, the ocean acidification and the modification of the pattern of precipitations will continue in all climate scenarios, even in less severely so. These natural changes will provoke four main aggregated impacts:

i) severe ill-health and disrupted livelihoods will increase due to storm surges, sea level rise and coastal flooding;

ii) an expected increase in extreme weather events will cause the destruction of the infrastructure network and the interruption of the critical services;

iii) the eventual increase of floods and water insecurity will also provoke a loss of rural livelihoods and income;

iv) there will be severe impacts also on nature, with a loss of ecosystems, biodiversity, natural goods, functions and services.

All these impacts will unevenly increase across the world, where the poor people will be the most affected, especially in the developing countries of Latin American and Africa (IPCC, 2014). In these countries the communities are also poorly prepared for the negative effects of climate change and they generally rely more than other countries on the natural resources. The agriculture sector is a pillar of the economy of these nations and it is usually rain-fed, therefore completely dependent on the pattern of the precipitations.

Thanks to this wide spectrum of climate change impacts, adaptation is essential and urgent, even though it is not the sole measure possible in the attempt to face these challenges. The mitigation policies are the other key pillar of this political framework. The IPCC glossary (2014) distinguishes the climate change mitigation with the disaster risk mitigation, defining the first as "*a human intervention to reduce the sources or enhance the sinks of greenhouse gases*", whereas the latter represents "*the lessening of the potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability*". The mitigation urgency has been recognised in the '90s. The United Nations Framework Convention on Climate Change (UNFCCC, 1992) declares in Article 2 that "*the ultimate objective* (of the Convention) *is the stabilization of greenhouse gas concentrations, at a level that would prevent dangerous anthropogenic interference with the climate system*". The adaptation relevance emerged instead later, in the Cancun Adaptation Framework (2010): "*adaptation must be addressed with the same priority of mitigation …and requires to enhance adaptation actions and support*".

The need of balanced efforts between the two political fields has been also recognized by the literature (Tietenberg and Lewis, 2018). First of all, both adaptation and mitigation have upward-sloping marginal costs functions, meaning that an optimal approach requires the presence of both strategies. Without a balance between the two different strategies, the costs of tackling climate change will be higher, using the public resources in an inefficient way. Moreover, IPCC highlights with "medium confidence" that "*limits to adaptive capacity exist at +1.5°C of global warming, becoming more pronounced at higher levels of warming and varying by sector, with site-specific implications for vulnerable regions, ecosystems and human health*" (IPCC, 2018). Without investing in mitigation efforts, there will be limits for the adaptation measures, because of the presence of too many high climate change impacts, requiring higher and inefficient social and economic resources in the attempt to adapt.

Another important element relates to the target of the measures. Mitigation policies are basically global policies, i.e. the aim of the mitigation policies is the reduction of the greenhouse gas emissions and the place where these reductions are made is irrelevant. Developing mitigation policies in poor countries might be cheaper and economically more efficient, because it can take advantage from the economic and social transition of these nations, driving the investments on a more sustainable pathway. However, apart from these considerations, the place where the emissions are reduced is not important; the essential goal is the reduction of the overall global emission of greenhouse gasses and the concentration of these elements in the atmosphere. The focus of the adaptation policies is completely different. Even though there is a need of a comprehensive and coherent framework coming from national and international strategies (e.g. the European Union Strategy to Climate Change), adaptation is basically a local issue and it requires a strong commitment of regional and municipal governments and local private and public stakeholders. The local administrations have a more detailed knowledge of the vulnerabilities, resources and goals of the communities affected by climate impacts and usually they have the most effective political and technical instruments for the development of adaptation measures. Therefore, a mix of mitigation and adaptation measure could be again beneficial, taking advantage of the characteristics and resources of the institution considered.

Lastly, there is a different timing between the two main political fields, where mitigation should be implemented now, but adaptation requires a more complex balance between urgent needs and waiting for more precise information. The debate about the right timing of the mitigation interventions is basically focused on the costs of the policies. Abating greenhouse gas emissions with the current technological progress might be more expensive than waiting for more effective technologies in the future, with a lower cost-efficacy rate. However, a reduction of the carbon dioxide emissions is generally recommended, because it will inevitably have positive effects on the limitation of climate change. Thus, apart from a technological issue which can modify the costs of the mitigation efforts, the abatements of the greenhouse gas emissions are generally useful. The adaptation policies depend instead on the magnitude of the climate changes and they could produce negative effects if they have been designed without a good knowledge of the climate and its features. In some cases, e.g. the no or low-regret policies, the adaptation measures are effective in every climate scenario and, in these cases, they can be immediately implemented. However, a large part of the adaptation measures requires the forecast of the climate change expected scenarios and impacts. Here, supposing a high cost of the adaptation measure, the decision-maker might decide to postpone the policy, waiting for better data in the future. The improved information could be decisive for a better design of the measure, increasing the efficacy of the intervention and limiting the waste of public resources. The possible discrepancy between the timing of the mitigation and adaptation measures is another important difference of the two policies and again it suggests the opportunity to mix the efforts in a balanced engagement towards the reduction of CO_2 emissions and the adjustment to the changing climate.

1.1.2 The climate change adaptation political framework

The magnitude of the climate change impacts, the special needs of the deprived communities and the complementarity with the mitigation policies are therefore the key reasons why an adaptation problem has globally emerged, especially during the last thirty years. The adaptation response has been consistent both on a global and a local scale, engaging central governments but also local administrations, citizen communities and the private sector in general.

The first mention of the adaptation policies at the institutional level is contained in the United Nations Framework Convention on Climate Change (approved in 1992 and entered in force in 1994). As we mentioned above, the key article of the convention, n°2, which presents the objective of the agreement, is dedicated to the mitigation interventions. The goal is to stabilize the emissions at a level that would prevent dangerous anthropogenic interference with the climate system. The convention states also that "*such a level should be achieved within a time-*

frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". Therefore, here adaptation is seen just as an autonomous practice of plants and humans which should not be stressed by the magnitude of the climate changes. In this text there are no articles exclusively dedicated to adaptation, even if the adaptation policies are present in various part of the convention. Adaptation is mentioned in the key article 4, which presents the commitments of the signatories. Paragraph 1.e states: "*parties shall cooperate in preparing for adaptation to the impacts of climate change; develop and elaborate appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification as well as floods*". Article 1.f refers to the mainstreaming principle: "*parties shall take climate change considerations into account, to the extent feasible, in their relevant social, economic, environmental policies and actions*". In paragraph 4 the developed countries are called "*to assist the developing countries in meeting the costs of adaptation*".

A more comprehensive agreement about the adaptation issue has then been carried out by the Cop 16 at Cancun, Mexico, where the Cancun Adaptation Framework (2010) has been adopted by the UNFCCC. The Cop 16 has been a milestone in the recognition of the relevance and urgency of adaptation interventions, especially in the developing countries, already affected by climate impacts, more vulnerable and more reliant on natural resources than the developed countries and therefore more sensitive to the effects of the climate changes. The Cancun Adaptation Framework also identified some key characteristics of the adaptation policies, the special needs of the Least Developed Countries, the responsibilities of the developed nations and it creates the Adaptation Committee and the Green Climate Fund, two important institutions for managing and financing the adaptation processes. Thanks to this new agreement, adaptation acquired the same importance compared to the mitigation policies.

A dedicated article to adaptation was then designed in the Paris Agreement (2015). Article 7 declares: "*Parties hereby establish the global goal on adaptation of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal referred to in Article 2*". Among the various important commitments stated in this key article, there is a request of adaptation planning processes by all the Parties. Each Party shall: "*engage in adaptation planning processes and the implementation of actions, including the development or enhancement of relevant plans, policies and/or contributions, which may include: (a) The implementation of adaptation actions, undertakings and/or efforts; (b) The process to formulate and implement national adaptation plans; (c) The assessment of climate change impacts and vulnerability, with a view to formulating nationally determined prioritized actions, taking into account vulnerable people, places and ecosystems; (d) Monitoring and evaluating and learning from adaptation plans, policies, programmes and actions; and (e) Building the resilience of socioeconomic and ecological systems, including through economic diversification and sustainable management of natural resources*". An adaptation communication has to be submitted and reviewed periodically by every country, including in the text the nation's priorities, needs and actions planned. In the Paris Agreement (2015), countries decided to collect 100 billion dollars each year from 2020, in an attempt to adequately finance both mitigation and adaptation policies (these resources must be additional to the financial resources aimed at traditional development policies).

Climate change adaptation has been a key issue even of the international agreements about sustainable development. The United Nations dedicated one of the 17 main goals of the Sustainable Development Goals (2015) to the climate change issue. Goal 13, called "*Take urgent action to combat climate change and its impacts*", identifies various goals: strengthening resilience and adaptive capacity to climate related hazards; integrating climate change measures in national policies, strategies and planning; improving education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning; mobilizing 100 billion dollars each year for both mitigation and adaptation, as requested by the UNFCCC.

Furthermore, climate change is a cross-cutting issue and it is critical for the accomplishment of several other SDGs. Taking for example the SDG 1, i.e. "*End poverty in all its forms everywhere*", there are various targets that are affected by the pattern of the climate changes and by the implementation of adaptation efforts, e.g.: target 1.1 states "*by 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day*" whereas target 1.5 declares "*by 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters*". The achievement of these two targets is radically linked to the success of the climate change policies. Mitigations measures are necessary to reduce the impacts of climate change, reducing the obstacles to the eradication of the extreme poverty and limiting the intensity and frequency of the extreme events. Adaptation interventions are instead essential for the increase of the resilience and adaptive capacity of the communities to these adverse impacts. Anyway, the connections between climate change adaptation and the SDGs are numerous, going from the SDG 2, "End hunger, achieve food security and improved nutrition and promote sustainable agriculture", to the SDG 10, "Reduce inequality within and among countries". A key target of the SDG 2 is the 2.4 on the sustainable agriculture, which states: "*by 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality*". The issue of the inequalities is inevitably connected to climate change as well. The impacts of climate change are indeed particularly dangerous for the most poor, emarginated and vulnerable people, thus increasing the socio-economic differences among countries or communities.

Moreover, adaptation policies have been recognized also by the single national governments, firstly in the developing countries context, but then also spreading in Europe and other regions. A first milestone group of political documents to strategically drive the climate change adaptation process in the developing nations is composed by the National Adaptation Programme of Action (NAPA). Created at the Cop 7 (2001) in Marrakesh, these documents are specific for the Least Developed Countries and they are aimed at identifying their vulnerabilities, setting country-driven adaptation goals and measures. The LDCs is a particular group of poor nations recognised by the United Nations since the late 1960s and included also in the climate change framework thanks to the article 4, paragraph 9 of the UNFCCC (1992): "*The Parties shall take full account of the specific needs and special situations of the least developed countries in their actions with regard to funding and transfer of technology*''. Since the first NAPA, made by Mauritania in the 2004, a further fifty documents have been drafted, the last one in the South Sudan in the 2017. These strategies are mandatory for the concession of the financial aid of the Least Developed Countries Fund (LDCF), managed by the Global Environment Facility (GEF). Thanks to the Cancun Adaptation Framework (2010) another instrument has been developed: the National Adaptation Plan (NAP). The NAPAs were made for the most urgent and immediate needs of the LDCs, focusing on the new risks emerging due to climate change and taking advantage of win-win measures; whereas the NAPs have been instituted as a basis for a more comprehensive adaptation process, with a medium and long-term approach to reduce the vulnerability to the adverse effect of climate change that is integrated with national development planning strategies. These plans will be monitored and reviewed and then updated periodically. 13 plans (data updated at October 2019) have been submitted since the 2015 (Brazil, Burkina Faso, Cameroon, Chile, Colombia, Ethiopia, Fiji, Kenya, Saint Lucia, Sri Lanka, the State of Palestine, Sudan, Togo).

Besides the developing countries, moving to the economically developed context, the European Union had a central role in the promotion of adaptation measures, producing a European Adaptation Strategy in 2013 (a first evaluation report was published in the 2018), with three main declared goals: i) stimulating the EU countries in promoting national strategies (NASs), through the concession of policy guidance and funding, and supporting adaptation in cities; ii) promoting better informed decision making, through the development of the climate-adapt web-platform; iii) promoting adaptation in key vulnerable sector where the European Community is responsible (agriculture, fisheries and cohesion policies). Thanks to these efforts, 25 of the 28 Member States adopted NASs by early 2018. Strategies are being developed in the remaining three Member States (Latvia, Bulgaria and Croatia) but have not yet been adopted. The commitment of the European countries is even older than the communitarian effort, where the first European strategies are respectively dated 2005, Finland, and 2007, France. A detailed analysis of the political efforts made by every European nation has been carried on by the European Commission with the first evaluation report of the EU Adaptation Strategy (2018). Various dimensions have been assessed in this document, ranging from the institutional structure, the quality of the vulnerability assessment, the funding mechanism to the monitoring scheme.

Even in the United States the adaptation policies have been widely planned, both by the central government, states, regions, tribes and local communities. In 2009, president Obama created the Interagency Climate Change Adaptation Task Force, with the aim of understanding the impacts of climate change and coordinating the adaptation efforts of the Federal Government. Even though there is no a federal overarching strategy for adaptation, this task force called for a participatory approach by the federal agencies, which developed some thematic strategies: the National Action Plan: priorities for managing freshwater resources in a changing climate (2011); the National Ocean Policy Implementation Plan (2012); the National Fish, Wildlife and Plants Climate Adaptation Strategy (2013). In the United States, state, local and tribal governments have the authority and responsibility for many decisions requiring adaptation action, such as infrastructure investments, local land use planning and zoning, and emergency management. As a result, across the United States many communities are taking their own action on adaptation, and developing innovative tools, methods and policies. Many states have started to take action on their own initiatives to address climate impacts. As of July 2012, 14 states had completed adaptation plans and two more were in the process of developing an integrated adaptation plan (Mullan et al, 2013).

The role of the subnational governments is a pillar of the adaptation political framework, due to the proximity of these administrations to the adaptation needs of the local communities. States, regions, municipalities are all developing and promoting networks and organisations with the aim of increasing the impacts of their commitments and sharing their innovative policies.

One of the main initiatives regarding states and regions is Regions Adapt, a global network launched at the Cop 21 in Paris. Regions Adapt regards all the intermediate public entities between the central states and the local authorities. The network is now composed by 71 governments, representing 270 million of people, in 26 countries on 5 continents and it is focused at planning and sharing adaptation policies. Taking part in the network, the public administrations commit to define a strategy/plan on adaptation, implementing concrete actions in at least one of the priority areas of the deal and reporting data on the progress made on an annual basis. Another relevant network is the Compact of State and Regions, an initiative designed to provide a transparent, global, picture of efforts to tackle climate change on the part of state and regional governments in a single, standardized account. The Compact of States and Regions was signed at the UN Climate Summit in New York in 2014. Even if this network is fundamentally oriented to the implementation of mitigation policies, the regional governments are encouraged to identify and develop adaptation measures also. Adaptations policies are presented in the annual report of the organisation. R20, Regions for Climate Action, is another international network for subnational administrations. R20 is a not-for-profit international organisation founded in 2011 by former Governor of California Arnold Schwarzenegger in cooperation with a number of regions and NGO's, the United Nations, Development Banks and Clean-Tech companies. Their mission is to accelerate sub-national infrastructure investments in the green economy to meaningfully contribute to the Sustainable Development Goals (SDGs), also promoting projects that increase local resilience to the impacts of climate change.

Moving to the urban field, in 2014 the EU launched Mayors Adapt, a voluntary programme with the aim to bring together the commitments and the experiences of the European municipalities towards the development of adaptation measures based on the local assessment of the specific vulnerabilities. In 2015 this programme joined the Covenant of Mayors (focused on mitigation), introducing an integrated approach on mitigation and adaptation, i.e. the Covenant of Mayors on Climate and Energy. A survey of the European Commission stated that by 30 April 2018, 1076 Covenant signatories from 25 EU Member States, covering around 60 million inhabitants, had committed to conducting vulnerability and risk assessments, and to develop, implement and report adaptation plans. 40% of the EU cities with more than 150,000 inhabitants have already adopted adaptation plans. On the 22nd June 2016, this network promoted by the European Union was linked to the global initiative Compact of Mayors, creating a worldwide campaign called the Global Covenant of Mayors for Climate and Energy (GCoM). According to the latest available reports (GCoM, 2018), the GCoM has reached 9,149 cities, covering a population of more than 780 million. Other important initiatives developed by municipalities are 100 Resilient Cities (2013) and C40 – Cities Climate Leadership Group. The first one is not directly dedicated to adaptation policies, but it regards the general increasing of the urban resilience as an instrument also to face the rising climate change challenges. First of all, the programme, funded by the Rockfeller Foundation, assists the cities financing the enrolment of a Chief Resilience Officer, a new position which cooperates with the chiefs of the various departments of the municipality trying to develop a coordinated effort toward the improving of the resilience. Thus, it provides instruments, such as policy guidance or monitoring tools, for the development and the implementation of a Resilience Strategy. C40 was instead created in the 2005 and it joins 96 large cities and it is mainly focused on reaching ambitious mitigation targets.

The adaptation issue has been considered as a pillar for the sustainable development also by the private sector and many actions by no-profit actors, the business community and the citizens' organisations have been developed, especially in the last ten years. We Mean Business is a global coalition of no-profit organisations with the aim of collecting commitments by the business community, both on mitigation (energy efficiency, science-based reduction green-house gas reduction targets, renewable energy) and adaptation topics (efficient management of water resources). This network is financed by the Stichting INGKA Foundation, the philanthropic organisation of the IKEA company. This organisation has developed several interventions on the adaptation issues, focusing on sustainable agricultural programmes, experimenting new crops able to deal with increasing droughts, or promoting design and creativity in the climate change intervention strategies. In 2017 the foundation created the Climate Action Challenge, a global contest with the aim of identifying innovative solutions for the reduction of the impacts of the natural disasters and for the adaptation to climate change. On the whole, the overall landscape of private philanthropic foundations interventions on the climate change theme is wide and rich, especially in the United States. In 2008 a group of important foundations (William and Flora Hewlett Foundation, KR Foundation, John D. and Catherine T. MacArthur Foundation, Oak Foundation, David and Lucile Packard Foundation) joined together in the Climate Works network, in an attempt to build up the effectiveness of their resources, financing virtuous interventions all around the world. Another relevant network is the European Climate Foundation, created in the 2008, and mainly focused on mitigation efforts.

1.1.3 An uneven implementation framework

Although the relevance of the adaptation issue and the presence of climate change in various important international panels, the implementation of adaptation policies does not seem straightforward and uniform all over the world. Thus, even though various commitments on adaptation have been developed, both at national and local level, there is still a lack of coherent and homogenous adaptation practices. Ford et al (2015) reviewed a number of studies on the adaptation policies and indicate that "*while adaptation has appeared on the political agenda, implementation is lacking, with policies often labelled as 'adaptation' having limited concrete effects on reducing vulnerability or reflecting rebranding of existing policies focused on risk reduction*". They state that the lack of an organized practice of implemented adaptation measures becomes itself a limit for the development of adaptation policies. The effectiveness of the measures cannot be measured and the adaptation policies cannot be prioritised on the basis of their performances alone.

Thus, although the climate change science is growing in reliability and accuracy, thanks to refined climate models and a better understanding of natural processes, the concrete adaptation initiatives are still difficult to frame, especially in developed countries (Wise et al. 2014; Berrang-Ford et al., 2011; Ford et al. 2011). The implementation of adaptation is sometimes slower than the increasing needs brought by climate change and the "adaptation deficit" is getting wider (Eisenack et al., 2014). The adaptation policies are mainly developed on a local scale, with a focus on disaster risk reduction, without considering climate change as the sole or primary motivation of the intervention (Wise et al. 2014). The partial lack of implemented adaptation measures seems to contrast with the previous mentioned diffusion of several policy documents among the developed countries, like in the EU in the last twenty years.

Lesnikowski et al. (2015) present some interesting data about the implementation of adaptation measures especially at national level, thanks to a structured and consistent analysis of adaptation practices. They have collected information about adaptation policies from the National Communications to the UNFCCC, analysing commitments and reports from 117 parties, for an overall amount of 3,395 initiatives. Although there are several databases and indexes about the climate change policies, this inventory is a new and comprehensive source of information about the real adaptation actions implemented by governments. Even though this survey is based on the declaration made by governments and the efforts made at local level by municipalities and regions might have been less considered, the information collected is significant and organically presented. Lesnikowski et al. (2015) divides the adaptation measures into two categories: i) groundwork actions, i.e. those initiatives aimed at informing and preparing, at engaging the stakeholders, at assessing the impacts and the vulnerabilities, at promoting the adaptation research and the refining of the climate change scenarios and at developing policy recommendations; ii) Adaptation level actions, i.e. initiatives that are implemented to tangibly improve the resilience of human and natural systems to climate change. 73% of the whole amount of measures considered lies in the group of groundwork measures, whereas just 23% contains tangible adaptation actions (4% overlaps between the two categories). Inside the groundwork activities, the impact and vulnerability assessments are the most frequent, constituting 43% of the dataset. Moreover, while most of the groundwork measures are stand-alone initiatives, the adaptation measures are mainly implemented through the mainstreaming into existing programs and plans (74% of groundwork actions are autonomous activities, whereas 63% of adaptation actions are mainstreamed) (Lesnikowski et al., 2015). The presence of a high amount of mainstreamed action might mean a more effective engagement of the public sector and a better use of available resources, but it might also imply a lower amount of transformative adaptation measures and lower commitment on developing something new, dedicated to the adaptation needs. In any case, the paper concludes stating that: i) the progresses on concrete adaptation measures are limited with a prevalence of incremental measures on the transformative ones; ii) there is a prevalence of few sectors, while other important climate sensitive sectors including transport and insurance are poorly reported; iii) attention to vulnerable groups (women, elderly or children) basically emerges just in the vulnerability assessments, whereas there are seldom tangible measures aimed at these fragile categories.

The lack of evidence of concrete adaptation policies has been also noticed by Ford et al. (2011) in their previous study focused on adaptation case studies reported in the scientific literature. They surveyed all the 1,741 documents coming from a research with the key topic terms “climat* chang*” and “adapt*”, published between 2006 and 2009, finding that just 2% of them (39) regarded intentional adaptation actions implemented in developed nations, i.e. policies with an explicit recognition of climate change as a contributing motivator and involving the implementation of an intervention (the intentions or proposals to act have not been considered). This narrow share of concrete adaptation experiences is mainly focused on municipalities (67%), with a discrete engagement of regions and central governments too, but no participation of non-governmental organisations or civil society. The main goal of these works is the management of the coastal systems and low-lying areas (50%) and there is a lack of evidence of actions to capitalise the potential benefits of climate change. However, the grey literature has not been considered in this analysis, because of the considerable number of documents and their high variability in terms of quality.

Furthermore, in the scientific literature, there are various examples of adaptation experiences specifically dedicated to the developing countries and they are mainly focused on the agricultural context or on ecosystem-based measures in rural, resource-dependent communities. There are several case studies of these practices: information services, livelihoods management, technical solutions, promotion of financial approaches, land-use zoning, changing organisational structures and the rules governing the decision-making processes (Rickards and Howden, 2012; Wise et al., 2014). The Green Climate Fund states that, by February 2019, the organisation has financed 93 projects, 25% of them dedicated to adaptation and 36% on cross-cutting issues between adaptation and mitigation. On the website[1] of the organisation it is possible to view the documents of the single adaptation projects.

Despite the increasing importance of adaptation, we have limited and fragmented understanding of these policies and how they are currently taking place, with the majority of adaptation research and debate identifying adaptation needs, characterising vulnerability, and developing methodological frameworks (Ford et al, 2015).

Ford et al (2015) developed a review of the adaptation policies implemented in Asia and Africa, similar to the one designed by Ford et al (2011). The review focused on identifying human adaptation actions, explicitly identified within the documents as adaptations purposefully targeted at climate change impacts and designed to reduce vulnerability and/or enhance resilience. Obviously, the analysis should be interpreted with caution. This is because several adaptation efforts are undocumented and many common policies, not specifically considering climate change, may increase the adaptive capacity of a community, improving its preparedness to the climate change impacts.

The first finding of the review is that documented activities has significantly grown since 2006. The peer-reviewed literature describing adaptation has emerged predominantly since 2008 and has grown rapidly. They considered policies coming from 47 “hotspot” nations of Africa and Asia, and they collected 2,084 documents (peer-reviewed publications and grey literature) that present adaptation measures. They retained 261 documents which discuss adaptation initiatives for a more detailed analysis and they added to them 27 National Communications to the UNFCCC coming from developing countries. Thus, they identified 760 unique adaptation initiatives. A first insight coming from the analysis of these policies is that the 74% of them is from African nations, whereas there is an absence of reporting on adaptation in Central Asia. They also found that 30% of the most vulnerable countries included in this study are also among the lowest adaptors based on reported adaptation measures. Of the 760 adaptation initiatives documented, 48% were classified as groundwork and 52% adaptation actions. This is in contrast to the previous work (Berrang-Ford et al, 2011; Ford et al, 2011) which has highlighted a predominance of groundwork actions in adaptive response both globally and in high-income nations. One third of the policies analysed (220) are then dedicated to agriculture, which are predominantly national assessments of impacts and adaptation opportunities within the agriculture sector, institutional guidelines for adaptation, and recommendations or public awareness programmes for adaptive measures to reduce risk. The other key issue faced by these measures is the disaster risk management, which is the aim of 15% of the policies, especially dedicated to the flood management in large river basins. Interestingly, infrastructural based adaptations (e.g. flood protection) were not widely reported (Ford et al, 2015). The third sector reported is the healthcare. Just the 4% of the measures is specifically dedicated to the health effects of climate change.

Another interesting dimension analysed in this review regard the identification of the administrative level in charge of implementing the policies. Documented adaptation actions are fundamentally being developed and led by national governments (26%), international institutions, e.g. the UN, (23%) or by non-governmental organisations (21%). Surprisingly, just the 2% of the policies is led by municipal governments and less than 1% by the state/provincial level.

[1] https://www.greenclimate.fund/home

Furthermore, although climate change effects do not respect the boundaries of the nations and some environmental problems should be faced with the collaboration of various administrative institutions, the measures taken in partnership between two or more nations, NGOs or international institutions were documented in only 3% of the whole cases. 8 among the overall 23 interventions planned in partnership is dedicated to water management, especially for large African rivers (Nile, Limpopo, Orange and Niger). Then, adaptation initiatives analysed are equally split between planned or anticipatory actions (45%) and reactive (55%), designed in response to climate effects that have already been observed, and dedicated to measures which are aimed at immediate impacts. 87% of the measures planned by the national level are proactive. Another surprisingly insight is that the inclusion of the most vulnerable groups in the adaptation policies is scarce. Approximately one-fifth of documented initiatives considered socioeconomically disadvantaged populations, while one in ten considered the vulnerability of women. There was limited consideration of vulnerability among children, the elderly or indigenous population.

Due to the sizeable amount of adaptation strategies, plans, policies developed at the various administrative levels, there are few papers in literature that review the concrete implementation of adaptation measures and this analysis is one of the most significant and comprehensive.

1.2 Critical obstacles and challenges for the design and development of adaptation measures

As discussed in the previous paragraph, even though the adaptation to climate change has emerged as an important issue, the implementation of concrete measures has been uneven. The lack of an homogeneous and widespread implementation of policies can be referred to three main problems: i) the abundance of concepts and terminology, which creates a confusing theoretical picture of the adaptation policies; ii) the presence of limits and constrains which can impede the realisation of the measures; iii) the presence of a significant uncertainty about the expected impacts of climate change, that hampers the assessment of the costs and benefits of the adaptation policies. This following section will try to shed some light on these three important dimensions.

1.2.1 Framing the adaptation topic, a complex task

The first key elements in the understanding and tracking of adaptation measures is the lack of a fixed and well-defined conceptual framework. Even though the Intergovernmental Panel on Climate Change has produced several reports and a glossary with well-defined concepts (IPCC, 2014), the practice of adaptation policies seems ambiguous and confused. Several authors present the issue of the abundance of information and definitions about adaptation (Schipper, 2007; Hall, 2017; Fankhauser, 2017; UNFCCC LDC Expert Group, 2012), with no universal agreement on a precise definition. This complicated taxonomic framework is a challenge in the process of identifying adaptation policies because it hampers the comprehension of the characteristics and the boundaries of the issue.

There are several ambiguously defined concepts and terminologies. The term “adaptation” has various meanings and definitions and it evolved since the United Nations Framework Convention on Climate Change (1992). During the ‘90s the adaptation policies had been considered as a technical response to a specific impact or vulnerability in a specific place (Moore, 2010). Both in the UNFCCC (1992) and in the first report of the IPCC (1990), the adaptation measures were basically technical interventions with the goal of reducing the impact of climate change, especially in coastal areas or in the agriculture sector. Then, thanks to the fourth (2007) and the fifth (2014) assessment report, the concept became multifaceted, including the vulnerability of both natural and human systems, the opportunity to take advantage of the favourable occasions created by climate change and the presence of links with the sustainable development. The scientific literature has followed these two main paradigms, identifying different ways to present the adaptation topic. Hereby, adaptation can be seen as a specific policy focused on the climate change impacts or even as a general measure rising the resilience and the preparedness of a community or a vulnerable group (a literacy program for women or an investment in a water network). Anyway, there is still no agreement on the nature of adaptation, which can be viewed whether as an adjustment, or a process or an outcome (LDC Expert Group, 2012). Moreover, sometimes it seems complex to separate the concept of development policy from adaptation measures, and in literature the two concepts are often seen as overlapped (Schipper, 2007).

Furthermore, adaptation has been also recognised in different other thematic fields and it is not just related to climate change or environmental topics. The disaster risk reduction sector is one of the most significant area where a consistent effort with the adaptation policies has been recognised. Climate change is expected to increase (and has increased) the frequency and severity of extreme events, requiring both mitigation (in terms of reduction of greenhouse gasses with the aim of containing the severity of the effects) and adaptation policies. The connection between climate change and the risk of disasters has been highlighted in several important treaties, such as the Hyogo Framework for Action (UN, 2005) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), where it is stated that "*disasters, many of which are exacerbated by climate change and which are increasing in frequency and intensity, significantly impede progress towards sustainable development*". The synergy and the overlapping elements between climate change adaptation and disaster risk reduction have been presented also by the European Environment Agency in a report (2017) emphasising the importance of coherence between the two topics in the attempt to avoid a duplication of policies and helping to develop common efforts towards a better knowledge base.

Table 1.1: The definitions of adaptation

Source	Definition
Burton et al. (1998)	Refers to all those responses to climate change that may be used to reduce vulnerability
Pielke (1998)	Refers to adjustments in individual, group and institutional behaviour in order to reduce society's vulnerabilities to climate.
Rennie and Singh (1996)	Adaptive strategies are ways in which local individuals, households and communities have changed their mix of productive activities and modified their community rules and institutions in response to vulnerabilities, in order to meet their livelihood needs.
Scheraga and Grambsch (1998)	Adaptive actions are those responses or actions taken to enhance resilience of vulnerable systems, thereby reducing damages to human and natural systems from climate change and variability
Smith (1993)	Involves adjustments to enhance the viability of social and economic activities and to reduce their vulnerability to climate, including its current variability and extreme events as well as longer term climate change
Stakhiv (1993)	Means any adjustment, whether passive, reactive or anticipatory, that is proposed as a means for ameliorating the anticipated adverse consequences associated with climate change.

United Nations Development Programme (2005)	Adaptation is a process by which strategies to moderate, cope with and take advantage of the consequences of climate events are enhanced, developed and implemented
Organisation for economic co-operation and development (2011)	Improving country resilience against climate risks
LEG (2011)	Human driven adjustments in ecological, social or economic systems or policy processes, in response to actual or expected climate stimuli and their effects or impacts
Moser and Ekstrom (2010)	Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting non-climatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities.
Government of Rwanda (2011)	Additional activities needed to prepare for climate change. This typically involves specific interventions (larger storm drains or new crop varieties) but can also involve broader social or economic strategies (e.g. migration to urban centres could be an adaptation strategy in some contexts)
United Nations Framework Convention on Climate Change (2014)	A range of approaches to address loss and damage associated with the adverse effect of climate change, including impacts related to extreme weather events and slow onset events
IPCC TAR (2001)	Adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. This term refers to changes in processes, practices, or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in climate. It involves adjustments to reduce the vulnerability of communities, regions, or activities to climate change and variability.
IPCC AR4 (2007)[2]	Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.
IPCC (2014)[3]	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustments to expected climate and its effects. Incremental adaptation: adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale. Transformational adaptation: adaptation that changes the fundamental attributes of a system in response to climate and its effects.
IPCC (2018)	Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (high confidence). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies.

Source: author's elaboration of the matrix made by Schipper (2007)

[2] IPCC, 2007: Glossary, AR4
[3] IPCC, 2014: Glossary, AR5

Several elements emerge in these definitions. Firstly, adaptation is not always exclusively connected with climate change. It sometimes generically refers to the reduction of the vulnerability of the system, where it is not clear if it relates to present or future climate stressors. Climate change has well studied effects in the present, but according to the scientific community, there will be even more consistent impacts also in the future and therefore it is surprising that these aspects are not always explicitly mentioned. The main elements emerging from these definitions are the following:

- adaptation is mainly and generically focused on the reduction of vulnerability;
- according to Fankhauser (2017) the term adaptation is often considered a synonym of resilience;
- it might be aimed at reducing the damages caused by climate change, but the climate change dimension is not always included in the definition;
- the subject of the adaptation process varies from the individuals, to the country or a more ambiguous system
- adaptation measures can be focused on both human systems and, just in a few definitions, on the natural environment;
- both current and expected climate effects could be considered;
- adaptation might be aimed at both the climate variability and the extreme events;
- two definitions consider adaptation as a multidimensional intervention, which might be passive, reactive or anticipatory;
- adaptation should consider the interaction between the climate variables and the non-climatic changes;
- there could be the possibility of exploiting beneficial opportunities, even if this dimension is only mentioned in the IPCC framework;
- adaptation is generically considered a target, but even an outcome or a process;
- adaptation might be also aimed at addressing the loss and damage (the harmful effects of climate change on the developing countries, which are not responsible of greenhouse-gas emissions);
- there is both a public and private dimension of adaptation;
- adaptation could be autonomous (i.e. spontaneous and self-organised) or planned;
- adaptation has important synergies with sustainable development.

According to these various dimensions, some interesting questions emerge:

i) Does adaptation refer only to measures which consider the climate change stimuli? Are climate change projections necessary to design an adaptation policy? Otherwise, is it enough that the aim of the policy is the reduction of the current vulnerability or the increase of the resilience?

ii) Who is the subject of the adaptation process? Households, public governments or firms and private sector in general? Which role is there for these actors? How should the autonomous adaptation should be considered and included in the shaping of the adaptation policies?

iii) What is the role of adaptation in exploiting beneficial opportunities of climate change? Is that a part of the adaptation issue? Are there examples of this kind of measure?

iv) How are the adaptation policies connected with the concept of resilience and sustainability?

This ambiguity in the terminology used by political administrations and scholars has two important consequences: first, it causes a proliferation of policies called adaptation, despite the policy coherence with future climate change scenarios, often confusing with the traditional development assistance; second, it complicates the monitoring of financial resources needed and granted for adaptation measures (Hall, 2017). In this uneven and ambiguous framework, finding what is effectively additional and assigned specifically to adaptation purposes seems a demanding task. The paper by Hall (2017) analyses these problems in depth, showing that this ambiguity affects the concession of global public aids. These financial resources are therefore poorly monitored, and they financed adaptation projects which lacks a clear connection with the reduction of the vulnerability to climate change in 75% of them (AdaptationWatch, 2015). This problem is obviously less important in the mitigation framework, where there is a clear and unambiguous measurement of the progresses made (the greenhouse gas emissions avoided). The challenging task of defining adaptation policies brought concrete problems also in the assignment of the Green Climate Fund financial resources. The latest AdaptationWatch report (AdaptationWatch, 2017) presents ambiguous case studies in Bangladesh and Ethiopia, where projects about the increasing of the adaptive capacity of women in a coastal area and the preparedness of the farmers to droughts have been rejected because of the missing explicit link with the climate change topic. The Green Climate Fund preference seems to be directed to technical solutions, easier to be measured and monitored.

1.2.2 Adaptation constrains and limits

The complexity of the epistemic framework is a relevant and typical problem of the adaptation policies. The definition of the meaning of the adaptation policies is a difficult task, hampering the capacity of the public administrations to develop concrete and effective measures. However, this is not the unique challenge to the implementation of the adaptation policies. The scientific literature has identified several other obstacles which can decrease the capacity of a person or an organisation to successfully adapt to climate change. These are concrete barriers or limits that could impede the definition and the implementation of adaptation interventions. These elements characterise the adaptation theoretical framework and they contribute to the complexity of the topic.

The obstacles which people have to face in developing and implementing adaptation measures are usually called adaptation constraints. The adaptation constraints are defined as factors that make it harder to plan and implement adaptation actions (IPCC, 2014). Adaptation constraints restrict the variety and effectiveness of options for actors to secure their existing objectives, or for a natural system to change in ways that maintain productivity or functioning. The adaptation constraints are often alternatively called barriers or obstacles (IPCC, 2014). The adaptation constraints might be the lack of resources (economic, technological or about knowledge), the institutional shortages (corruption, lack of democracy, lack of coordination between the different administrative level, …) or the constraints regarding the natural environment, such as the bad connection between the ecosystems. Even if these barriers are not exclusive to the climate change adaptation framework, some of them especially arise in this context, e.g. the conflicting timescales, requiring a commitment in the present based on distant concerns, or the institutional fragmentation, as many adaptation strategies depend on the interaction of various sectors and from various policy levels. Moser and Ekstrom (2010) define barriers as obstacles that make adaptation less efficient, less effective or may require changes that lead to missed opportunities or higher costs. They state that barriers can arise from three sources: the actor making adaptation-related decisions, the context in which the adaptation takes place or the system that is the risk of being affected by climate change.

An important constraint category regards the lack of knowledge, awareness and technology. This can influence the perception of risk and the design of effective and adequate policies, able to deal with the whole range of plausible climate scenarios. Furthermore, especially in the developing countries, this constraint could be particularly challenging. The production and the dissemination of information and knowledge might be unsuccessful in facing this barrier, due to the presence of strong traditional and cultural backgrounds. IPCC shows some examples coming from the literature, where the local traditional knowledge is a strong component of the target community, therefore requiring a dialogue between these habits and the scientific information coming from external actors.

Another constraint might regard the physical limits of adaptation, that can be posed by existing natural conditions or even by human development. These barriers can hamper the capacity of a plant species or of a community to migrate to other places, in an attempt to find better environmental conditions. Economic development might provoke the over-exploitation of natural resources or it might bring to the development of a municipality in areas subject to increasing risks.

Then, there are biological constraints, which are biological characteristics of the individual that define the capacity to adapt to different climate conditions. Biological constraints also include the degradation of the environment, because it is an essential source of sustainable livelihoods and it provides precious ecosystem services. Losses in biodiversity and in the quality of the environment can be dangerous for both humans and nature resilience to climate change, limiting the ability to cope with climate changes and connected extreme events.

Furthermore, there might be also constraints connected to economic dimensions. A first component is related to the monetary availability, to the development pathway followed and to the link with environmental resources highly dependent on the climate. The second economic dimension considered is instead connected to the financial resources available for a particular project or adaptation target. Human resources could be another adaptation constraint, due to the preparedness of the people to face climate change stresses and the importance of leadership in organising adaptation measures and policies. The lack of resources is also mentioned by a report made by the OECD (Muller et al, 2013). They made an analysis on the adaptation strategies and plans developed by the country members of that organisation. They found that the majority of political documents on adaptation does not explicitly discuss funding requirements and sources in their national plans or strategies. Several countries generally state that the adaptation measures will be financed through standard budgetary processes, whereas France is the only nation which assigns a cost to each of the policies selected. The report highlights that this problem emerges because of the lack of data about the costs of the impacts of climate change and of the benefits of the adaptation policies.

The last two dimensions regard the social and cultural aspects and the institutional characteristics. Adaptation can be constrained by social and cultural factors that are linked to societal values, world views, and cultural norms and behaviours. These social and cultural factors can influence perceptions of risk, what adaptation options are considered useful and by whom, as well as the distribution of vulnerability and adaptive capacity among different elements of society. There is a part of the literature on adaptation that underlines the essential roles of personal and community values and judgments. Values are considered as criteria to guide individual or group actions but also which influence judgments, evaluations, attitudes and choices (O'Brien and Wolf, 2010). The values are a strong element in the choices of everyday life but also in regard to the desires about the own personal development and future. Thus, the values are an element that should not be ignored in shaping public adaptation decisions, otherwise they might affect the efficacy of the policies, leading to short-sighted decisions. Indigenous and cultural values might assign different judgments about the importance of local environmental resources or the meaning of a traditional economic activity. A policy for agriculture, should consider the importance that a crop can have for a community, before suggesting a radical change in the production due to expected climate changes. An effective policy towards heat waves might consider the perception of the elderly about this risk and the awareness of the neighbourhood about the presence of these vulnerable people.

The concept of value is recurring in the adaptation literature (Adger, 2003; Adger et al. 2013). Adger et al (2013) consider values as "*personal and societal judgement of what is valuable and important in life*". These values then become actions because they shape how societies develop rules and institutions to govern risk, and to manage social change and the allocation of scarce resources (Ostrom, 2005). Values and relations are a pillar resource of a society. However, different actors bring diverse own values which could conflict becoming a source of limits to the implementation of adaptation policies at the same time.

Adger et al. (2013) identify four main sources of barriers to adaptation: i) ethics; ii) knowledge; iii) risk; iv) culture and environment. Ethics refers to conflicting goals emerging in the society due to the presence of diverse actors with their own specific values. Adaptation could be developed at different scales, with diverse kind of stakeholder considered. The interests and thus the adaptation goals of the citizens of a community might be conflicting with the ones of the public government, especially in the case of bigger administrative levels like the regional or national one. The issue becomes even more complex when the intergenerational needs are considered, looking at the significant effects that climate change can bring in the future. There is a range of possible goals of adaptation and the different policy pathways emerge as a relation between society and institutions; the barrier is where there is divergence between these objectives or where the needs of a part of the society are not fully considered in the adaptation policy. The second obstacle identified by Adger et al (2013) is instead connected with the lack of knowledge about the climate change impacts. There are three main sources of the knowledge about climate and weather: the social memory of past weather extremes, the present or recent experience of weather and the forecasts about the future climate. Every actor assigns different and personal weights to these three dimensions, thus having a different perception about the adaptation measures needed. This uneven knowledge about climate change impacts is another element of complexity for an effective adaptation action. The third dimension regards the perception of risk. As mentioned in the seminal work of Kahneman (Kahneman, 2003; Kahneman and Tversky, 1984), personal experiences and knowledge define the personal perceptions of risk, and thus the behaviours of different actors in the face of risk. Social and individual characteristics are a key part of this dimension. The fourth barrier to the implementation of adaptation policies lies in the complexity of considering the symbolic losses in culture and environment connected with climate impacts. Physical changes brought by climate change can have profound cultural and symbolic impacts. Therefore, the evaluation of these effects should be included in the adaptation policies analysis; e.g. landscapes have important symbolic meanings and may have profound cultural implications. The range of these impacts depends on the society proximity to the environment. This represents a barrier to adaptation because although the impact of cc might be disruptive (especially in symbolic terms), there is a scarceness to consider cultural and environmental impact in the analysis. This dimension is highlighted also in the Sussman et al (2014) paper on the challenges to welfare economics and cost-benefit analysis posed by climate change. They talk about intangible impacts, such as the loss of cultural heritage, which cannot be defined in quantitative terms or measured. Differences in values may affect and hamper the adaptation policy process, creating a conflict between what is considered rational and effective by governments and planners and what is judged valuable by individuals and communities.

Going back to the classification of the adaptation barriers proposed by the IPCC, a last constraint is connected to the quality of the administrative structure. These are the institutional constraints and they depend on the priority assigned to climate change in the government agenda and on the preparedness of the staff to develop effective adaptation policies. Corruption might be a relevant barrier among the institutional constraints and in some regions is particularly dangerous for the efficacy of adaptation policies (IPCC, 2014). Other important constraints are named “cross-scale” and they regard the quality of the relations between the different administrative levels (municipalities, regions and central states) or among the various sectors of the public administrations. Climate change requires coordinated interventions among different actors, everyone working on its specific competencies and with its own resources. Adaptation is fundamentally a local issue, because it needs the comprehension of the local vulnerabilities and the relations with the impacts of climate change. However, the local policies should be designed according to the objectives and the overarching strategies proposed by the regional and national governments. A cross-scale constraints could also be temporal, provoked by some decisions in the present which can limit the solutions available in the future, narrowing the possibility to adapt.

The adaptation constraints can lead a community, an institution or a natural system to an adaptation limit, i.e. a stage where the level of risk is too high for their adaptive capacity, limiting the possibility to reach important goals and needs. Every system has its own adaptation limits, represented by the specific level of risk or the intensity of an impact which cannot be faced by the available adaptation options. There is a difference between hard limits, unavoidable threshold even in the long run, and the soft adaptation limits, where the adaptation options are not currently available, but they might be ready in the future. The impossibility to migrate to a safer place is an adaptation limit and it might be influenced by adaptation constraints, such as the lack of economic resources, the unpreparedness of the public government or the lack of effective social relations among the members of the local community. In the literature the concept of limit is not straightforward and sometimes is used as synonymous to barriers. The IPCC AR5 (2014) and other works (Moser et al, 2010) keep these two concepts separate. Limits are considered as fixed thresholds, which represent the maximum level of adaptation that a society can reach. Beyond these thresholds, the existing activities, land uses, ecosystems, species or system states cannot be maintained, neither in a different shape. Exceeding these limits means suffering irreversible losses or radical system shifts to another equilibrium. As previously stated, barriers are instead considered an equivalent of the constraints and therefore an obstacle to the effective implementation of adaptation policies.

Lastly, different from the concepts of barriers and limits, there is the issue of the adaptation deficit, which is defined as the gap between the current state of a system and a state that minimises adverse impacts from existing climate conditions and vulnerability.

1.2.3 A critical obstacle to the decision-making processes: The uncertainty issue

The design of adaptation measures is therefore a complex task and it requires a good knowledge of the adaptation epistemic framework and the interaction with several possible constraints and limits. In the previous paragraph a series of barriers was presented, showing the plurality of challenges that a person or an administration have to face when it tries to adapt to climate change. Biological, administrative or information constraints have been briefly described, in the attempt to give a comprehensive, even not complete, picture of the possible problems. However, there is a particular constraint that is especially important for the climate change adaptation issue. It has been frequently discussed by the scientific literature both in the mitigation and adaptation framework. This barrier regards the uncertainty connected to the assessment of the costs of the climate change expected impacts and of the benefits of the adaptation measures.

Anthropogenic climate change modifies the natural pattern of the evolution of the climate. The rising of the medium temperature, related to the human greenhouse gas emissions, is producing dangerous effects in the evolution of the water precipitations, the distribution and length of the droughts, the composition of the air and it is changing other equilibria, towards a more uncertain path. Forecasts about the future have been made in the last years, the IPCC has refined and improved its climate scenarios and the climate models are growing in affordability. Nevertheless, climate change remains unpredictable in some of its attributes, e.g. the expected average temperature of a specific location in the future, the amount of precipitations, or the expected changing in the flow rate of a particular river basin. Trying to assess the effects of an adaptation intervention is a demanding task too, due to the impossibility to accurately forecast and identify the outcome of the policy. The lack of comprehensive, complete and affordable information about these essential features can undermine the decision processes for the identification of the optimal policies. Trying to define adaptation measures the knowledge of the costs and benefits of the adaptation policies is indeed an essential information. However, these multifaceted uncertainties hamper the identification of the expected local impact of climate change and ultimately the benefits of the adaptation responses. Furthermore, this uncertainty gets worse in the distant future, when climate change effects might become significant and particularly dangerous. Due to this rising uncertainty, the long-term investments are especially complex and they might be compromised by the unpredictability of the future climate change impacts.

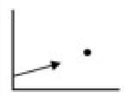
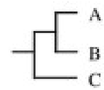
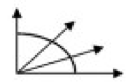
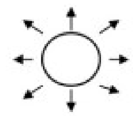
Thereby, the discussion of this dissertation goes along further with the analysis of this key dimension of the climate change analytical framework, the uncertainty issue. Literature defines the uncertainty connected to climate change as a Knightian uncertainty (Knight, 1921), i.e. the impossibility to describe a future event with objective probabilities. Uncertainty is not just a climate change dimension. Climate change could exacerbate the uncertainty related to public policy decisions, but uncertainty is a pervasive dimension of our complex world. In a UKCIP technical report on climate change adaptation (2003), the concepts of risk and uncertainty are well defined as follows: "*risk is the combination of the probability of a consequence and its magnitude; therefore, risk considers the frequency or likelihood of occurrence of certain states or events and the magnitude of the likely consequences associated with those exposed to these* *hazardous states or events*". Whereas, "*uncertainty exists where there is a lack of knowledge concerning outcomes. Uncertainty may result from an imprecise knowledge of the risk, i.e. where the probabilities and magnitude of either hazards and/or their associated consequences are uncertain. Even when there is a precise knowledge of these components there is still uncertainty because outcomes are determined probabilistically*". The IPCC (2014) defines the two concepts as follows, in a quite different way: uncertainty is "*a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable*"; risk is "*the potential for consequences where something of human value is at stake and where the outcome is uncertain*". In the climate change framework, uncertainty is usually described as "deep", referring to the conceptualisation made by Walker (Walker, 2003; Kwakkel et al, 2010), where this adjective is used in case of multiple equally plausible futures or alternatively when the future is unknown (the step before complete ignorance). Lempert and Groves (2010), states that deep uncertainty occurs when the parties to a decision do not know or cannot agree on the model that relates actions to consequences and the prior probability distributions on key input parameters to those model(s).

Walker (2003) has made a comprehensive analysis about uncertainty, trying to find an effective way to describe it. He identified three key dimensions of uncertainty: the location, the nature and the level. The location is related to "*the identification of where uncertainty manifests itself within the whole model complex*" and is divided in five other sub-dimensions: a) context – refers to the identification of the boundaries of the system to be modelled, and thus what is inside and outside our analysis; b) model uncertainty – refers to the conceptual model and it is divided in model structure uncertainty (the form of the model) and the model technical uncertainty, which is related to the computer implementation of the model; c) Inputs – refers to the values/data used in the model that characterise the analysed system (also external driving forces that have an influence on the system and its performance); d) parameter uncertainty – associated with the data and the methods used to calibrate the model parameters; e) model outcome uncertainty – "*the accumulated uncertainty associated with the model outcomes of interest to the decision-maker*".

The nature of uncertainty describes instead the source of uncertainty and identifies two extremes: a) epistemic uncertainty – the uncertainty connected to the imperfection of our knowledge, which may be reduced by more research and empirical effort; and b) variability uncertainty – the uncertainty related to the inherent variability, which is especially applicable in human and natural systems and concerning social, economic and technological development.

The third dimension is the level. This parameter describes the size of the uncertainty, identifying five categories: determinism (perfect and complete knowledge), statistical uncertainty (a well described uncertainty, where it is possible to assign probabilities to it), scenario uncertainty (it is not possible to attach probability to the event but it could be feasible to define possible future scenarios), recognised ignorance (uncertainty about the mechanism and the functional relationships, thus it is not possible to define scenarios), total ignorance (a deep level of uncertainty).

Table 1.2: The progressive transition of levels of uncertainty from determinism to total ignorance

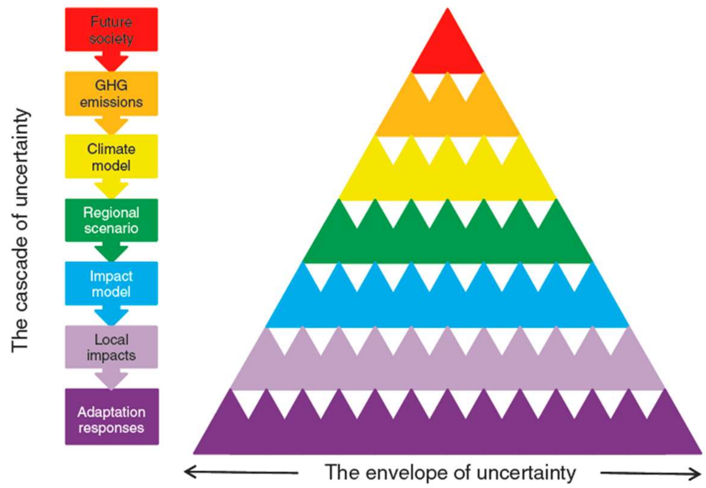
		Level 1	Level 2	Level 3	Level 4	
				Deep Uncertainty		
Determinism	**Context**	A clear enough future 	Alternate futures (with probabilities) 	A multiplicity of plausible futures 	Unknown future 	Total ignorance
	System model	A single system model	A single system model with a probabilistic parameterization	Several system models, with different structures	Unknown system model; know we don't know	
	System outcomes	A point estimate and confidence interval for each outcome	Several sets of point estimates and confidence intervals for the outcomes, with a probability attached to each set	A known range of outcomes	Unknown outcomes; know we don't know	
	Weights on outcomes	A single estimate of the weights	Several sets of weights, with a probability attached to each set	A known range of weights	Unknown weights; know we don't know	

Source: Kwakkel et al, 2010

There are other various contributions about uncertainty in the scientific literature (Morgan and Henrion, 1990) with the aim to discuss this wide topic. However, my dissertation would frame the key dimensions of uncertainty in the specific climate change adaptation context, presenting how uncertainty hampers the decision-making process and trying to describe where the scientific research has found possible instruments to help decision-makers in defining adaptation measures. Therefore, here the analysis focus on the dimensions of uncertainty in the climate change framework.

The scientific literature presents several components of uncertainty, recognized with different names depending on the author considered. In this work these dimensions will be described aggregated in four main topics. These categories will be presented following the order of the "*uncertainty cascade*" (Schneider, 1983). The climate change uncertainties are indeed all connected, starting from the pattern of the greenhouse gas emissions, determined by the development pathways followed by society, until the local impacts of climate change and the effects of the adaptation policies. The size of the uncertainty exponentially increases from the first source of uncertainty until the identification of the costs of climate change and benefits of adaptation estimated at the local sites, provoking a so-called "*cascade effect*". The "*uncertainty cascade*" is presented also by Wilby and Dessai (2010) with an interesting figure. The pyramid (Figure 1.1) represents the increasing level of uncertainty, starting from the development of future society and the greenhouse gas emissions, until the identification and the evaluation of the benefits of the adaptation measures. The increasing number of triangles at each level symbolise the growing number of permutations and hence expanding envelope of uncertainty.

Figure 1.1: The cascade of uncertainty



Source: Wilby and Dessai, 2010

Herein the thesis goes further in the next paragraph with the discussion about the various source of uncertainty connected to climate change. Differently from the figure presented by Wilby and Dessai (Figure 1.1) the uncertainties are going to be grouped into four main categories: the emission uncertainty, which collects the uncertainty of the future development of the society and of the GHG emissions; the scientific uncertainty, grouping the climate models and the regional scenarios; the impact uncertainty, which refers to the impact model and the local impacts; and the adaptation responses uncertainty.

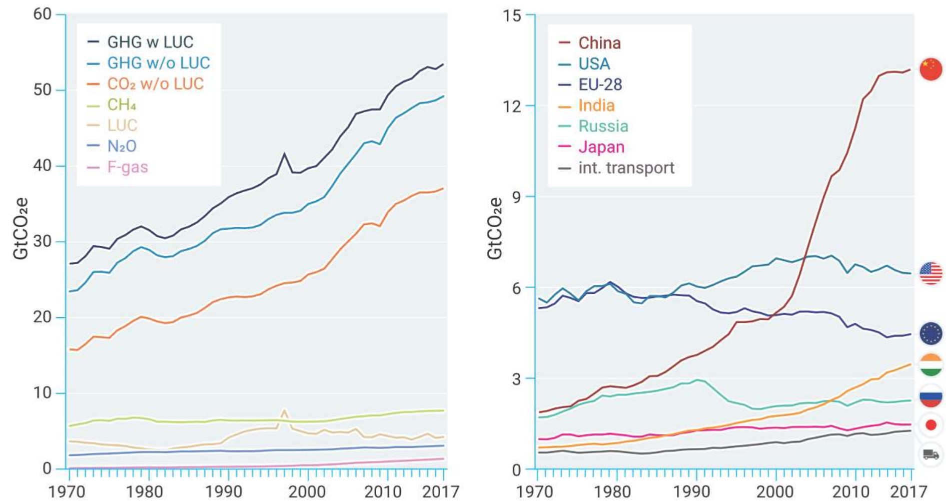
1.2.3.1 Emission uncertainty

The first source of uncertainty is the emission uncertainty and it refers to the unpredictability of the greenhouse gas (GHG) emissions trajectory. It is recognised by different authors (Heal and Millner, 2014; Hallegatte et al, 2012; Climate Adapt website; Heal and Kristrom, 2002; Rogelj et al, 2016) and it is characterised by various components, some of them connected with the public governments' mitigation policies and others with the private economic and social behaviours. GHG emissions have been highly unpredictable, although the commitments made by the developed countries since the Kyoto Protocol, entered into force in the February 2005 and then renegotiated in 2012, with commitments by 2020. Even though these engagements, total GHG emissions have increased steadily since 1970, with trend variations usually explained by changes in economic output (such as recessions, Peters et al, 2011). In 2017, the total GHG emissions, excluding emissions from land-use change (LUC), reached a record 49.2 $GtCO_2e$. Including LUC adds another 4.2 $GtCO_2$, bringing the total to 53.5 $GtCO_2e$, which is an increase of 0.7 $GtCO_2e$ (1.3%) compared with 2016[4]. All GHGs have shown strong growth in the last decades except for emissions from LUC, which have remained relatively steady (UNEP, 2018). Between 2014 and 2016 there was a stabilisation of the greenhouse gas emissions,

[4] Global GHG emissions in 2030 need to be approximately 25 percent and 55 percent lower than in 2017 to put the world on a least-cost pathway to limiting global warming to 2°C and 1.5°C respectively (UNEP, 2018).

even if the global GDP increased. This happened due to an unexpected fast decrease in the energy and carbon intensity.

Figure 1.2: Trends of the global greenhouse gas emissions



Source: UNEP, Emission Gap Report, 2018

The figure presents the pattern of the greenhouse gas emissions since 1970, showing their continuous increase, the slowdowns in 2008-2009 due to the economic crises and the one in 2014 and 2016 connected to the decreases in the energy and carbon intensity. The right side of the figure shows the contribution given by the different countries.

China emits 27% of the whole GHG emissions, with an increase of 6% each year during the period from 2004 and 2014 and a slowdown between 2014-2016, with a considerable role of the CO_2 reductions due to a marked decline in coal consumption. China has per capita CO2 emission of 7.5 metric tons, considerably lower than the values of other leading economies, such as US 16.5, Russia 11.9, Japan 9.5, Australia 15.4 and Canada 15.2 (World Bank[5]). Furthermore, even though China is the larger greenhouse gas producer at national aggregated level, they are reaching the goals they identified for their NDC. China pledged to reduce the intensity of CO_2 emissions by 40–45 percent by 2020 and its NDC includes 4 major targets for 2030: (1) peak CO_2 emissions around 2030, making best efforts to peak earlier; (2) reduce the carbon intensity of Gross Domestic Product (GDP) by 60–65% from 2005 levels; (3) increase the share of non-fossil fuels in primary energy consumption to around 20 percent; and (4) increase the forest stock volume by around 4.5 billion m 3 from 2005 levels. Independent studies, including those recently published (IEA, 2017; CAT, 2018), suggest that China will likely achieve emission level targets in line with its Cancun pledges and NDC targets. Green and Stern (2017) design an accurate macroeconomic analysis about the development of China since the beginning of the twenty first century. They identified various significant changes between the fast-growing coal and industry based economic growth of the 2000-2013 period and the "new normal" model started in the late 2013. This approach is based on three important policy documents, characterising the most significant sectors for a transition to a more environmentally sustainable economy: The National Climate Change Plan, the Energy Development Strategic

[5] https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

Action Plan and the Air Pollution Prevention and Control Plan. Thanks to these new documents and to the decreasing role of the most pollutants branch of the industrial production, the authors states that the goals of the NDC will be reached (targets for wind and solar energy have been consistently revised upwards by China energy planning agencies as costs have fallen and the industries in these sectors have grown) and that the peak of the CO2 emissions will be probably achieved between 2020 and 2025 (Green and Stern 2017).

The European Union and the USA have a key role in the reduction of the greenhouse gas emissions, because of their historical responsibility. According to data of the Centre for Global Development[6], the European Union emitted the 40% of the whole greenhouse gasses between 1850 and 2011, whereas the US reached the 22%. If the whole group of the developed Nations is considered (thus excluding the emissions by China and India), these countries account approximately the 79% of the entire emissions that generated climate change. Now, Us and EU together account for more than 20% of the current global GHG emissions (excluding land-use change). The emissions in the USA approximately peaked in 2007 and decreased at an annual rate of 0.4% from 2004 to 2014, with a considerable faster reduction from 2014-2016 (-2%), due to less coal-powered electricity generation. Emissions decreased slightly in 2017 (-0,3%). The EU has had steady declines in GHG emissions since 1990, with accelerated reductions of -2% per year from 2004 to 2014. However, EU emissions have been increasing since 2014 (on average 1% per year), reversing the long-term trend. Increases in CO_2 emissions due to strong growth in oil and gas use are largely responsible for the overall rise. According to the UN Emission Gap report (2018) and other independent studies (Climate Action Tracker, 2018; European Environment Agency, 2017) the current efforts are falling short in the achievement of the EU commitment by 2030, i.e -40% compared to the 1990 CO_2 levels.

Due to its large population, India's GHG emissions represent 7.1% of the global total, despite its low per capita emissions and large parts of the population needing better living standards. Indian emissions grew strongly in the 2004–2014 period, at an annual rate of 5%, with only a slight pause during the 2014–2016 period, when the annual rate dropped to 3%. India's GHG emissions are estimated to grow at a rate of 3% in 2017. According to the statements contained in the NDCs, 53 countries will reach the peak of the emissions in the 2020, accounting for a 40% of the total greenhouse gas emissions, whereas by the 2030, the number will grow to 57, for a 60% of the total emissions. Even though these results, the G20 countries are collectively not on track to meet their unconditional NDCs for 2030. Around half of the G20 members are in late about the achievement of their statements (E28 and USA are among them), whereas Brazil, China, as mentioned before, and Japan are on track and India, Russia and Turkey are projected to reach emissions levels 10% lower than their commitments. These achievements obviously also depend on the ambition of the initial commitments.

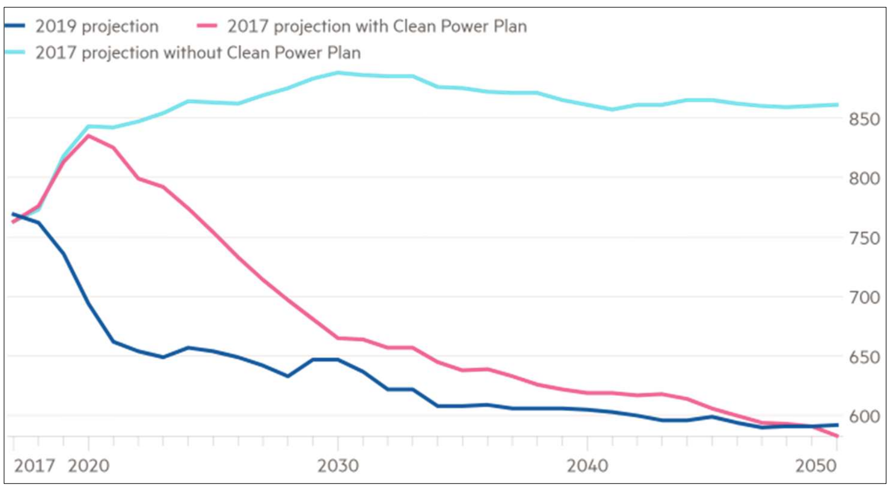
These patterns were highly influenced by some uncertain parameters, e.g. the economic growth, the technological progresses and the rising role of renewable energies. The dimensions that influence the path of the GHG emissions are highly uncertain. The GDP is a first important element that can significantly modify the pattern of the greenhouse gas emissions. The 2008 economic crisis had a key role in slowing the pace of the emissions in those years, whereas the increase of the GDP in the 2017 (approximately +3.7% worldwide), together with a slower improvement of the

[6] https://www.cgdev.org/topics/climate-change

energy efficiency, were the reasons of the 1.1% increase of the global emissions between 2016 and 2017 (excluding land use change).

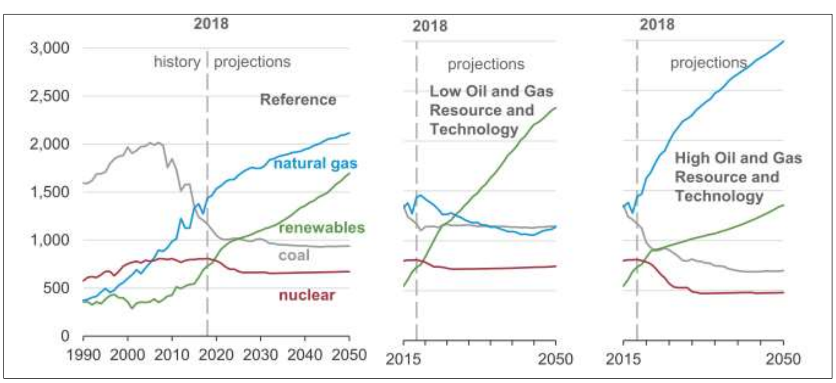
The unpredictability of the public environmental policies, and the mitigation commitments in particular, are a significant part of this source of uncertainty. An example is the reshaping of the mitigation policies between B. Obama (2009-2017) and D. Trump (2017-…) administrations, resulting in the retreat from the Paris Agreement and the decision to abandon the environmental policies developed by Obama for the coal sector (one of the main sources of GHG emissions). Even though there is a strong uncertainty connected to the political willingness of the different politicians, the uncertainty is also present in the effects produced by the governments' decisions. In 2019, the US Energy Information Administration (EIA) estimates that, even without the Clean Power Plan (abandoned by US president Trump), the US coal production is expected to decrease, reaching a pace even faster comparing with what was originally expected in 2017.

Figure 1.3: Patterns of the US coal production (millions of tons)



Source: Energy Information Administration, 2019

Figure 1.4: Electricity generation from selected fuel (billion kilowatt hours)



Source: Energy Information Administration, 2019

According to the EIA, the pace of the electricity generated by coal will be highly influenced by the pattern of the other resources, which is also influenced by international market factors and geopolitical relations. The persistent low natural gas prices have decreased the competitiveness of coal-fired power generation, thus leading the 2017 coal-fired generation level to be only about three-fifths of its peak in 2005. The future use of coal will also be influenced by the employment of the renewable resources, which are now positively pushed by the availability of tax credits and the declining capital cost of solar photovoltaic (EIA, 2019).

This uncertainty about the public policy decisions, will probably not be reduced by the Paris Agreement (2015) and the related Nationally Determined Contributions (NDCs), which will enter into force in 2020. Even if it is an unprecedented deal, engaging the whole global community towards the implementation of mitigation commitments, the Paris Agreement will probably not reduce the uncertainty related to the future patterns of the emissions. This is because the countries commitments of the Nationally Determined Contributions (NDCs) are not binding: countries can retire from the agreement, without incurring in sanctions systems. Then, the Paris Agreement does not require a common metric for measuring the commitments, thus complicating the accounting and the monitoring of the engagements made. Rogelj et al (2016) published on Nature a study on the Intended Nationally Determined Contributions (INDCs) submitted in the Paris Agreement (an INDC become an NDC with the ratification of the agreement), presenting some considerations about the countries' commitments contained in these official documents. The GHG emission projections of countries that have submitted INDCs are uncertain, particularly if targets are not unambiguously translatable in absolute emission reductions. In various documents the GHG reductions are straightforward, linking a precise reduction to a reference period. However, "*about 75 INDCs are defined relative to hypothetical 'business-as-usual' or reference scenarios in the absence of climate policy. In some cases, governments do not define their reference scenario, and in other cases official projections differ substantially from those from international and national modelling teams. […] Another complicating factor is that several countries put forward targets that do not directly specify emissions (such as a renewable energy target) or targets on emissions intensity. […] Finally, many countries (about 30, amounting to approximately 6% of global emissions) include mere qualitative descriptions of mitigation actions in their INDCs, which complicate a precise quantification"* (Rogelj et al, 2016). Looking at the reductions stated in these documents, the INDCs will reduce the actual level of the GHG emissions, though remaining far from reaching the targets of the Paris Agreement. They discovered that with the actual commitments the temperature will presumably reach an increase of +2.6°/+3.1° C by the 2100 (Rogelj et al, 2016), even if the accord requires that the commitments declared by the countries in their next NDCs have to be incremental compared with the initial ones.

Furthermore, beside the governments' willingness towards the environmental policies, there is also a private dimension in the emission uncertainty. The technological shift, the demographic variables (the massive increase of the population in India and China has been a key driver for the increase of the GHG emissions in these countries) and the private consumption and investment preferences are key elements in determining future greenhouse gas emissions too and they add another layer of uncertainty to the analysis. Technology determines the scale and carbon intensity of economic activities. The rapid growth of the hydraulic fracturing between 2002 and 2012, which decreases the price of natural gas from 12$ to less than 4$ per mmBTU (million British Thermal Unit), replacing coal and reducing GHG emissions is a good example of the uncertainty connected to the technological progress (Heal, 2014). According to the International Energy Agency (2019), even though the presence of some tax credits and market reforms, this shale revolution was unthinkable during the first decade of the twenty first century. IEA forecasts that in the 2025 the US production of oil and gas will overtake the amount extracted in Russia (2019). In the 2000s OPEC and Russia produced 55% f the global oil production, whereas in the 2030 this share will decrease until 47%. This revolution in the international energy market was barely predictable. Fankhauser (2013) talks about the technological uncertainty, characterised by the impact of the technology, preferences and socio-economic structures on the definition of the amount of GHG emissions and related damages, and the effectiveness of the mitigation and adaptation technologies to reduce damages.

An important element of this kind of uncertainty is that there are no opportunities to learn or improve knowledge in the future with in depth analysis. This dimension of uncertainty will indeed remain unpredictable, because it depends on various complex relations between different components, some of them difficult to be forecasted. However, the scientific community has improved the analysis of these possible patterns of GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) produced diverse forecasts about the expected emission pathways, where the last ones, contained in the fifth Assessment Report (2014), are called Representative Concentration Pathways (RCPs). These pathways represent four different possible trajectories of the concentration of the greenhouse-gas in the atmosphere, depending on how many greenhouse gasses will be emitted in the next years. The four RCPs, called RCP 2.6, RCP 4.5, RCP 6, RCP 8.5, are labelled after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values. These scenarios are used in the climate change adaptation framework with the aim of identifying the range of the possible increase of the temperature in the next decades.

1.2.3.2 Scientific uncertainty

The second dimension of the uncertainty cascade is the scientific uncertainty (Heal and Millner, 2014; Hallegatte et al, 2012; Climate Adapt website; Heal and Kristrom, 2002). It refers to the process of converting anthropogenic emissions in temperature/climate variations and in local effects, according to the natural principles. The knowledge of the pattern of future greenhouse gas emissions is not enough for the identification of the future impacts of climate change. There are natural processes which convert the atmospheric concentration of the greenhouse gasses in an average increase of the temperature and in the changing of the weather components. The average increase of the temperature changes intensity in the various locations of the world, giving positive or negative outcomes depending on the geographic area. The modifications of the temperature produce changes also in the key dimensions of the weather, as the length of the drought periods, the distribution of the precipitations, the frequency of extreme events like heat waves or flooding. This uncertainty comes from an imperfect knowledge of the functioning of the climate system and the affected dimensions. It could be originated from data errors (e.g. biased or incomplete observations) or model failures (e.g. climate sensitivity function).

Climate sensitivity is an important dimension of the scientific uncertainty. The equilibrium climate sensitivity (units: °C) refers to the equilibrium (steady state) change in the annual global mean surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration (IPCC, 2014). Therefore, this is the key variable which converts the concentration of the greenhouse-gasses in the atmosphere to an expected modification in the average temperature. Then, this estimated increase of the temperature has to be transformed in local temperature modifications, forecasting also possible changes in the weather dynamics. The essential scientific tools for this purpose are the downscaling models, instruments which give climate predictions at different possible local scales. However, the possible failings in the affordability and accuracy of the downscaling models represent again other sources of uncertainty.

Sussman et al (2014) refer to the scientific uncertainty as the lack of predictability due to the inherent characteristics of the physical climate system and potentially large and poorly understood feedbacks. Pindyck (2007) refers to this dimension as the uncertainty over the underlying physical or ecological processes; whereas Hallegatte (2012) identifies both "scientific uncertainty/modelling uncertainty" and "natural variability", describing it as "*the fact that global climate variables have their own dynamics, linked to the chaotic behaviour of the climate system. Climate models provide information of statistical nature (averages, variance, likelihood to exceed thresholds, etc.), but they do not provide forecasts, i.e. deterministic prediction of the future. In other terms, they can estimate the average number of rainy days in the summers of 2060s, but do not say anything about the rain in any given day or even in any specific summer*". Climate Adapt website states that "natural variability" refers to the natural variations of the climate regardless of any human influence. Heal and Millner (2017) group the first two sources of climate change uncertainty (emission and scientific) in a comprehensive scientific uncertainty. Then, they divide it in the internal variability (connected with uncompleted knowledge of the initial conditions of the system that represent the pillars of the climate model and which could leads to significant modifications in the predicted outcomes), the model uncertainty (connected with the lack of knowledge about the physics of several important processes in the climate system, as the cloud radiative feedback) and the emission uncertainty (related to the impossibility to forecast the exact pattern of the future GHG emissions).

Hawkins and Sutton (2009) make a similar categorization, identifying three main dimensions of the uncertainty in the temperature predictions: i) the initial condition uncertainty, which refers to the initial differences between the assumptions made in the description of the current state of the world; ii) the emission scenario uncertainty, which relates to the different possible emission pathways; iii) the model uncertainty, which is connected to the different structures of the various models utilized for making climate projections. They state that in the next 20 years the initial condition uncertainty and the model uncertainty are going to be the most important, becoming even more significant than the model uncertainty and, after 50 years, the role of the emission uncertainty becoming crucial for the temperature projections. Even Adger (2006) presents the accuracy of climate predictions as dramatically limited by fundamental, irreducible uncertainties. He states that uncertainties can arise from limitations in knowledge (e.g., cloud physics), from randomness (e.g., due to the chaotic nature of the climate system), and also from human actions (e.g., future greenhouse gas emissions, population, economic growth and development). The 2003 UKCIP technical report on climate adaptation presents a crosscutting issue: the data uncertainty. Data uncertainty arises thanks to three main reasons: a) measurement error (random and systematic, such as bias); b) incomplete or insufficient data (limited temporal and spatial resolution); c) extrapolation (based on uncertain data).

According to the categorization proposed by Walker (2003), the nature of scientific uncertainty is generally epistemic, because much further research effort might bring new relevant findings, helpful for a deeper understanding of the natural processes and the consequent reduction of this specific uncertainty.

1.2.3.3 *Impact uncertainty*

The third main dimension of uncertainty is called impact uncertainty and it refers to the economic definition of the future local impacts of climate change and its economic costs without considering adaptation responses. It is essential for the selection of an efficient and effective climate change adaptation policy. However, in this step the uncertainty explodes (Heal and Millner, 2014), considerably hampering the identification of adaptation measures. According to the literature (Pindyck, 2007; Markandya et al, 2014; Heal and Kristrom, 2002; Schneider and Kuntz-Duriseti, 2002; Schneider, 2004; UKCIP, 2003), this entails some critical research questions: the analysis of the uncertain evolution of the socio-economic pattern; the economic appraisal of the environmental impacts considering their non-linear function; how to manage the irreversibility of some climate change impacts; the valuing of benefits and costs over long-time frames.

Firstly, in the attempt to characterise the future impacts of climate change it is essential to forecast and understand the expected socio-economic development of the target community. The transformation of the socio-economic components directly characterizes the evolution of exposure, sensitivity and adaptive capacity, such as the economic development of a municipality in a developing country that might bring a growing number of people into coastal areas deeply hit by storms and threatened by sea-level rise. The IPCC (2014) states: "*uncertainties about the future vulnerability, exposure and responses of interlinked human and natural systems are large. This motivates exploration of a wide range of socio-economic futures in the assessment of risks. Understanding future vulnerability, exposure, and response capacity of interlinked human and natural systems is challenging due to the number of interacting social, economic and cultural factors, which have been incompletely considered to date*".

Secondly, there is an issue regarding the function of the environmental costs, which is highly non-linear. Passing specific and in some cases unknown "tipping-points" could produce catastrophic consequences, considerably rising the expected value of the climate change impacts. For example, the damages caused by greenhouse gas emissions or water pollutants can increase with different speed and intensity depending on the characteristics of the system observed. This dimension could be critical in the economic measurement of the costs of climate change and the benefits of adaptation policies. Sussman et al (2014) talk about non-marginal impacts, where marginal modifications in the physical climate variables can drive other systems over dangerous and critical thresholds, into a new equilibrium state. "*Such movement to a new equilibrium may be irreversible on characteristic human historical timescales and could include the potential for fundamental changes in human systems or structural changes in the economy*" (Sussman et al, 2014). Tipping points are still poorly understood, and they might cause significant and permanent effects on the natural environment and socio-economic development.

Then, a third point regards the irreversibility issue which characterises both the impacts and the effects of the policies. Some changes may be irreversible, as could some adaptation policies. Therefore, there could be important hidden costs both in some adaptation policies and climate change impacts and waiting for more detailed information and scientific findings could have an important economic value. Instead of deciding for an expensive and highly irreversible investment, which significantly relies on the state of some natural resources possibly affected by climate change, the decision-maker could wait for more accurate information about the evolution of the natural environment. According to the speed of the changes in the availability of water resources in the actual climate changing era and considering the opportunity to have refined information in the forthcoming years, how are these considerations are going to influence the decision to develop a big dam project or a new expensive sewage network? Looking at the evolution of the climate information available during the past IPCC reports can suggest how the climate forecasts might evolve thanks to new scientific findings. The economic analysis has introduced the concept of option value trying to economically asses the value of a precautionary approach where decision-makers decide to wait better information in the future maybe choosing now more flexible measures.

Another important challenge emerges when long-term costs and benefits have to be included in the analysis. This dimension rises an important issue of valuing costs and benefits over long time horizons. This problem especially emerges in the context of hard investments with high sunken costs, with a long economic life, as the cultivation of perennial crops or the construction of an expensive infrastructure. The presence of costs and benefits in the far future requires the use of a social discount rate for the actualization of these distant economic values. The value of this parameter is a highly debated issue (Sussman, 2014). The discount rate topic is especially significant in the context of mitigation policies, where there is an important lag between the costs of the policy and the related effects in the future. The impact of climate change will be particularly severe for future generations and therefore the benefits of an intervention will rise in the far future. The choice of the discount rate is therefore essential in the judgment of the importance of these benefits and costs. This issue emerges also in the adaptation context, mainly in the presence of long-term investments (dams, large agricultural investments, sewage networks, …) where the economic life of the projects spans over decades and the investment costs are basically concentrated in the first years of the policy. There is a disagreement about both the parameters used for the definition of the discount rate: the pure rate of time preferences and the elasticity of the marginal utility of consumption (Heal and Millner, 2017). Both these parameters express distributional value judgments that have been hotly debated. The presence of a deep uncertainty about the future can have an influence on these parameters. Due to this great uncertainty, it is very complex to forecast the trajectory of the welfare of the future generations and, thanks to possible dramatic consequences produced by climate change, the economic wellness might be considerably worse in the next decades (Heal and Millner, 2014). The discount rate is a decisive issue in defining adaptation policies. With higher discounting both the social cost of carbon and the value of adaptation measures could be lower, suggesting to focus more on the present consumption than on future generations. A high discount rate can considerably reduce the monetary value of the impact of climate change in the distant future and therefore the benefits of an adaptation policy. Whereas a low discount rate gives higher value to the welfare of the future generations and it rises the need of climate change policies. In the field of adaptation policies economics, this dimension might be crucial in determining the urgency to invest in adaptation measures. It is especially critical in dealing with adaptation policies in the developing countries framework, where higher discounts rates are usually employed, according to the high needs of the present population and the belief that the future generations will be wealthier. There is a well-known scientific debate on the most suitable discount rates even for the mitigation policies (Stern, 2006; Nordhaus, 2007). A further discussion about the discount rate will be developed in the case study section of this dissertation.

In addition to usual monetary value of items and services traded in markets there are frequently some social and environmental dimensions which should be included in the analysis of the costs and benefits. Schneider et al (2000) introduce the classification of “the five numeraires”: (a) monetary loss, (b) loss of human life, (c) reductions in quality of life (including forced migration, conflicts over environmentally dependent resources, loss of cultural diversity, loss of cultural heritage sites, etc.), (d) loss of species/biodiversity, and (e) increasing inequity in the distribution of material well-being. Sussman et al (2014) reflect on the issue of valuing goods and services, affected by policies or by climate changes, which are not traded in markets. The IPCC (IPCC, 2014; IPCC, 2018) focuses on the cultural elements (e.g. the sense of community) hit by climate change, where the expected trajectory of the good according to climate change and the solutions to measure it are problematic. This is especially significant in the context of climate change, where impacts on public health, cultural heritage, environmental quality or ecosystems are significant.

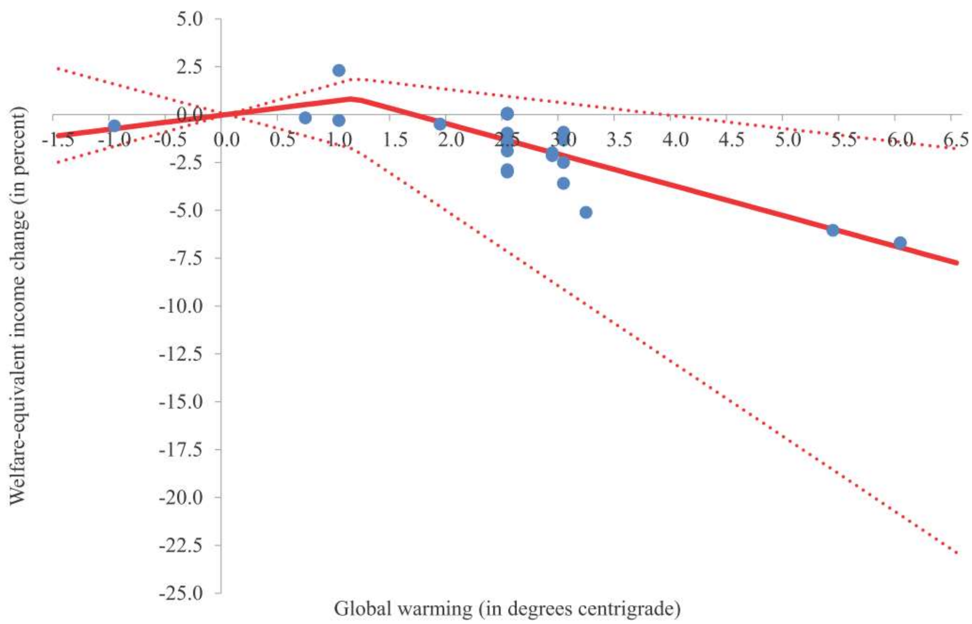
Due to these uncertainties connected to the estimate of the climate change impacts, there has been a debate among the environmental economists about the economic evaluation of the overall effects of climate change. These analyses are very important due to the need to find the most efficient balance between adaptation and mitigation efforts in a context of scarce economic resources available. This is why, according to Tol (2018), 27 estimates (contained in 22 works) about the welfare impact of climate change have been developed by some of the most representative economists. However, these estimates are disparate. Some authors state that the current economic instruments are not accurate enough for producing an affordable estimate of the whole impacts of climate change. Pindyck (2013) argues that these estimates of the economic impacts of climate change have no foundation in economic theory, while Heal (2017) writes that current models are "*not accurate enough to provide quantitative insights*" and he calls for a more intuitive approach to climate policy advice. Clearly, 27 estimates are a thin basis for drawing definitive conclusions about the total welfare impacts of climate change. Moreover, the 11 estimates for warming of 2.5°C indicate that researchers disagree on the sign of the net impact: 3 estimates are positive and 8 are negative. Thus, it is unclear whether climate change will lead to a net welfare gain or loss.

Table 1.3: Estimate of the welfare impacts of climate change

Study	Warming (°C)	Impact (% GDP)			
		Best	SD	Low	High
d'Arge 1979	−1.0	−0.6			
Nordhaus 1982	2.5	−3.0		−12.0	5.0
Nordhaus 1991	3.0	−1.0			
Nordhaus 1994b	3.0	−1.3			
Nordhaus 1994a	3.0	−3.6		−21.0	0.0
	6.0	−6.7			
Fankhauser 1995	2.5	−1.4			
Berz undated	2.5	−1.5			
Tol 1995	2.5	−1.9			
Nordhaus and Yang 1996	2.5	−1.4			
Plambeck and Hope 1996	2.5	−2.9		−13.1	−0.5
Mendelsohn et al. 2000	2.5	0.0			
	2.5	0.1			
Nordhaus and Boyer 2000	2.5	−1.5			
Tol 2002	1.0	2.3	1.0		
Maddison 2003	2.5	0.0			
Rehdanz and Maddison 2005	0.6	−0.2			
	1.0	−0.3			
Hope 2006	2.5	−1.0		−3.0	0.0
Nordhaus 2006	3.0	−0.9	0.1		
	3.0	−1.1	0.1		
Nordhaus 2008	3.0	−2.5			
Maddison and Rehdanz 2011	3.2	−5.1			
Bosello et al. 2012	1.9	−0.5			
Roson and van der Mensbrugghe 2012	2.9	−2.1			
	5.4	−6.1			
Nordhaus 2013	2.9	−2.0			

Source: Tol (2018)

Figure 1.5: The global total annual impact of climate change



Source: Tol (2018)

The analysis made by Tol (2018) is interesting due to the presence of a net annual GDP gain connected to small increases of the temperature, even if with higher values of the average temperature the losses are going to be significant. Furthermore, this figure shows the magnitude of the uncertainty related to the economic estimates of the climate change impacts. The dotted lines are the standard deviations of the values presented in the previous table and they show the range between all the possible forecasts. Tol (2018) states that the estimates are made by groups of economists who know each other very well and therefore probably start their analysis from similar perspectives. Consequently, the true uncertainty might be even higher in the reality. Another limit of this analysis is referred to the linear forecast. The impacts of climate change are usually found to be more than linear. A doubling of the average temperature is expected to give more than a double loss in GDP.

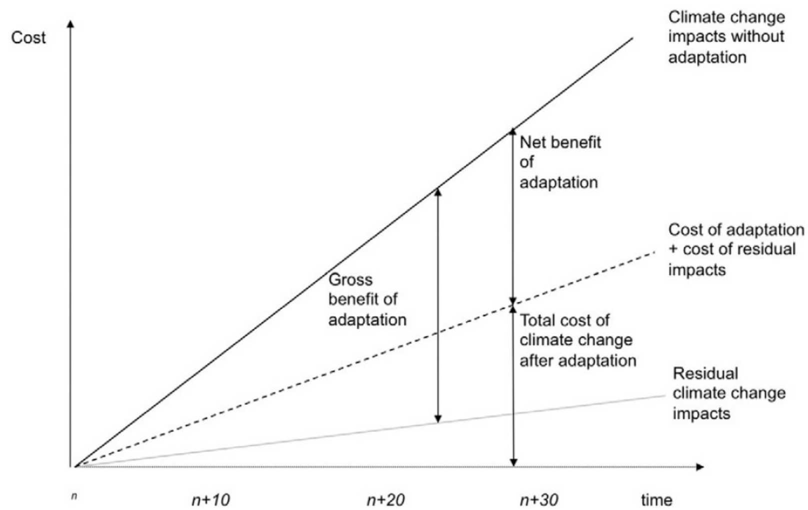
Even if, in some cases, these estimates present a slight loss in the aggregated world GDP, the costs of climate change are unevenly distributed among the different continents and nations. The effects on the most vulnerable countries, the developing ones, are going to be considerably more significant. This happens because the developing countries are more vulnerable to the impacts of climate change, according to three main reasons: i) they totally rely on natural resources like water and livelihoods coming from agriculture and livestock, leading them to be dependent to the climate components; whereas, usually, the developed countries have a more diversified economy, with a greater role of the services; ii) poorer countries are usually settled in the hottest area of the earth, highly hit by extreme events, and they are already challenged by these adverse conditions; furthermore, the increasing of the temperature and the worsening of the dangerous natural phenomena are going to be more heavily felt in these places (whereas in places like Norway or Great Britain, a warmer climate could sometimes even bring some benefits); iii) developing countries have a low adaptive capacity, due to the difficulties in their economic growths, social development and institutional frameworks.

1.2.3.4 Adaptation policies uncertainty

The last step in the evaluation of the costs of the climate change impacts is the identification of the effects of the adaptation measures. This dimension has two main components: first, the efficacy of the adaptation policies or of the evolution of people's self-adaptive behaviours (e.g. migrations, crops modifications, …); second, the economic assessment of the residual damage of the climate change impacts after the adaptation policy, which is essential for the estimate of the benefits of the adaptation policy.

As shown in Figure 1.6, given the overall amount of climate change impacts, the adaptation policies reduce the costs connected to these effects, resulting in a residual climate change impact. The difference between the climate change impacts without adaptation and the residual climate change impacts represents the gross benefit of adaptation. The difference between this value and the cost of the adaptation measures represents the net benefit of adaptation. However, the adaptation policies capacity to reduce the impact of climate change is something complex to forecast. Several questions emerge. Are the adaptation measures selected able to reduce the impact of climate change? To which extent? What will be the residual impact of climate change after the adaptation measures are defined and planned?

Figure 1.6: Costs and benefits of adaptation

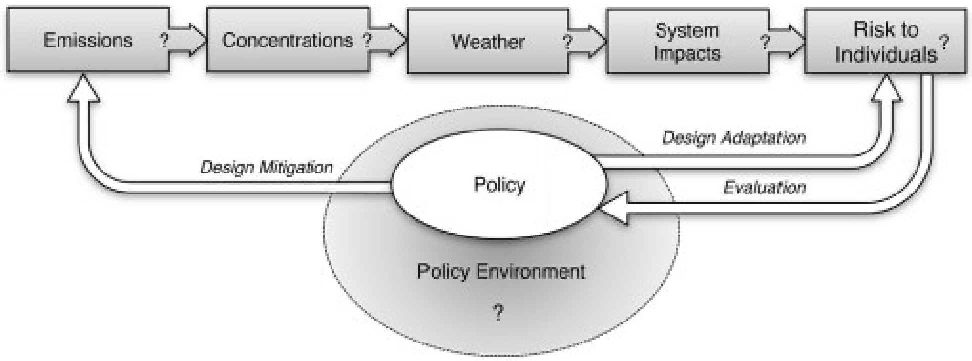


Source: Dittrich et al, 2016

A first problem in identifying the adaptation benefits is connected to the efficacy of the adaptation measures. Firstly, there are typical uncertainties that affect the performance of a policy in general: e.g. political uncertainties (e.g. if the policy will be supported by the coalition partners), budgetary uncertainties (e.g. competing demands for government budget), and uncertainties in the external environment that can affect climate adaptation decisions (e.g. a terrorist attack could move attention away from the climate discussion) (Smith and Stern, 2011).

Then, there is an uncertainty especially generated by the climate change framework. Due to the previous dimensions of the climate change impact uncertainty, the design of a proper adaptation policy is particularly challenging and its future efficacy could be at risk. As shown in the figure below, the definition of an adaptation policy is generally an outcome of the evaluation of the risks to individuals, who are themselves connected to the assessment of the previous steps of the chain (i.e. emissions, concentrations, weather and system impacts).

Figure 1.7: Casual Chain of climate change and the role of the policy



Source: Buurman and Babovic, 2016 (based on Smith and Stern, 2011)

The case study presented in this dissertation is dedicated to adaptation policies in the tea sector in Rwanda. Similarly to the uncertainty cascade here presented, the assessment of the benefits of the adaptation measures passes from the evaluation of the previous level of the uncertainty cascade. In the case study, the emission scenarios are selected firstly, looking at the possible futures that the scientific literature has identified. Then, the downscaled average increases of the temperature in these global scenarios are assessed, looking at the most accurate and reliable scientific analysis (e.g. in our analysis we will refer to a series of models aggregated by the World Bank). The increase of the average temperature is the climate change impact considered in our analysis. It is obviously a large assumption of this research, because of the presence of a wider and more complex variety of possible future climate change impacts (e.g. the modifications of the precipitations or the changes in the frequency of extreme weather events). Then the adaptation measure is applied. In the case study the adaptation policy is the settlement of the tea plantations in other locations, more suitable to the expected climate scenarios. Thus, the performance of the adaptation policy has to be assessed, finding the performance of the tea plants in these new “adapted” locations. The difference between the tea investment without considering the possible climate change scenarios and the benefits of going in other more “adapted” locations returns the benefit of the adaptation measure. However, as briefly discussed in this chapter, every step of the assessment process is highly uncertain and the residual impact of climate change is therefore inevitably a rough estimate.

Beside this multitude of dimensions regarding the complexity in designing adaptation interventions and predicting the efficacy of these measures, there is the demanding task of estimating the economic impact of an adaptation measure, similar to the aforementioned aspects which complicate the calculus of the climate change impacts. These dimensions regard the estimate of non-market costs and benefits, the inclusion of the irreversibility issue in the analysis of the adaptation measure and the inter-temporal evaluation of costs and benefits, considering the effects of the adaptation policies in the long run with an appropriate discount rate.

Conclusions

Climate change is a critical challenge of our time. The work of the scientific community, led by the IPCC, has highlighted the relevance of this topic and the current and expected impacts connected to the increase of the greenhouse gas concentration in the atmosphere. These insights have been recognised also by significant international political agreements and policy briefs, as the Paris Agreement (UNFCCC, 2015), the Sustainable Development Goals (UN, 2015) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015).

Climate change will persist for centuries and, following this emission pattern, an increase of +1.5°C and probably +2°C will be reached in the next decades. These changes in the average temperature are modifying the environment, causing significant impacts on human development, especially in the developing countries and on the most vulnerable people. Climate change affects the distribution and the intensity of extreme weather events, the rising of the sea level, the losses of biodiversity and natural services. These effects can significantly hit the agricultural production, the availability of water resources and the health of the communities, especially the ones living in coastal cities.

Because of these increasing challenges, new effective policies are needed. The global community has identified two main policy responses: i) mitigation policies, aimed at the reduction of the emissions of CO_2 and other greenhouse gasses; ii) the adaptation measures, which have the essential goal of adjusting the human systems and the natural environment to the actual and expected climate. An effective and efficient public intervention on climate change requires a balanced effort on both these tools.

This work focuses on adaptation, a key policy highlighted in 2010 by the Cancun Adaptation Framework developed by the UNFCCC. In the first two decades of the XXI century, there has been a proliferation of adaptation policy documents, policy briefs, adaptation strategies and plans, made by national governments, regional and local administrations. Despite this increasing number of documents, the implementation of concrete and proper adaptation measures has been uneven. This research work focuses on three main motivations of this problem: i) the lack of a well characterised and well defined theoretical framework for the adaptation topic, with a plurality of sometimes conflicting definitions about the adaptation dimensions; ii) the presence of various barriers and limits to the adaptation policies; iii) the uncertainty regarding the local costs of the climate change impacts and the benefits of the adaptation measures. These uncertainties start from the impossibility to predict the future pathway of the greenhouse gas emissions, pass from the lack of knowledge about some scientific principles which characterise the natural processes and it ends with the estimate of the local impacts, deeply connected to the expected development patterns of the local communities. Even the benefits of the adaptation policies are difficult to be predicted. The estimate of the economic benefits depends on the efficacy of the adaptation measures which is strictly related to the decision-maker ability to design a policy which can be effective in all the possible climate scenarios.

2 Methods for climate change decisions in an uncertain framework

Introduction

After the discussion of the adaptation framework and of the climate change uncertainty, the thesis here presents a review of the most significant methods and tools used for the identification and implementation of concrete adaptation measures. The chapter is basically divided into two main parts: i) the first part describing the new decision-making processes, fundamentally characterised by iterative procedures and plans which try to include the possible effects of climate change; ii) the second part presenting the tools that can assist the decision-maker in finding robust adaptation solutions.

The overview has the main goal to present a comprehensive and complete picture of the processes and instruments available for the adaptation to climate change. However, the review does not go in-depth with each tool, just presenting the key features and some applications coming from the literature. More can be written on every instrument presented, as this thesis has done in the third chapter, focusing on the Modern Portfolio Theory, the methodology used in this work. The essential aim of this chapter is to give to the reader an introductory analysis of the main possibilities available in the attempt to find adaptation policies considering the uncertain climate change framework, presenting strengths and weaknesses, and also concrete applications.

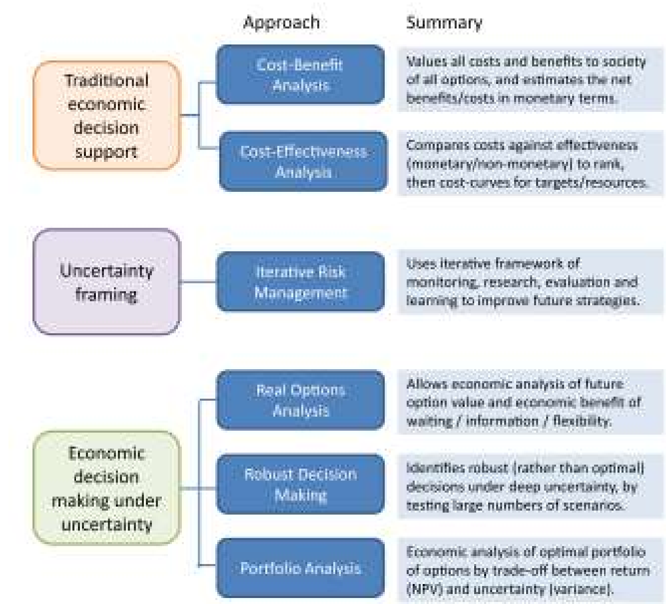
Not all the case studies here presented are exclusively focused on climate change adaptation, even if they are all dedicated to face the uncertainties coming from the management of natural resources.

2.1 A literature review of the most significant decision-making processes and tools for climate change adaptation decisions

Working on adaptation policies is a demanding task. The theoretical framework is wide, and puzzling and the decision-making processes are bound by the deep uncertainty raised by climate change. This research work has previously focused on the general discussion on the adaptation topic, especially analysing the main components of the climate change uncertainty. Now the dissertation goes further with the investigation of the possible approaches aimed at the identification of the best adaptation policies, helping the public administrations in moving from the planning phase to the implementation processes.

Commonly, traditional decision support tools are used, as the cost-benefit analysis, the cost-effectiveness analysis and the multi-criteria analysis. However, these instruments have some limits in the identification of climate change adaptation policies, and they could lead to inefficient decisions. Watkiss et al (2015) and Dittrich et al (2016) developed an analysis of the economic instruments aimed at the adaptation decisions and they begin their works presenting the traditional decision-making approaches and their limits in the context of climate change related decisions.

Figure 2.1: Decision support tools



Source: Watkiss, 2015

i) Cost-benefit analysis (CBA) tries to maximise the benefits of a project for the society, comparing its monetised costs and benefits over a defined timeframe to obtain the Net Present Value. In the framework of adaptation decisions, the economic values of the impacts of climate change have to be assessed. Therefore, climate projections under a range of greenhouse gas emission scenarios are downscaled. This output is then fed into impact models to determine, for example, changes in rainfall or in crop yields. Then, the same impacts, but considering the adaptation option, should be identified. The difference between the impact without and with adaptation represents the net benefit of the adaptation option. This benefit should be compared with the cost of the adaptation measures. However, as we discussed in the previous chapter, climatic changes are highly uncertain in the future. The more we go far in the next decades, the more we cannot predict the local impacts of global warming.

CBA works with costs and benefits occurring in the future and it has strategies to tackle the uncertainty. The first solution is the use of the Expected Net Present Value, which aggregates the NPVs occurring in the future because of a series of contingencies. These contingencies should be exhaustive, thus representing adequately all the possible futures, and mutually exclusive. Then a set of probabilities have to be attached to each contingency and they must each be nonnegative and sum to exactly 1. The probabilities may be based solely on historically observed frequencies; on subjective assessments by clients, analysts, or other experts based on a variety of information and theory; or on both (Boardman et al, 2018). The sum of the NPVs, weighted by the probabilities of their connected contingencies, gives the ENPV of the policy. However, such contingencies connected to climate change are usually highly unpredictable, as we are in context of the so called Knightian uncertainty.

Another way to assess the uncertainty connected to some parameters of the CBA is the sensitivity analysis. With this technique, the analyst varies the most critical parameters according to the possible values that can occur. The sensitivity analysis has the precise goal to show how sensitive predicted net benefits are to changes in assumptions. If the sign of net benefits does not change when we consider the range of reasonable assumptions, then our results are robust and we can have greater confidence in them. However, usually, there are various uncertain parameters in the CBAs and assessing all the possible combinations is unfeasible. Therefore, there are three main methods for performing a sensitivity analysis: i) the partial sensitivity analysis, where the analyst varies single assumptions, holding all others constant; it can be used to find the values of numerical assumptions at which net benefits equal zero; the probability at which net benefits switch sign is called the breakeven value and reporting the various breakeven values is often a useful way to show their importance. ii) the worst- and best-case analysis, which tries to identify the combination of reasonable assumptions that reverse the sign of the net benefits; iii) the third option is the Monte Carlo sensitivity analysis, a method that requires the analyst to make random trials for each uncertain parameter, in order to identify the casual realised net benefits (usually represented on an histogram).

CBA is widely used because it permits to evaluate a project in a single metric, that can be easily compared with other CBAs of different other projects, even if it has an obvious limitation that requires all elements to be expressed in monetary terms. In practice, the estimate of all the costs and benefits is indeed difficult, especially in the non-market sectors. This presents a challenge for adaptation, as capacity building and non-technical options are difficult to be quantified and assessed, and thus lower priority might be assigned to this kind of measures (Watkiss et al, 2015).

Future impacts are actualised in present values thanks to the Social Discount Rate (SDR). Even if it allows inclusion in the analysis benefits and costs rising far in the future, there is a debate in the scientific community on the value of this parameter. In the climate change framework, the future benefits and costs are highly relevant, due to the increasing severity of the impact of climate change in the future. Therefore, the number assigned to the discount rate is sometimes decisive in the context of climate change adaptation because it determines the economic relevance of the climate change impacts (and the connected adaptation benefits) in the far future. Generally speaking, CBA is therefore not suited to situations of high uncertainty or transformative changes in social and economic structures, where the assessment of the monetary values is difficult or impossible (IMPRESSIONS project D5.1, 2015). It could be instead particularly useful when the probabilities of the climate change risks are known and the uncertainty is not wide. The evaluation of the low and no-regret adaptation options might be a good framework for the use of CBA, since there are no significant effects of the different climate change scenarios (Watkiss et al, 2015).

ii) Cost-effectiveness analysis (CEA) is an alternative to cost-benefit analysis, especially when the monetisation of the benefits is difficult. The main target of the policy has to be identified (e.g. lives saved, reduction of risk, …) and then the policies that reach this objective are ranked according to their cost, from the cheaper to the most expensive. The measure selected should be the one that reaches the goal with the lower expense. CEA has been widely used in the environmental policies selections, because of the difficulties in assigning monetary values to some natural goals. CEA can be used to rank different projects, using cost per unit benefit. At the programme or policy level, it can assess the least cost solution to achieve a particular target.

This instrument has often been used in the air pollution or mitigation strategy sector. However, applying this tool in the adaptation policy decisions is more complex. The mitigation policies can be compared thanks to a unique metric, the dollars per tonnes of CO_2 avoided, whereas the adaptation policies should be evaluated from a wider range of perspectives, e.g. protection of people, reduction of erosion, protection of infrastructures and services, conservation of the biodiversity and the ecosystem services. The benefits of adaptation measures are location specific and time-dependent; this makes it impossible (or extremely challenging) to define a single, globally applicable metric for adaptation. CEA is mainly focused on technical options, where there is a clear, dominant impact, instead of capacity building or cross-sectoral studies on a plurality of possible climate change effects and adaptation benefits (Watkiss et al, 2015). It can include uncertainty testing multiple cost curves considering several socio-economic and climate model projections, or by comparing scenarios. However, it is not recommended in case of high uncertainty or transformative changes in social or economic structures (IMPRESSIONS project D5.1, 2015). Even in the case of CEA, the application is recommended to the situation where the impacts of climate change are not particularly uncertain, e.g. the case of the no or low-regret policies.

iii) Multi-criteria analysis usually consists of a plurality of quantitative and qualitative indicators that provide a ranking of alternatives based on the weight the decision-maker gives to the different indicators. The cost-benefit analysis might be integrated in that method, representing one of the criteria considered in the decision. The considerable uncertainty usually connected to climate change scenarios and impacts is a significant obstacle even to the application of this tool. As the two previous instruments, multi-criteria analysis can be ineffective when long-term investment decisions have to be taken or climate change considerably influences the outcomes of the project.

Governments and decision-makers face several challenges in applying these tools and methods to the adaptation policies because of the severe uncertainty discussed in the previous chapter. While the costs of adaptation measures can be immediately measured, the benefits of the adaptation measures are harder to be estimated, as these require planning and foresight about how the climate will change. There are indeed multiple dimensions which complicate the process of identifying the local impact of climate change and the expected effects of the adaptation policies. This is why new decision-support tools or decision-making processes have been tested in trying to define good adaptation measures, fostering the public policies when urgent. Although support for policy making and planning under uncertainty is not something new and has been developed over a long time, the need for climate change adaptation policies and investments has provided a stimulus for developments in this area (Wise et al, 2014). These new methodologies take into account a plurality of possible climate scenarios instead of valuing the policy just on the basis of a unique climate scenario. These solutions could be a new form of decision-making processes or new tools which are able to include in their evaluations a plurality of expected futures.

Before the discussion about these new methodologies, some simple rules about adaptation decisions are here presented. First of all, IPCC (2014) helps in the identification of the pillar elements of a good decision and a good climate decision. The first should emerge from processes in which "*people are explicit about their goals, consider a range of alternative options for pursuing their goals, use the best available science to understand the potential consequences of their actions, carefully consider the trade-offs, contemplate the decision from a wide range of views, including those who are not represented but may be affected and follow agreed-upon rules and norms that enhance the legitimacy of the process for all those concerned*". Whereas, a good climate decision instead requires integrating information on climate, its impacts, the potential risks and the vulnerability into an existing or proposed decision-making context.

Then, two main frameworks have been defined in tackling climate change decisions. The first one proposes that the governance of adaptation requires knowledge of anticipated regional and local impacts of climate change in a more traditional planning approach (Meadowcroft, 2009). This strategy is usually called "top-down approach", "predict-then-act", "model or impacts-first", "science first" or "standard approach". The top down approach requires the analysis of the regional and local climate models, starting from the expected climate scenarios and then estimated the impacts of climate change and their costs. Although this is the most widely represented approach within the scientific evidence reviewed by the IPCC, there are few tangible examples of anticipatory or planned adaptation decisions developed thanks to this process (Wilby and Dessai, 2010). This is because the presence of uncertainty hampers the process and makes the definition of an adaptation policy tricky. The other possibility is focusing on local resilience and sustainability with the aim to reduce the overall risk in a highly uncertain context (Adger, 2006), without relying on a detailed impact analysis. This is alternatively called "assess-risk-of-policy", "context-first", "decision-scaling", "bottom-up", "vulnerability and tipping point", "critical threshold" or "policy-first". In this framework the information providers or climate researchers should work closely with decision-makers, with the aim to understand their goals and objectives, updating the shape of the intervention with the new evidence about the climate change effects (IPCC, 2014). The term "bottom-up" is used because the decision-making process starts with the analysis of the local factors and conditions that enable successful coping with climate related threats at the level of individuals, households and communities. A set of no-regret or low-regret measures are usually identified in this framework, helping the local communities to increase their resilience to climate change, regardless of a detailed and comprehensive analysis on the climate scenarios and impacts.

These two strategies are differentiated but not mutually exclusive. The practice in the adaptation experience is indeed uneven and multifaceted, with weak boundaries between these two main frameworks. The evidence shows that the bottom-up strategies usually work on the dimensions which do not strictly depend on the future intensity of the climate changes and that can be changed over time according to the modifications of the climate. Whereas the top-down approach is basically more suited at shaping adaptation measures or climate related decisions which have high sunk costs, so difficult to be modified in the future, and long-term effects (the size of a dam, the planting of a perennial crop).

Moreover, according to Markandya (2014), in projects where climate change is one of the dimensions of the evaluation (e.g. the building of a new motorway), the uncertainty can be treated with common risk management techniques (i.e. sensitivity analysis); whereas in projects where climate change is the main issue and possibly the reason for implementing the policy, a robust approach is needed, focusing on three instruments: considering robust measures (measures which are suitable for diverse scenarios), building flexibility into adaptation measures (measures easily modifiable depending on the pattern of the climate), including flexibility in the decision process (iterative process – adaptation pathways).

Robustness, flexibility and iterative processes are elements highly recurring in the adaptation context. They are essential components of the new approaches in the decision-making processes, which converge on two main concepts: Adaptive Management (AM) and Adaptation Pathways (AP). The first is an established approach that uses a monitoring, research, evaluation and learning process (cycle) to improve future management strategies. It is known also as Iterative Risk Management (IRM). The other approach, sometimes called Route Maps framework, refers to the strategy of planning long-term alternative patterns of policies, characterised by tipping points and decision nodes where a new policy has to be chosen due to the loss of efficacy of the current one. This is fundamentally a way of anticipatory long-term planning, which identifies the sell-by-date of the policies and the related new opportunities, with the aim to avoid lock-ins and unexpected constraints. These two techniques are widespread in designing climate change adaptation policies and they are heterogeneously declined in various particular experiences, in a confusing epistemic framework. Besides these new decision-making processes, there are also economic tools which are designed to face the climate change uncertainty. The use of these instruments can be considered as a stand-alone solution for helping the public administration in selecting the most economic efficient measures or they can be integrated inside the decision-making processes informing the different decisions that have to be taken in the various steps of the decision framework.

In the next paragraph, these decision-making processes will be described firstly, then the most used decision support tools will be analysed, leaving to the next chapter the detailed discussion on the Modern Portfolio Theory, the instrument tested in the case studies section.

2.1.1 Dealing with uncertainty through robust, flexible and iterative decision-making processes

The landscape of the new public decision-making processes developed and experimented for the adaptation planning and for the implementation of adaptation measures is widespread and complicated. The fundamental issue is that choosing a unique optimal measure with a single decision in the present based on fixed climate conditions is no longer effective and it can lead to an inefficient use of economic and social resources. Thus, the new institutional processes should now consider a plurality of possible futures, engaging the stakeholders in designing flexible policies, easily to adjust according to the evolution of the key climate dimensions. This simple concept is the basis of a plurality of methods and approaches that can be summarised in two main strategies: i) developing an iterative process which is made by continuous sequences of design, implementation, monitoring and (eventual) modification of the policy; ii) producing an anticipated pathway of possible measures which evolves according to the occurrence of some threshold.

The first approach is usually called Iterative Risk Management - IRM (otherwise Adaptive Management – AM, or Adaptive Policy-Making – APM). We interchangeably use IRM and AM in this dissertation. The Iterative Risk Management is an established approach that uses a monitoring, research, evaluation and learning process (cycle) to improve future management strategies. IRM is based on the idea that current decisions are fundamentally limited by imperfect knowledge and cognitive bias, and cycles of revisions are thus necessary to improve the performances of the selected interventions. Iterative Risk Management is deeply connected with the concept of resilience, which is based on the capacity to learn from the experiences and willingness to address specific system failures.

IPCC (2013) defines Adaptive Management as "*a structured process for improving management policies and practices by systemic learning from the outcomes of implemented strategies, and by taking into account changes in external factors in a proactive manner*"; whereas, Polansky et al. (2011) identify Adaptive Management as "*an iterative decision-making process under uncertainty that is designed to learn and incorporate new information and thereby improve future decision-making*". In the glossary of the AR5 IPCC report (2014), Iterative Risk Management is instead presented as "*a process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables*". ECONADAPT project (2016) states that the process of anticipating and responding to climate change does not constitute a single set of judgments at some point in time, but rather an ongoing assessment, action, reassessment, and response that will continue – in the case of many climate-related decisions – indefinitely. IRM is based on this assumption and it incorporates learning at the core of its methodology.

There are various applications of IRM/AM methodology, therefore it is complicated to identify a straightforward sequence of steps and tasks. Generally speaking, the approach is flexible, it gives the possibility to change strategy according to the changing circumstances and it can be applied to projects or sector analysis. It is most relevant for medium-long-term strategies where there is a potential to learn and react. The key advantage of IRM is that rather than taking an irreversible decision now - which may or may not be needed depending on how climate change evolves - it encourages decision-makers to ask "what if" and develop a flexible approach, where decisions are adjusted over time with evidence (Reeder and Ranger, 2011). This helps ensure the right decisions are taken at the right time. Benefits can be expressed in physical terms; therefore, it does not require monetary valuation. This aspect increases the applicability to non-market sectors. It can be applied where uncertainty is high, e.g. where probabilistic information is low or missing.

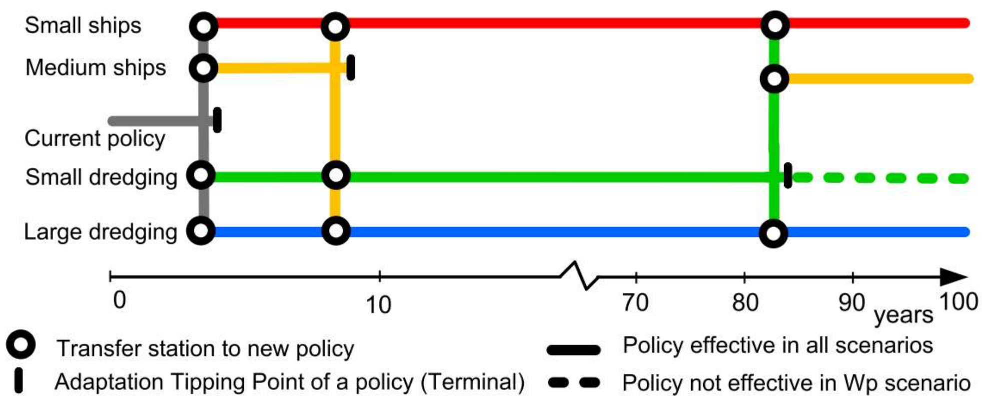
IRM methodology usually starts with the reduction of the current vulnerabilities and the adaptation deficit, searching and facing the most urgent threats of climate change for the present society. Thus, IRM firstly attempts to empower the adaptive capacity of the selected community, implementing low and no-regret options. Then, it identifies areas of long-term concern that requires early investigation or action. Iterative Risk Management is the recommended solution in the case of high uncertainty, long timeframes, opportunity to learn over time and possibility of modifications in both the climate and the socio-economic dimensions. Decision-makers, under adaptive management, are expected to be flexible in their approach, and accept new information as it become available, or when new challenges emerge, and not be rigid in their responses (IPCC, 2013). IRM has been applied several times at local and regional level, whereas there are few examples of the practice of this methodology at national level. There is a prevalence of ecosystem management and disaster risk management projects. IPCC (2013) states that a complex dimension of the IRM/AM method is the definition of an effective procedure to integrate the information progressively learned by scientists and engineers. Watkiss et al (2014) state that a limit of the approach regards the identification of suitable risk thresholds, in cases where there are multiple risks acting together, under different scenarios and threshold assumptions.

Tompkins et al (2008) present an interesting case study about the integration of Adaptive Management into the disaster risk management of the Cayman Islands. The adaptive governance of the risks generated by hurricanes was effective in 2004 for the management of the hurricane Iva, which only caused two fatalities even though it was similar in magnitude to hurricane Katrina that hit New Orleans in 2005. The National Hurricane Committee (NHC) is the learning-based organization which is responsible for the effective management of these risks. It learns from its successes, but more importantly from mistakes made. Each year the disaster managers actively assess the previous year's risk management successes and failures. Every year the National Hurricane Plan is revised to incorporate this learning and to ensure that good practices are institutionalised. Evidence of adaptive governance can be observed, for example, in the changing composition of the NHC, its structure, network arrangements, funding allocation, and responsibilities.

The approach used in the development of the Thames Estuary 2100 project (TE2100) collects some elements of the Iterative Risk Management framework (Ranger et al., 2013). It is one of the first major infrastructure projects to explicitly recognise and address the issue of the deep uncertainty in climate projections throughout the planning process. The method is defined as "dynamic robustness" (Ranger et al., 2013), a process based on flexible strategies that can change according to the new information learnt and the modifications of the climatic conditions. This strategy combined four key elements: i) a "decision centric" process; ii) the combination of numerical models and expert judgment to develop narrative sea level rise scenarios; iii) the adoption of an "Adaptation Pathways" approach to identify the timing and the sequencing of possible pathways of adaptation measures over time under different scenarios; and iv) the development of a monitoring framework that triggers defined decision points.

The Adaptation Pathways approach represents another opportunity for planning adaptation measures (Haasnoot et al, 2012; Haasnoot et al, 2013). This is a method experimented in a case study located in the Rhine Delta in the Netherlands at it is characterised by the anticipated definition of a decision tree (Figure 2.2) with various possible pathways that are made by different adaptation tipping points. These are the points where a particular action is no longer adequate for meeting the plan's objectives and a new measure is therefore needed. There are various possible pathways, which are presented like a metro map and the policy-maker can shift from one to another when an adaptation tipping point (a node) is reached. Therefore, there is not just one possible pattern of policies, but a plurality of pathways characterized by different combinations of measures, with their own relative costs, target effects and side effects. The concept of the iterative decision-making is sometimes embedded in the Adaptation Pathways approach.

Figure 2.2: Adaptation pathway map



Source: Haasnoot et al, 2012

Siebentritt and Stafford Smith (2016), in their Users Guide to Applied Adaptation Pathways, define 6 steps for the implementation of an Adaptation Pathways process. Firstly, the scope and the key area of the decision making should be defined – the area and the objective considered could stem from a general regional plan, which considers various targets in different policy sectors, to a site-specific adaptation plan, considering the opportunity to make a big infrastructure investment (e.g. a dike or a bridge). Then, the fundamental and specific impacts of climate change should be assessed, and the local vulnerabilities should be estimated. The second step regards the analysis of the main limitations of the current practices, assessing the needs for an adaptation policy. In this step the engagement of the stakeholder is essential, also in the attempt to imagine the shape of new possible practices. The third step requires the discussion of triggers and thresholds of the system. A trigger is the point where a reaction and a new response has to be taken. A threshold is defined as a point at which a system starts to operate in a significantly different way. An example coming from the User's Guide: "*sea level rise might reach a point where a large storm could destroy infrastructure, even if this has not actually occurred; the threshold would be the actual failure of that infrastructure, which is a real change in system function; the trigger is the sea level rise reaching a level at which a decision needs to be made, even though it may not yet have resulted in the threshold actually being crossed*". In the fourth phase the adaptation options must be identified, starting from current measures which could eventually be modified. The timing of the options has to be defined, deciding which ones should be implemented first and which ones later and a use-by-date of the different measures could be determined, identifying when the options are no longer effective due to climate change. The definition of the main responsibilities for the implementation of the measures is essential. The fifth step aims at the development of a draft of the adaptation pathway map, which is composed of two axes: a) the x axis, where the time of the review of the process or the steps of the climate change must be shown (usually time series of 5/10 years or, for example, the rising of the sea level, e.g. 10cm, 20cm, 30cm); b) the y axis, with the list of the adaptation options identified in the previous step. The adaptation options should be organised starting from the current practice until the options that are currently ruled out. Each option is characterised by a line, parallel to the x axis. Each line starts when the option is activated, therefore the current adaptation measures should start at the time 0 and should continue until the use-by-date is reached. The options that are delayed but require preparatory work should be initially represented in a lighter colour. The line can be continuous if the measure is absolutely useful for reaching the adaptation targets, whereas it can also be dashed if the option contributes to the adaptation process but only in part. When a new measure is needed, requiring a modification of the previous policy, a decision node has to be settled. Decision points are represented by circles located over existing lines that relate to each adaptation option. The decision nodes usually emerge in connection with particular thresholds or a regular review point in a planning cycle (e.g. every ten years). The sixth step regards the sharing of the adaptation pathway draft with the stakeholders, in the attempt to verify the coherence of the pattern defined and with the aim to discuss the preferred pathways of the different actors and perspectives. A coloured line can be used to show the chosen pathway. In the last phase, there is the possibility to merge the different pathways eventually produced by diverse sectors, identifying a unique, cross-sectoral, adaptation pathways map.

The approach developed by Haasnoot et al (2013) instead combines this basic procedure for the definition of adaptation pathways with the adaptive policy making approach. Their approach is divided into 9 steps which are similar to the classic steps of the Adaptation Pathways theory but, at the same time, they include also elements coming from the Adaptive Management literature. The method entails the identification, in advance, of actions which can help to manage future failures, preparing actions that can be triggered later according to possible negative events and developing a monitoring system that can regularly check the effectiveness of the project and the necessity to implement the contingency actions. The Rhine Delta pathway proposed by Haasnoot et al (2013) starts in the middle of the scheme, where the current policy is placed, representing the initial conditions of the system. Then the measures for the supply and for the demand are grouped separately, putting the more expensive and harder measures on the upper and lower extremes of the scheme and the no-regret options closer to the current policies. It is also suggested to keep the scope of the adaptation pathway as simple as possible, trying to avoid a spreading on different goals. The more the final scope of the plan is narrow and straightforward the easier it is to make a good adaptation pathway. Another interesting consideration is about the adaptation measures. The measures should be previously classified with a matrix, defining their effectiveness and describing their costs and benefits. Measures can also be considered in portfolios. Another important step is the selection of the preferred pathways. As proposed in the Users' Guide (2016), the stakeholder engagement is a key resource also here. Once the pathways are defined, both public and private stakeholders should be engaged in order to select the best sequences of measures for their own perspectives. It could be interesting to identify different preferred pathways, underlying the views of different actors, from the citizens, to the public government and the private companies.

Again relevant concepts of the Adaptation Pathways literature return: the trigger points (the points in time at which the measures have to be implemented, according to new conditions); the sell-by-date of an adaptation option (the moment where the adaptation action is no longer useful and suitable for the current climate and socio-economic framework); the decision nodes (moments in the future where the decision-makers have to take a decision about new available pathways to follow).

Another important analysis of the Adaptation Pathways framework has been made by Zandvoort et al. (2017). This article compares four initiatives of adaptation pathways in different countries and institutional contexts. Here, four fundamental steps are considered in the development of the adaptation pathways: i) setting the objectives, performance metrics and related threshold values, in an attempt to identify objective based thresholds; ii) assessing adaptation tipping points for the current policies or management situations, based on thresholds under different scenarios, with the aim of tackling uncertainty; iii) exploring and selecting policy responses and assessing their adaptation tipping points; iv) combining the different responses into sequences of alternative pathways, assessing the costs and benefits and selecting the preferred pathway considering multiple decision criteria. An effective monitoring scheme should be settled to collect information for early warning signals (triggers) to alter or adjust (i.e. advance or postpone) policy responses.

Four case studies are presented in the paper:

- The Ijsselmeer area. It is an estuary dammed and separated from the Wadden Sea, which became the biggest lake in Holland. It is essential for the flood safety and for the delivery of fresh water, especially for agriculture. The objectives of the pathway were to sustain long-term flood safety and the regional water supply. The pathway for this area was built on the measures and risks presented in the Delta Program (a program for the management of water in The Netherlands) and the pathway was used to assess the possible evolution of the current options and to communicate them to the non-governmental stakeholders.

- The management of the coast in the area of the municipality of Ilhavo and Vagos in Portugal. It is a highly vulnerable stretch of a low-lying dune barrier, particularly exposed to costal erosion, storm surges and flood risks. According to the range of interests and responsibilities over the management of this area, the pathways were developed thanks to a large engagement of public and private stakeholders (based on the Scenario Workshops method). There was no predefined objective and during the first workshop two main goals were identified: the preservation of the food safety and the empowerment of the local economy preserving the sandy beach. The adaptation measures were selected by another workshop and were then analysed by a multi-criteria study before the generation of different pathways. Different groups, with different aims and perspectives, developed several distinct pathways and then the pathways were grouped and harmonized (in collaboration with local stakeholders).

- The city of Prague. In district 6 there were several redevelopments of the area. The effects of these changes and the aim to lower the Urban Heat Island were the main reasons for the development of the adaptation pathway. UHI tools were used, pathways and mapping of stakeholder' preferences with workshops. Nevertheless, the paper states that the development of a coherent and effective process was complex and incomplete due to the lack of information about the effects of different planning measures on the UHI.

- The city of Rotterdam area. The adaptation pathways were used to define a strategy for the long-term management of the floods. The pathways were managed by the regional government of the area and the framework was defined by the local Delta Programme. Due to the complexity of the issue, there were difficulties in assessing the adaptation measures, but the engagement of the stakeholders gave useful elements and a unique adaptation pathway was developed at the end.

The paper analyses the most important elements that emerge from the comparison of these experiences. The geographic scale of the pathway influences the complexity of the pathway, the sectors considered, and the amount and type of stakeholders involved. The selection process of the measures is important too, since it influences the structure of the pathway and the need for specific indicators. Therefore, there are essential choices that have decisive effects on the development and the success of the adaptation pathways. There are other elements which influence the efficacy of the process: i) the variety of stakeholders engaged and the structure of the process (top-down/bottom-up); ii) the planning culture; iii) the different framing of objectives and uncertainty. Similarly, to the previous experiences analysed here, the paper considers essential the framing of the tipping points and the lock-ins of the adaptation measures.

Barnett et al. (2014) present another adaptation pathway experience, here focused on the management of coastal areas. They state that the development of adaptation strategies for coastal sea rising is demanding for local governments, because building consensus around the adaptation measures is complex. The adaptation pathways could help in facing this impasse in the decision-making process. Adaptation is again considered as a process to be managed over time, driven by key steps called adaptation tipping points, conditions where the adaptation measures stop to be effective and new measures become necessary. The case study is about a little coastal town in Australia, a small community where an effective engagement of the citizens is feasible and fruitful. It is interesting because many of the most famous examples of adaptation pathways are instead referred to large and complex sites. There are two important findings in this experience: ii) they have developed thresholds and triggers based on social impacts that are salient for local people, instead of just focused on environmental conditions; ii) they have actively engaged the local community through interviews about what they hold dear of the city. As a matter of fact, people initially did not care about climate change and its impacts. But then, when the project asked them which are the places and the key elements of the city that hold a social value for them, they identified concrete and precise locations, helping the adaptation process in focusing on the most significant impacts for the community and improving the awareness of the population about the climate change effects. Barnett et al (2014) state: "*The approach we developed was readily understood by, and appealed to, local residents and decision-makers for the following reasons: it is simple (at least relative to other pathways that entail complex sets of options for future action); it creates the time and space for building collective action; it is flexible in the light of new information, technologies, and social and environmental conditions; it accommodates diverse lived values; and it distributes responsibility for decision-making and the costs and benefits of decisions across generations*".

Another interesting example of the application of the adaptation pathway methodology was developed in New York City in 2012 (Rosenzweig and Solecki, 2014). The process started in 2008, when the first city panel on climate change was organized, and it brought to the definition of a flexible adaptation pathway approach. This strategy merged two main concepts: resiliency, focusing on recovery skills; and dynamic robustness, identifying short term actions to reduce risk iteratively, inside a framework to guide future actions in an attempt to create flexible interventions. A set of indicators and a monitoring scheme every three years was designed and a cooperation between local stakeholders and the scientific community was settled, with the aim to inform the city on the most recent and affordable climate information.

2.1.2 Decision support tools

Besides the development of these new public decision processes, a complex framework of decision support tools and decision criteria have been developed in the scientific literature. The landscape of these tools is wide and uneven and in some cases these instruments are associated or developed in synergy with the decision processes discussed in the previous paragraph. This is why the distinctions between processes and tools are sometimes narrow.

These new tools are fundamentally an update of the more traditional tools, as the cost-benefit analysis or the multi-criteria assessment, and they have been used in the attempt to deal with the uncertainty posed by climate change. Usually, in the decision theory framework, probabilities help decision-makers and researchers in measuring the risk and taking rational decisions also in an uncertain context. However, because of the presence of uncertainty about the climate change impacts and the benefits of adaptation, probabilities may be bounded, and decision-makers need other instruments for setting the right shape and timing of their investments (Polansky et al, 2011; Dittrich et al, 2016).

In this section of this dissertation, a literature review of this new instruments will be presented.

2.1.2.1 Robust decision making

The concept of Robust Decision Making (RDM) is not new and it has been used in different variants, but it is fundamentally linked to the RAND Corporation (Lempert et al., 2003), a non-partisan think-tank whose original focus was national security. RDM was initially designed for decision-making in poorly characterised uncertain contexts with a subsequent application to climate change adaptation (Lempert, et al 2006). RDM involves testing strategies across a large number of plausible futures. A key aim is therefore to help take robust decisions today, despite imperfect and uncertain information about the future (Watkiss et al., 2015). RDM conducts an iterative vulnerability-and-response-option analysis by running computer simulation models multiple times, using the resulting database of model results to characterize the vulnerabilities of proposed strategies, identify ways to ameliorate those vulnerabilities, and evaluate the trade-offs among potential new strategies (Lempert and Groves, 2010).

RDM uses decision criteria based on robustness rather than optimality. A decision analysis based on the optimality criteria usually identifies a probability distribution for the expected futures and then it designs one best solution according to this prediction. On the contrary, the RDM method follows an “agree-on-decisions” approach, which inverts these steps. RDM begins with one or more political strategies under consideration, uses models and data to evaluate the performances of the policies over a wide range of plausible paths into the future, and then utilises the information in the resulting database of runs to characterize vulnerabilities of the proposed strategies and to identify and evaluate potential responses to those vulnerabilities. Thus, this approach seeks to expand the range of futures and alternatives considered and, rather than provide a prescriptive ranking of options, often seek to present trade-offs among not-unreasonable choices (Lempert, 2019).

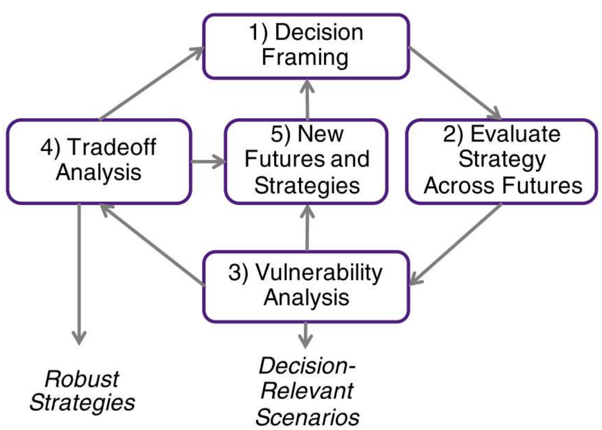
Another pillar element of the RDM approach is the Assumption-Based Planning (ABP), a methodology originally developed to help the US Army in adjusting its plans in the aftermath of the Cold War. ABP requires the decision-maker to write its management plans, identifying the load-bearing assumptions that justify the shape of the intervention planned. Planners can then judge which of these load-bearing assumptions are vulnerable, i.e. it might fail during the lifetime of the plan. After the identification of the vulnerable, load-bearing assumptions, ABP considers shaping actions (those designed to make assumptions less likely to fail), hedging actions (those that can be taken if assumptions begin to fail), and signposts (trends and events to monitor in order to detect whether any assumptions are failing).

A third key characteristic of the RDM methodology is the use of scenarios (i.e. projected futures that claim less confidence than probabilistic forecasts) instead of a unique commonly agreed future (Lempert, 2019). A set of scenarios seeks to represent different ways of looking at the world without an explicit ranking of relative likelihoods (Wack, 1985). In the case studies presented in this work, the scenarios considered are not just related to possible future climate conditions, but actually they describe different possibilities for the evolution of other important parameters like the socio-economic dimensions and the demographic ones.

RDM integrates these three concepts (Decision analysis based on an "agree-on-decisions" approach, Assumption-Based Planning and scenarios), through the Explanatory Modelling (EM). This is a computer program that analyses different assumptions about the future and shows their consequences without privileging one set of assumptions over another (working differently from the usual systems, that collect information about the likelihood of various happenings and dimensions in the future and create a unique, validated, view of the future). Exploratory models are useful when no single model can be validated because of missing data, inadequate or competing theories, or an irreducibly uncertain future. RDM requires a multiple interaction between humans and computers, where analysts check the information and proposals designed by the programs and vice-versa.

RDM is based on diverse steps, differently characterised by the various scientific literature conceptualisations (Lempert and Groves, 2010; Lempert, 2013; Lempert, 2019). In this work the Lampert (2019) is chosen (Lempert, 2019), and its five main stages are here described.

Figure 2.3: Stages in a Robust Decision-Making Analysis



Source: Lampert, 2019

i) Firstly, the problem is structured and the stakeholders have to jointly define the key factors of the analysis: the decision-makers' objectives and criteria; the alternative actions they can take to pursue those objectives; the uncertainties that may affect the connections between actions and consequences; and the relationships between actions, uncertainties, and objectives. The strategies are identified, considering the original policy or some new solutions coming from the engagement of the public or private stakeholders. Besides these intervention plans, the uncertain future scenarios have to be identified, in order to have a series of possible evolutions of the most fundamental variables characterising the context and the policy. In the case study described by Lempert and Groves

(2010), regarding the water management plan in the Western US, both the climate scenarios and the socio-economic development scenarios were produced, thanks to simulation models. These models are used to create large ensembles (thousands or millions of runs) of multiple plausible future scenarios without assuming a likelihood of the different scenarios. The costs and benefits of different strategies are determined with the use of a value function.

ii) Then, the strategies are tested in the different scenarios designed, according to the variables identified as significant for the efficacy of the policies. For example, Lempert (2019) proposes an explanatory case study regarding technological subsidies in facing greenhouse gas emissions reductions and he designed a model which had thirty input parameters representing the deeply uncertain factors, including the macroeconomic effects of potentially distortionary taxes and subsidies on economic growth, the microeconomic preferences that agents use to make technology adoption decisions, the future costs and performances of high (e.g. coal), low (e.g. gas), and non-emitting (e.g. solar) technologies, the way information about new technologies flows through agent networks, and the impacts of climate change. He runs the different combinations of taxes and subsidies for technological improvements considering all these uncertain parameters and the possible combinations among them. A database collecting the performances of the different strategies in the various scenarios is here produced.

iii) Thanks to this information, the performances of the selected strategies are analysed in the multiple scenarios and the characteristics of the futures in which the policies fail or succeed are grouped, identifying the most decisive variables. Commonly, RDM analyses use statistical Scenario Discovery (SD) algorithms to identify and display for users the key factors that best distinguish futures in which proposed strategies meet or miss their goals.

iv) In the fourth step, analysts and decision-makers may use these data and materials to display and evaluate the trade-offs among strategies. The aim is to present strengths and weaknesses of the proposed interventions rather than providing a unique order of preferred options.

v) Analysts and decision-makers can then use the scenarios and trade-off analyses to identify and evaluate potentially more robust strategies, ones that provide better trade-offs than the existing alternatives. Moreover, they can also propose solutions and adjusting interventions with the aim to face the vulnerabilities of the strategies proposed, in order to reduce the possibilities that the policy will fail or lose efficacy in the future. The key principle of RDM is that "*a strategy which perform well under a plurality of possible future scenarios is usually preferred over a strategy that performs optimally under expected conditions*" (Lempert and Groves, 2010).

Although the strengths of this approach are significant, RDM has some limits too, basically due to the need of a vast amount of information and technical skills. This methodology is indeed usually considered data and resource intensive. The development of the simulation models, the metrics, the acceptable risks, the benchmark for testing the strategies, as well as plausible scenarios and their upper and lower bounds need to be clearly defined (Dittrich et al, 2016). These steps require both an important engagement of the local stakeholders, analytical skills of the consultancy responsible for the study and the use of affordable and powerful computer programs. These ICT tools run highly complex models and test big numbers of possible futures and interacting parameters, producing a database of technical information that the analysts should handle for the description of the characteristics of the strategies proposed.

Other considerations come from the experiences presented in literature. Lempert and Groves (2010) use RDM to analyse the performance of the ongoing water management plans of the Inland Empire Utilities Agency, the water services management organisation of South California. They engaged the agency's stakeholders and decision-makers in a series of workshops aimed at identifying the scope of the plan, the performance metrics to be used in the evaluation and the main possible risks and uncertainties in the realization of the strategy. Then they develop a Water Evaluation and Planning (WEAP) simulation model, outlining the functioning of the observed water management system, through which it assesses the performances of the plan over a multitude of possible scenarios. The WEAP model differs from many conventional water planning tools because it is specifically designed to evaluate the performance of a variety of different types of management strategies under numerous scenarios. Thus, six key uncertainties, dangerous for the realization of the plan, have been selected and added to the main plan identifying other possible adaptive strategies.

Table 2.1: The uncertainties considered in the simulation model

Uncertain key factors	Representation within WEAP model
Future climate key factors	450 sequences of monthly temperature and precipitation reflecting trends in temperature −0.4 °C to +2.75 °C and precipitation from −27% to +19% over 30 years.
Future water demand	Water intensity of new development ranging from 0 to 30% more efficient than existing housing stock
Impact of climate change on imported supplies	Range of maximum climate change-induced declines in imported supplies between 30% and 50%
Response of groundwater basin to urbanization and changes in precipitation patterns	Change in percentage of precipitation that percolates into the groundwater basin (e.g. runoff) from 0% to 10%
Achievement of management strategies	Delay in recycling program achievement between 0 and 10 years Achievement in groundwater replenishment goals between 80% and 100%
Future costs	Annual cost increases in imported supplies between 2.5% and 8% Annual cost increases in efficiency achievement between 2.5% and 8%

Source: Lempert and Groves, 2010

Then, they used a modelling software to run 450 designed futures (as a combination of the six uncertainties previously mentioned) and to evaluate the strategies over these different conditions. They demonstrate that the current water management plan will be likely to perform poorly and lead to high shortages and water provisioning costs just under the simultaneous concurrence of three specific conditions (among the six uncertainties tested): i) large declines in precipitations, ii) larger-than-expected impacts of climate change on the availability of imported supplies, and iii) reductions in percolation of precipitations into the region's groundwater basin. In all the other combinations of the uncertainties, the original plan will perform well. However, in order to reduce the uncertainties connected to the plan, they suggest some robust measures: expanding the size of one of the groundwater banking programs, implementing its recycling program, monitoring the region's supply and demand balance, and assigning additional economic resources in efficiency and storm-water capture. Lempert and Groves (2010), state that, according to the findings of their work, the adaptive strategies, those that are explicitly designed to evolve over time in response to new information, can have a significant impact in reducing the effects of the uncertain climate changes. However, they recognise that the Metropolitan Water District of South California have difficulties in implementing such strategies, even if it always had strong skills and economic resources for the definition of effective strategies, being one of the world's most sophisticated water management agencies.

Another RDM example focused on the water management is the one proposed by Dessai and Hulme (2007), who try to verify the robustness of a Water Resource Plan in the East of England. They produce sensitivity analyses for particular uncertain parameters of the climate change, as the emission scenarios, the climate sensitivity, the aerosol forcing, the regional climate response and the ocean diffusivity. Although they have tested these uncertainties separately, the current management plan appears to be robust to every parameter considered. Grove and Sharon (2013) present a case study focused on the evaluation of the Louisiana 2012 Comprehensive Master Plan for a Sustainable Coast. The Master Plan defines a set of coastal risk-reduction and restoration projects to be implemented in the attempt to reduce hurricane flood risk to coastal communities and restore the Louisiana coast. In another example, the RAND Corporation has been commissioned to conduct an independent study about the management of the Colorado River in an uncertain climate changes context (Groves and Sharon, 2013). The basin is already stressed by a high human demand and drought periods and climate changes are projected to bring additional challenges, exacerbated by the uncertainty connected to the climate forecasts (although the shortages are projected to increase, some studies predict a decline of the precipitations of up to 15% over the next 50 years, while others forecast an increase up to 11% over that time). Thus, RAND researchers applied the RDM approach, working on four main tasks: i) identified future vulnerable conditions that could lead to imbalances that could cause the Basin to be unable to meet its water delivery objectives; ii) developed a computer-based tool to define "portfolios" of management options reflecting different strategies for reducing Basin imbalances; iii) helped evaluate these portfolios across a range of simulated future scenarios to determine how much they could improve Basin outcomes; iv) analysed the results from the system simulations to identify key trade-offs among the portfolios. Like other RDM studies, this is the leading question of the analysis: under which futures does the Basin not meet water delivery objectives, and what future external conditions lead to vulnerabilities? This inquiry leads the analysts and the decision-makers to understand and discuss the effects of the different possible futures on the management strategies and how to tackle the identified vulnerabilities.

A last case study regards the flood risk management in Ho Chi Minh City, in Vietnam (Lempert et al, 2013). This is a low-lying and fast-growing metropolis of 7.4 million inhabitants, with significant and growing flood risk. Over the last fifteen years, the city has developed a series of infrastructures in the attempt to face the increasing inundations, investing billions of dollars and developing 6,000 km of canals and pipes to increase the discharge capacity of the storm water system and 172 km of dikes and river barriers for tidal control. However, these sizeable investments have been developed considering just one expected future, as produced by the scientific analysis at the time. Now the projections are more accurate but there is still no possibility that a unique prediction can precisely describe what will be before of the following decades, due to the unpredictability of the climate changes and of some socio-economic parameters. This is why they have used RDM to suggest alternative management plans, testing them among a plurality of possible futures or external conditions. As the previous RDM examples, even in this case study, the methodology has been particularly helpful in identifying the possible weaknesses and vulnerabilities of the flood management measures available, understanding and arguing with the decision-makers the key future climate conditions that will compromise the diverse strategies.

2.1.2.2 Real option analysis

Real Option Analysis (ROA), an instrument able to value flexibility (Dixit and Pindyck, 1994), originally comes from the finance world (Merton, 1973; Watkiss et al, 2014). A financial option gives the right, not the obligation, to buy financial assets in the future. Thanks to this option, an investor can wait for more information about the evolution of the financial market, deciding later to buy or not to buy the asset (IMPRESSIONS project D5.1, 2015). Therefore, the risk is transferred from the buyer to the seller and the buyer will pay something more with the aim of being free from risk. Thanks to this instrument the decision-maker can estimate if the benefits of waiting are better than the cost of delaying the investment. This tool has been extensively used in the energy sector and mitigation policy contexts, but it would be useful also in the adaptation framework.

The issue of the option value originated with the seminal paper by Krutilla (1967) who presented some thoughts about the value of natural environment and the importance of conservation activities. He stated that technology can slow the rate of consumption of natural resources but it cannot recreate a deteriorated natural area which has been destroyed by the human activities. Natural amenities are unique, they cannot be substituted by other similar assets and the modifications to these assets are usually irreversible. Furthermore, he emphasized the growing utility of natural environment in the future. There is a learning by doing process by which people experiment the possibilities provided by a natural area and then the heirs will more probably increase the time spent in this area and they will attribute a wider value to these activities (even because the natural amenities are expected to be scarcer). Therefore, the value attributed to these assets in the future is still unknown and it is difficult to be forecasted. The uncertainty about the value of the environment in the future is particularly significant in the case of pharmaceutical purposes. Many drugs are based on plants and various natural components and many of these scientific principles have not been yet discovered. Therefore, the expected increasing demand of the natural environment and the uncertainty about the rate of this increase should suggest a need of further conservation activities of the natural environment. “If consumption-saving behaviour is motivated also by the desire to leave an estate, some portion of the estate would need to be in assets which yield collective consumption goods of appreciating future value” (Krutilla 1967). This is why Krutilla introduced the issue of option demand. People want to preserve some natural environment for a future use. This value represents the willingness to pay for the future availability of an asset that is impossible to replace or for which no close substitute is available. This value is not referred just to the use of a particular natural area for recreation purpose, but it could regard the mere existence of the asset, regardless of the intention to use it. He mentioned the example of the WWF affiliation. People pay WWF for its work aimed at the preservation of the natural environment but they are not necessarily interested in visiting all these places.

The presence of an increasing demand of natural resources in the future generations has been discussed also by Fisher, Krutilla, Cicchetti (1972) who observed that the benefits of not developing an uncontaminated area appear to be increasing over time. The demand for recreation in wilderness area is going to be higher in the future, especially because the expected growth of the population and the increase of the per capita income, with extra income used by consumers in part to “purchase” more leisure for themselves (Fisher et al, 1972). This leisure is increasingly associated to natural environments because of the rising education levels, which usually increase the growth in demand of wilderness natural areas.

Option value is inevitably influenced by the scarcity of the natural asset, the uncertainty about its availability in the future, the uncertainty connected to the future demand connected to the risk aversion and to the preferences of the population interested in this asset. Pareglio (2007) summarise the dimensions which compose the total economic value of a natural resource or a particular natural environment. Option value and quasi-option value are an important part of the overall economic value. These parameters are influenced by several dimensions: i) the nature of the good (reversible or irreversible, replaceable or irreplaceable); ii) availability, actual and expected demand and uncertainty about these dimensions; iii) characteristics of the consumers (such as present and expected income, awareness level, risk attitude, ethical and moral beliefs). These dimensions influence the economic value of the option value and of the quasi-option value.

However, Arrow and Fisher stated (1974) that "the point about uncertainty, information, and irreversibility might be made still more generally, i.e., without reference to environmental effects. Essentially, the point is that the expected benefits of an irreversible decision should be adjusted to reflect the loss of options that the irreversible decision entails". Given the possibility to learn during time from experiences made, underinvestment can be remedied before the second period, whereas mistaken overinvestment cannot, and the consequences of the development made in the first period will persist in the future. Therefore, the presence of uncertainty leads to a reduction of the net benefits from an activity with irreversible environmental costs. However, the presence of an irreversible decision should not lead to underinvestment in any case, but the cost of irreversibility should be compared to the benefit of the investment, with the aim to assess the overall economic effect of the decision. Even the continuing cumulative production of (small quantity) pollution could be considered an irreversible effect, especially when a long time-frame is needed for removing the pollutant from the environment (such as in the case of carbon dioxide).

The problem could be analysed even with a different perspective. We wait to implement some irreversible decisions, because we are uncertain about the effects of these decisions and we want better information about the effects of these investments. Therefore, information has an economic value. The value of this information is the value of the acquired flexibility in the investment choice. This value should be compared with the cost of waiting. Investment should be undertaken only when the costs of deferring the project exceed the expected value of information gained by waiting. Uncertainty, because it increases the value of waiting for new information, retards the current rate of the investment (Bernanke, 1980). Kontogianni (et al 2014) state that the value of waiting for additional information depends on the extent to which the uncertainty affects the cash flows of climate adaptation investments, how far in the future the uncertain event is, and the likely quality of the information that will be gained by waiting.

One of the most common examples of the application of the ROA analysis in the climate change adaptation framework refers to the hypothetical construction of a dam. Assuming that an old dam should be replaced because it requires great refurbishments but there are big uncertainties about the future precipitations and floods intensity, there are basically three possible measures: i) continuing with a more frequent maintenance of the dam, waiting for better information about the future; ii) building a new flexible dike, which can be eventually raised in the future, when more precise information about the expected precipitation will be discovered; iii) building a taller dike, which have the capacity to manage even a massive increase in the heavy precipitations and consequent floods. This third solution might be useless if the worst-case scenario is not realised, presumably wasting significant economic resources, whereas a flood defence system that is constructed in an innovative way enabling increases in the level of protection to be readily achievable if it is required, is an example of embedding a real option. The option to raise the level of protection (e.g. raise the crest level) is purchased at the beginning, building a more flexible dike with bigger bases. The decision whether to exercise the option is delayed to a future date when more information about the future climate change impacts is known. Even the first option, the continuous maintenance, could be considered an option, thought it might be more expensive than building a new flexible dike and thus it might be a short-term solution, in the case the uncertainty about the future environmental conditions is expected to be resolved soon. The benefits of the flexibility gained through the continuous maintenance need to be considered with the potential increase in risk from poorly performing structures and the potential increase in maintenance costs as the structures deteriorates.

Therefore, the conversion of this approach in economic terms requires the comparison of the costs and benefits of each identified strategy along each possible climate scenario. In the case of flood risk management policies, the benefits represent the present value of the reduced flood risk in the analysed area over a long-term planning horizon due to the implementation of a specific policy, when compared to a "do nothing" scenario. Risk is usually defined in terms of the expected annual damage (EAD). Costs represent the present value of the total costs incurred over the same time period due to the implementation of the measures, the operation and maintenance costs. The multitude of the available strategies is frequently represented as a decision tree, with decision nodes in the future, where further investment decisions have to be made. The estimate of the costs and benefits has to be done for each pathway of measures of the tree and for each climate change scenario considered in the analysis. In the ROA there are no assumptions about the likelihood of the climate change scenarios, and everyone is considered equally likely.

ROA is effective when three key circumstances are present: i) the investment decision is irreversible, thus, there is no possibility to easily modify the measure when it has been realised (e.g. building a seawall); ii) there is the opportunity to develop the investment in more than one stage, in a flexible approach (e.g. developing a dike able to be raised in case of more severe precipitations); iii) the decision-maker has the opportunity to learn and to gain more information in the future (e.g. the knowledge about the natural mechanisms regulating the rise of the sea level). This approach is potentially useful in the economic analysis of major investment decisions, notably major flood defences, water storage systems or for justifying flexibility within major projects.

The "option" could also be seen as the value of the information (Boardman, 2018). Considering the previous example about the construction of a hypothetical dike, the investment in the complete highest dam will be recommended to the decision-maker if the amount of precipitation remains over a certain value. Due to the presence of climate change it is not possible to know the amount of the precipitation in the future, however by financing a scientific research, it will be possible to forecast this quantity exactly for the next fifty years (non-realistic assumption). The difference between the expected net present value of the dam with the current probabilities of each scenario and the expected net present value of the project with the affordable climate information represents the option value, the value of the information. If the meteorological research costs are under or equal this value, the investment in the research program is desirable. Information have values if they conduct to another decision. The value of waiting for better information will be higher if: i) the degree of uncertainty regarding the cost-effectiveness of the project is greater; ii) the duration of the period of waiting before information gained is shorter. The value of waiting needs to be balanced against the costs of waiting, because obviously, during the period of waiting, there will be no revenues and/or services coming from the project, compared with the scenario with the project. ROA, therefore, provides decision-makers with a new investment criterion that takes account of uncertainty. Projects should be realised if the difference between benefits and costs is positive and if the overall amount of production eventually lost in the case of waiting for better information is higher than the value of this information. ROA is therefore also helpful in analysing the evolution of the project in the various temporal stages, identifying the connections between the set of measures and the possible evolutions of the climate and the related environmental dimensions.

This instrument could be helpful in two ways: i) it can be effective in finding the right time-frame of an investment, integrating in the analysis the possibility to wait and learn in the future according to new and more precise information gained; ii) this tool can design the path of the policy response to the climate change impacts, showing the linkages between the different options and identifying the measures that should be developed firstly in the attempt to keep open the range of the solutions available. This second property is important in pursuing flexible measures and decision-making processes (IMPRESSIONS project D5.1, 2015).

In the European project ECONADAPT, a case study on the use of ROA for the management of flood risk in the Basque city of Bilbao is presented. The investment decision regards the modification of a part of the estuary of the Bilbao river, with the aim to reduce the economic values exposed to risk due to flooding. The expected damage is estimated considering a business-as-usual and scenarios with increasing impacts produced by climate change and socio-economic development (the economic value of exposed goods and services grows). Then a decision tree is developed, with two main goals: i) identifying different timing for the investments; ii) comparing the net present value of the damage in the case of an immediate investment and the ones in the case of the deferment of the flood defence measure. ROA is here described (Econadapt, 2015) as a highly complex tool, requiring a considerable amount of data and analytical skills. However, the decision trees can help to identify the decision nodes available, helping the understanding of the possible futures and the consequences of the different choices. In their opinion "*ROA is useful as a guide to some of the key parameters in the public sector decision-making for adaptation, but it is not really suitable for use as a standard tool that can be applied in a straightforward manner*".

Woodward et al (2014) apply the ROA approach in the context of flood risk management in the Thames Estuary area, under climate change uncertainty. Flood defences are gradually deteriorating, and climate change brings new challenges to the management strategies. Thus, they identify 79 possible measures and they group them into five groups according to defence characteristics and locations. Then, they imagined two different situations: i) one where there is no uncertainty and one optimal solution is recommended; ii) another more realistic situation when there is massive uncertainty about the future conditions and alternative flexible pathways could be defined in order to deal with the various futures. In the article, a decision tree is thus developed, defining possible chains of measures in two decision points (time 1, at the beginning, and time 2, after 50 years). The various pathways have been evaluated over one thousand of possible sea rise levels, with the aim to find the solutions which is more robust against all of these futures and to identify the best solutions to implement in each climate conditions and time.

Buurman et al (2013) illustrated an approach where Adaptation Pathways, Adaptive Policy Making and ROA are integrated for the development of drainage policies and measures to address flooding in Singapore. This is a low-lying, tropical and urbanised island, where climate change and urbanization are increasing the risk of flooding. Four main measures were identified and adaptation pathways were designed on the basis of six decision nodes. Some measures fail in satisfying the policy objectives at some time in the future and finally, 12 different pathways emerge from the analysis. For each branch of the decision tree the costs and benefits have been calculated. Then, a model was set up in which in each year there is a random chance of a flood event. The probability of flooding in each year increases over time due to climate change and can be reduced by the proposed measures. The investment and the maintenance costs and the benefits (avoided damage due to the measure) are discounted to the present, resulting in a net present value for each branch.

2.1.2.3 Portfolio analysis

Portfolio analysis is an instrument coming from the financial markets, with the aim of maximizing the return of an investment, with a particular level of risk acceptance (Watkiss et al, 2015). The key principle of this economic tool is that spreading the investment on different assets with diverse performances in the alternative possible scenarios can help in reducing the risk, making the return of this investment more robust (Markowitz, 1952). This decision tool starts with the assessment of the single adaptation options, using a Cost-Benefit Analysis for the evaluation of their expected net present values. Then, portfolios of different shares of the overall investment assigned at different adaptation measures are identified and their economic outcomes are estimated. Lastly, the performances of the portfolios are analysed focusing on their economic revenues and the variances of these results in the different scenarios. The portfolios are then presented on a graphic, identifying the efficient frontier, the curve which collects the best investment solutions, according to their correlation among net present values and variances. The decision-maker can then choose the preferred investment solution among the ones on the efficient frontier, according to her/his personal risk attitude.

This is the tool used in this research work and it will be carefully discussed in the next chapter.

2.1.2.4 Non-probabilistic approach – maximin decision rules and minimax regret

There are cases where the decision has to be taken in a context of complete ignorance, with no available judgment about the likelihood of a particular scenario. This research work has discussed the deep uncertainty of the climate change framework and the impossibility to assign probabilities to the future scenarios, hampering the classic decision-making processes. These decision criteria are used in these specific cases, ranking policies about their performances, without any judgment on the occurrence of a specific state of the world. These decision rules are called maxi-min and mini-max regret criterion.

2.1.2.4.1 Maxi-min criterion

The maximin decision rule ranks policies according to their worst performances, choosing the one with the best worst outcome (IPCC, 2014; Heal and Millner, 2014, Polansky et al, 2011). The maxi-min rule is the most conservative decision method and it suggests to the decision-maker the less risky choice. Anyway, this criteria judges just the worst outcomes, without considering the other possible performances and the correlation between them. This criterion has been criticised due to this functioning focused just on the worst outcome. Polansky et al (2011) present an example for this rule. There are three possible pollution control strategies and three possible impacts of the pollution, represented by three possible states: zero, low or high damage.

The choice of the policy with same probability assigned to each state

	Zero damage	Low damage	High damage
Stringent control	-9	-10	-11
Moderate control	-1	-5	-14
Lax control	0	-10	-30

The choice of the policy with maxi-min criterion

	Zero damage	Low damage	High damage
Stringent control	-9	-10	-11
Moderate control	-1	-5	-14
Lax control	0	-10	-30

If we assign the same probability to each state (1/3), the solution recommended would be the moderate control, because it would give an expected net benefit of -6.67, higher that the outcome of the other options, -10 and -13.33. However, if we decide to use the maximin criteria, because of the presence of deep uncertainty and the impossibility to assign likelihood to each scenario, the results will be different. The worst outcomes of each option are all in the high damage state and they respectively are -11, -14 and -30. Therefore, the first policy would be chosen, due to its best performance among the worst ones.

2.1.2.4.2 Mini-max regret criterion

The mini-max regret criterion has been proposed by Savage (1954). The aim of this criterion is to consider the regret of the options, that is the distance of the policy performance in each state with the best performance possible in that specific state considered. The maximum loss is found for each option and the one with the lower regret is chosen. Therefore, this decision rule is focused on the missed opportunities instead of on the worst outcome. Again, considering the previous example, the decision criterion is hereby used:

The choice of the policy with mini-max regret criterion

	Zero damage	Low damage	High damage
Stringent control	-9 – 0 = -9	-10 – (-5) = -5	-11 – (-11) = 0
Moderate control	-1 – 0 = - 1	-5 – (-5) = 0	-14 – (-11) = -3
Lax control	0 – 0 = 0	-10 – (-5) = -5	-30 – (-11) = -19

The worst regret of each policy is in the green square, whereas the chosen option is hooped in red.

2.1.3 Some considerations about the tools and processes presented

In this part of the dissertation a plurality of alternative decision-making processes and tools for the climate change adaptation policies has been presented. In the following paragraph, a brief comparison between these methods will be proposed, in the attempt to introduce some of their essential strengths and weaknesses, trying also to identify the contexts where these methodologies are more effective.

Iterative Risk Management. IRM is the recommended solution in the case of high uncertainty, long timeframes, where there is an opportunity to learn over time and a possibility of modifications in both the climate and the socio-economic dimensions. This strategy could be an effective way to start the adaptation process, facing the most urgent needs and identifying recurring moments in the coming years to integrate the scientific updates. The methodology assists the decision-maker in designing step-by-step adaptation strategies, instead of taking irreversible decisions at one single decision point. There is no single method, but various different applications of this decision process. This flexibility gives the opportunity to use this tool in various context and to integrate the process with other tools, such as the Cost-Benefit Analysis or the Multi-Criteria Analysis. Lastly, it could be particularly useful in context where there are not monetised benefits (e.g. management of ecosystems and biodiversity).

The methodology presents also some limits. The presence of a plurality of applications and different methods could be a confusing element, limiting the dissemination of this tool to another context. Furthermore, it requires the engagement of the public administration over multiple years, whereas the commitment of the administration might vary after elections or internal reorganizations. Thus, a long-term and binding commitment of the public administration is needed. Furthermore, it is challenging when there are multiple risks acting together. In the River Thames case study, there is basically a single risk threshold, i.e. the sea level rise, and the development of the adaptation measure is fundamentally connected to this key parameter. In other context the application of this method might be too complex. This is one of the reasons why IRM has been applied several times at local and regional level, whereas there are few examples of the practice of this methodology at national level. There is a prevalence of ecosystem management and disaster risk management projects, whereas the application of this tool to another framework is not common. IPCC (2013) states that a complex dimension of the IRM/AM method is the definition of an effective procedure to integrate the information progressively learned by scientists and engineers.

Adaptation Pathways. This approach has been used in various context and it has been often combined with the Iterative Risk Management methodology, creating a confusing framework where the identification of the two distinct approaches is quite complicated. However, the AP methodology is presented in various guidelines, with some key recurring steps. This well-defined structure could be helpful in the transfer of the method to various context. Various applications exist and the lessons learned in these case studies could be useful for an effective dissemination in other contexts. The Adaptation Pathways methodology has two relevant strengths: i) the definition of the pathways requires the decision-makers to imagine possible future long-term developments of their community and of the connected impacts of climate change, a milestone in designing an effective adaptation strategy; ii) it is a straightforward and engaging way to present a sequence of adaptation policies and of the possible effects of climate change. The metro map proposed by Haasnoot et al (2013) is a good example of the effectiveness of this representation. The adaptation pathways literature also introduces an interesting terminology about adaptation policies, such as the concepts of trigger points (the circumstances that require the implementation of a new adaptation policy), tipping points (the time when the adaptation measure is no more effective) and decision nodes (the time in future when the decision maker has to select a new intervention). Furthermore, this tool requires the engagement of a wide array of stakeholders, both public and private, with the goal to highlight the preferred pathway of each member of the target community. This stakeholder engagement has been a key issue of most of the case studies analysed in the previous paragraph.

However, there are also some limits to the application of this method. The adaptation pathways process is complicated and it is composed by a sequence of challenging tasks. It requires an important commitment of the public administration and the engagement of multiple technical competencies in order to identify the adaptation measures, their sell-by-date and the possible long-term effects of climate change. Due to this complexity, the adaptation pathway approach is highly effective when it is focused on small local management projects, whereas it could be difficult to apply it in a regional or national plan.

Robust Decision Making (RDM). RDM is an effective tool for decisions in highly uncertain context. Even though this tool can be used in an iterative process, the literature review shows examples of applications in case studies with a single decision point. In the RDM approach, the adaptation strategy is tested along different multifaceted future scenarios and no probabilities are attached to the various futures. Therefore, this methodology could be effective even in a highly uncertain framework, such as the climate change environment. Furthermore, with this method is possible to jointly consider various risks and possible challenges (such as the socio-economic dimensions and the demographic ones), instead of limiting the analysis just to the climate change impacts and thresholds. This methodology has been widely used in the past (RAND corporation is historically committed with national security), assessing projects and strategies in different areas and frameworks. Thus, the method is consolidated, with recurring steps and computer programs that guide the analysts. Lastly, RDM can work both with physical or economic metrics, enhancing potential for application across non-market sectors such as biodiversity or health. The method could be effective analysing both local projects and bigger development plans.

However, there are also significant barriers to the application of this tool, basically connected to the complexity of the software. The methodology requires expert knowledge of the computer programs, strong computational skills and familiarity with ICT tools. RDM is inevitably based on a multiple interaction between humans and computers, where analysts check the information and proposals designed by the programs and vice-versa. Therefore, a proficiency in dealing with software and ICT tools is necessary. Moreover, a vast amount of information is needed. The methodology is usually considered data and resource intensive, because the scenarios should be accurately designed, considering a wide ensemble of parameters, in the attempt to simulate the real-world processes. However, even an informal version could be used, assessing the strategies only on climate change risk.

Real Option Analysis. ROA is a tool for the economic assessment of the value of flexibility, i.e. keeping the adaptation strategy open to modifications in the future waiting for better information about the climate change impacts. With ROA methodology, a decision tree (in some way similar to the one of the Adaptation Pathways method) is designed. Then a Cost-Benefit Analysis of each possible pattern should be developed, considering a plurality of possible scenarios. Thus, the strategy with the immediate intervention will be compared with the strategy with delayed measures, estimating the costs and benefits of waiting.

ROA is effective when three key circumstances are present: i) the investment decision is irreversible, thus, there is no possibility to easily modify the measure when it has been realised (e.g. building a seawall); ii) there is the opportunity to develop the investment in more than one stage, in a flexible approach (e.g. developing a dike able to be raised in case of more severe precipitations); iii) the decision-maker has the opportunity to learn and to gain more information in the future (e.g. the knowledge about the natural mechanisms regulating the rise of the sea level).

This approach is potentially useful in the economic analysis of major investment decisions, notably major flood defences, water storage systems or for justifying flexibility within major projects. This tool can be jointly used with other methods and decision-making processes, such as the Adaptive Management or the Adaptation Pathways. ROA is based on monetary terms; thus, it can aggregate diverse dimensions in a unique measure but, at the same time it can incur in ethical dilemmas. ROA can be useful for the definition of the right timing of an adaptation investment, integrating in the analysis the possibility to wait and learn in the future according to new and more precise information gained. In the case studies presented in this chapter, ROA is described as a highly complex tool, requiring a considerable amount of data and analytical skills. Costs and benefits of the adaptation measures have to be assessed, as well as the physical and economic values of the expected climate change impacts and their effects on the performance of the policy.

Maxi-min and Mini-max Regret. These are not tools or decision frameworks but decision criteria that are used in contexts of high uncertainty. Probability are not used with these methods. In the maxi-min criteria the adaptation strategies are assessed in the various climate change scenarios and the worst performance of each policy in considered. The policy with the best worst performance should be recommended. This methodology is effective in a context of complete ignorance about the probability of the future impacts of climate change. The maxi-min rule is the most conservative decision method and it suggests to the decision-maker the less risky choice. However, it does not consider the other performances of the policies, ignoring eventual good results in some scenarios.

The mini-max regret criterion considers the distance of the policy performance in each state with the best performance possible in that specific state considered. The maximum loss is found for each option and the one with the lower regret is chosen. Therefore, this decision rule is focused on the missed opportunities instead of on the worst outcome. Again, the tool is effective in a highly uncertain context, but, in this case, even the good performances are in some way included in the economic analysis. The tool can be used with both economic and other quantitative measures and it can be applied to various adaptation problems.

The strengths and limitations of the **portfolio analysis** will instead be accurately described in the next chapter, completely dedicated to the analysis of this tool. The tool is used in the case study of this dissertation, therefore the considerations coming from the literature review are then assessed thanks to a concrete application of the methodology.

Conclusions

Due to the presence of the wide climate change uncertainty, planning and developing adequate adaptation policies are demanding tasks. Thus, first of all, some general recommendations for the implementation of adaptation measures have been presented. The decision maker should use the most reliable and updated scientific information about the climate scenarios and the expected impacts of climate change, considering the data coming from the most trustworthy organizations and institutions (IPCC, WMO, World Bank Climate Change Knowledge Portal, National or Regional official climate assessment). Then, the scientific literature suggests to consider a plurality of values and perspectives, the specific development goals and priorities of the local communities and marginalised people in particular. Initially, the implementation of no and low regret policies should be assessed, with the aim to have good performances over a wide variety of possible futures, even in a context where the climate information is not particularly mature. The climate change knowledge and the adaptation objectives should be mainstreamed into the common administrative plans and programmes, instead of developing autonomous and new documents and branches that could lead to an inefficient and ineffective use of economic resources. When the climate information is not accurate and it is not sufficient for the identification of the expected local impacts, other methodologies could be applied, e.g. “policy first” approaches, in the attempt to increase the overall resilience of the local community and to better prepare the society to possible generic stressors; in context where climate change is the main issue and possibly the reason to implement the policy, flexible measures (easy to be adjusted) in flexible decision making processes (iterative and short term assessments) should be considered.

Besides these general insights for the climate change adaptation planning, in this chapter this dissertation has presented the most important decision-making processes and decision support tools that emerged by a literature review about adaptation policies:

i) Adaptive Management and Adaptation Pathways Approach: these are long term decision-making processes which design a sequence of adaptation measures and identify in advance some key trigger points where a decision about the strategies to follow has to be made. There is a multitude of examples in this area, each of them characterised by an original approach and a specific terminology. Generally, these methods require a continuous iterative planning process, where the essential steps (designing, implementing, monitoring and reviewing) are continuously repeated.

ii) Real Option Analysis: with this tool the flexibility of adaptation measures and the value of postponing policies in the future, waiting for more accurate information, can be included in the economic analysis of the policies. A decision tree of the possible adaptation strategies is designed and every branch is evaluated in economic terms in all the possible climate scenarios.

iii) Robust Decision Making: with this method, complex computer programs are used for the assessment of the adaptation strategies over hundreds of possible futures, identifying the key vulnerabilities of the strategies and suggesting corrections in an attempt to make them more robust.

iv) Portfolio Analysis: an instrument coming from the financial sector which aggregates different alternative (non-perfectly correlated) adaptation policies with the aim to find investment solutions that have a better trade-off between economic return and its variance (investment risk).

v) Non-probabilistic criteria: decision criteria, like the mini-max regret and the maxi-min, which can help the decision-maker in finding economically efficient measures in a context of deep uncertainty (no distribution of probabilities) about the future scenarios.

This chapter has developed a first brief comparison between these methods, trying to show the key strengths and limits of each tools. Some indications about possible applications of these instruments are proposed. In the next part of this thesis, the Modern Portfolio Theory framework will be discussed in detail. This is the methodology which has been selected in this research work and that it has been tested in a case study regarding adaptation interventions in the agricultural sector.

3 Methodology: The key steps and the practice of the Modern Portfolio Theory

Introduction

In the first chapter the climate change adaptation issue has been discussed, presenting some key concepts and research questions. Adaptation is a multifaceted topic and it inevitably deals with the deep uncertainty characterizing the climate change impacts. Therefore, the definition of optimal adaptation policies requires the knowledge and use of new decision methods and criteria able to deal with an uncertainty called Knightian, due to the impossibility to characterise it with an objective probability distribution. Several decision instruments have been analysed in the second chapter, considering the strengths and weaknesses of each in turn.

This work now focuses on one of such, the Modern Portfolio Theory (MPT), a tool, coming from the financial sector, which helps the decision-maker in identifying a set of alternative investment solutions, including in the analysis the estimate of the returns and their variability in relation to a set of possible scenarios. This is the methodology applied in the case study (chapter 4), where tea investments in Rwanda have been assessed considering the possible future impacts of climate change. This tool has been selected among the other methodologies due to four essential reasons: i) the climate change uncertainty cannot be completely resolved in the future and the development plans of the Rwanda Government require to set the plantations in the first years, leaving no opportunity of waiting for better climate data; ii) no MPT has been applied to agricultural investments in a climate change framework; iii) the efficient frontier is an effective tool for the communication of the results; iv) basic hardware and software are necessary for the application of this method (normal laptop and Microsoft Excel).

This part of this research work will thus discuss the main steps of the Modern Portfolio Theory methodology, also presenting some concrete applications in the field of the natural resource management and the climate change related investments.

However, the reader should bear in mind the essential purpose of this economic analysis: helping the decision-maker to find good investment solutions considering the possible effects of climate change. The tool should be effective for this task and it should be easy to run in every context, both in developing and developed countries. Therefore, this dissertation will only focus on the essential elements of the Modern Portfolio Theory and the new technical developments relating to the financial domain are partially ignored. There is a vast literature on the Modern Portfolio Theory indeed, which analyses all the capabilities and technical features of this methodology. In this work a basic use of this methodology is proposed, focusing on the decision rules introduced and the essential elements proposed by the leading authors of this area.

3.1 Why has the MPT been selected for this research work?

The aim of this work is to test the key strengths of the Modern Portfolio Theory in the context of the climate change policies. This methodology has been progressively employed in the natural resource management framework, but it has remained partially excluded from the climate change decisions analyses. Few examples exist (Ando and Mallory, 2012; Mallory and Ando, 2014; Crowe and Parker, 2008) and no one considers the agricultural investment decisions. However, the impacts of climate change adaptation on the agriculture sector are going to be sizeable, creating relevant socio-economic effects on the communities both in the developing and developed countries. In the developing world, agriculture represents an essential asset, giving livelihoods to local people and sometimes sustaining the precarious economic equilibria of the countries. Even in the developed context, agriculture is an essential asset, having connections with various important food products, with a high economic value. In both places, the local agricultural products also have an essential symbolic role, defining important cultural aspects.

Even if there are no portfolio theory experiences connected to climate change, the MPT is an effective tool in helping the decision-makers to identify the best shape of the investment to be made. Portfolio theory is effective in dealing with uncertainty, similarly to other instruments explored in the previous chapter. However, differently from other sources of uncertainty, climate change uncertainty is expected to remain also in the future, because of the impossibility to predict some key dimensions of this issue. Therefore, trying to identify flexible policies, postponing the choice among the available options, might be ineffective in facing climate change in the agriculture sector. In this work the decision is supposed to be taken in just one time, due to the impossibility to delay it in the attempt to find better information about climate change. This condition is perfectly suitable with the climate change framework.

MPT is also helpful for the climate change decisions because it assists the decision-maker in mixing the policies available, with the aim to reduce the variability of the investment, identifying more robust decisions able to deal with a plurality of possible futures. Therefore, apart from the decision criteria used in the selection of the portfolios among those on the efficient frontier, the process of the portfolio selection is interesting in the climate change framework and it might be helpful in assisting some complex decisions.

Another interesting element is the graph representation of the efficient frontier, one of the outcomes of the portfolio analysis. As it will be accurately discussed in the next chapter, the efficient frontier is a curve connecting all the portfolios with the better trade-offs between the expected net present value and its variance. This figure might be an interesting tool in communicating the uncertainty connected with the climate change decisions and the opportunity to find a balance between revenues and variability that can be accepted by the investor.

Therefore, here are the main reasons why this work tests this particular instrument:

i) Climate change uncertainty cannot be completely resolved in the future, therefore an instrument able to suggest decisions robust enough for all the futures available is needed. Agricultural investments in perennial crops are made in this context of uncertainty and they cannot be easily reversed in the future, because of the high sunk cost included. As Ando and Mallory (2012) state "*MPT is effective when the uncertainty will be resolved in the far future*"; Furthermore, the Government of Rwanda wants that the plantations are settled in the first years of the agricultural development plans and the farmers cannot wait many years in the attempt to gain better climate data.

ii) No MPT has been tested in the context of agricultural investment in the climate change framework;

iii) The representation of the efficient frontier is effective in communicating to the decision-makers the trade-offs between the expect revenues and the risks connected to each possible investment solution. This point could be decisive in a developing country context, engaging the private farmers and the local communities in identifying robust investment solutions.

iv) There is no need of complex computer programs that could represent a barrier to the application and dissemination of this method. A basic laptop, the Microsoft Excel software and a good knowledge of these tools are enough for the application of the PA methodology. However, even a good proficiency with Cost-Benefit Analysis procedures and principles is recommended.

3.2 Modern Portfolio Theory, the theoretical framework

Modern Portfolio Theory is fundamentally based on the seminal work of Markowitz (1952), which started to systematise some key concepts of this discipline. This instrument has the capacity to help the decision-makers, both private and public, in planning investments in an uncertain framework, giving them the opportunity to find ways to reduce the variability of the expected outcomes, without losing economic returns. This is why MPT overcame the boundaries of the finance sector and it has been widely used also in other fields: energy sector (Ringer et al, 2007), fishery harvesting decisions (Alvarez et al, 2017; Sanchirico et al, 2008), biodiversity conservation (Figge, 2004; Koellner and Schmitz, 2006; Hoekstra, 2012), forest management (Matthies et al, 2015; Knoke et al, 2005; Knoke, 2008), agriculture (Castro et al, 2015), water resource management (Marinoni et al, 2011), invasive pest and disease surveillance (Yemshanov et al, 2014), spatial planning (Hills et al, 2009; Halpern et al, 2011) and conservation under climate uncertainty (Crowe and parker, 2008; Ando and Mallory, 2012; Mallory and Ando, 2014). Scientific research in ecology has also recognised an effect of the diversification, like in the portfolio management, in natural systems, by which communities with high diversity tend to produce more stable streams of ecosystem services (Alvarez et al, 2017).

The link between the finance world and the natural resource management is something recurring. In both cases there is the need to maximise the benefits of the investment facing two essential limits: i) a budget constraint and ii) a severe uncertainty about the expected return of the investment choices made in the present. In the finance sector, people need help in finding the most effective solutions for reaching profits investing their savings, with a range of possible outcomes of economic performances of their assets in the future. The behaviour of a public government in the natural resource management is similar. Preserving the biodiversity of a specific site is a demanding task, due to the lack of knowledge about certain characteristics and strengths of the plants of that natural site or the adaptability of that place to the uncertain future climate.

Nevertheless, MPT is not the only instrument, coming from finance, which is able to deal with uncertain outcomes and which has a strong potential also in the natural resource management. For example, when investment outcomes are uncertain but more detailed information are expected to come in the future, there is a value in postponing irreversible investment choices, called "option value" (Dixit and Pindyck, 1994). In the field of natural reserves protection, temporary conservation contracts can permit to preserve more parcels than complete purchase or permanent easements would allow. This temporary contract can also keep the lands endangered for some years, until some new relevant information about the ecological functioning or the future climate of that place is discovered (Ando and Hannah, 2011). However, the instrument of the option value is effective in specific cases, characterised by three main conditions: i) there is uncertainty about which investment (land preserved) will give the best results in the future (if the decision-maker has to choose between solutions with the same expected return, paying the price of waiting is obviously useless); ii) at least a part of this uncertainty will be reduced in the future and more information about the return of the investment is going to be discovered; iii) the investment decisions should be irreversible (Ando and Hannah, 2011). In spite of the strengths of this instrument, as a basis for the precautionary approach, the natural resource management environment and especially the climate change field are contexts where the uncertainty is widespread and it is difficult to reduce it in the future, especially because of the unpredictability of the countries' greenhouse-gas emissions and the complexity of the scientific principles about the mechanisms of the nature (this part has been extensively discussed in the previous chapter). This is why the Modern Portfolio Theory can be particularly useful for the climate change decisions, giving the opportunity to guide the public decision-makers in facing this exceptionally complex environment. Furthermore, adaptation policies are particularly urgent in developing countries, places where the complexity of the option value approach could become an obstacle. As we are going to discuss in the next pages, the Modern Portfolio Theory requires data and good computational skills but it usually produces straightforward recommendations and rapid results.

In addition, MPT emphasizes the importance of diversification in the investment, with the aim to reduce the variability of the possible outcomes. However, the importance of diversification is not something new with Markowitz analysis. In 1952, the same year of Markowitz's seminal paper, Earl O. Heady (1952) wrote "Diversification in resource allocation and minimization of income variability", recognizing the power of diversification for the income of a farm. He stated that the practice of diversification has been highly discussed in the agriculture sector, although it has still not accurately systematized. "Portfolio selections" (Markowitz, 1952) is the first contribution of Markowitz on this topic, but it will be followed by several other articles (Markowitz, 1956; Markowitz, 1991; Markowitz, 1999) and books (Markowitz, 1991; Markowitz and Todd, 2000). In these works, Markowitz explained the theoretical basis of this discipline and the steps of the analysis. In the following paragraph these MPT essential milestones will be accurately discussed.

3.2.1 Essential milestones of the Modern Portfolio Theory

The starting point of Markowitz's research is the refusal of the idea that the goal of the investor is the maximization of the discounted expected revenues of his investment. Investment decisions are made in a context of uncertainty about the future conditions and outcomes, therefore there is no perfect knowledge about the investment revenues. The investor surely considers the expected revenues as a desirable thing, but he looks also at the variability of this amount according to the plurality of possible futures. The aim of the investor, and the reason why he decides to diversify his investment in a portfolio, is the maximization of the expected return given his tolerance of risk. Alternatively stated, an investor seeks to minimize the risk at which he is exposed given some target expected return (Fabozzi, 2008; Aerts et al., 2008; Watkiss et al, 2015; Francis and Kim, 2013).

3.2.1.1 Identification of portfolio manager and assets selection

In MPT the investment decisions are structured in assets, which can be collected in various portfolios. “Assets” are usually considered securities whose value is deduced from a future flow of benefits. The payoff from each asset is usually called the “asset’s return”, and a “risky asset” is an investment for which the return that will be realised in the future is uncertain. In such situations, the deciding agent, called the “portfolio manager”, must choose which asset to invest in and he is presumed to be seeking high returns at low level of risk.

Modern Portfolio Theory initially worked in the finance sector and therefore it considered stocks and bonds as risky assets and portfolios as an investment with a mix of various shares of these assets. However, as previously mentioned, this tool can be applied also to other frameworks. For example, in the agriculture sector the portfolio manager will probably be the farmer and the assets might be different variety of crops or different possible land uses; whereas in the energy sector the portfolio manager, as a public government decision-maker, has to decide among various mix of alternative sources of energy available, i.e. renewable or fossil. Fisheries and range managers, land and seascape planners, and agencies in charge of planning and preparation for long term environmental changes could be all examples of potential natural resource portfolio managers which try to maximise their revenues and to reduce the uncertainty connected to these gains.

Thus, the first step of the portfolio analysis requires two connected tasks: i) the identification of the portfolio manager, analysing her targets and her specific point of view; ii) the definition of the assets available to the portfolio manager. Choosing the asset is a demanding duty, since the characteristics of the securities are essential in reaching the main aim of the portfolio analysis, i.e. the reduction of the risk connected to the investment. Indeed, an effective portfolio is more than a list of various good stocks and bonds (Markowitz, 1991). The performance of the portfolio strictly depends on the mix of the assets considered which have to be accurately chosen, considering the relations between them. Therefore, first of all, information about the different assets available should be collected, with the aim to describe their past performances and their expected future outcomes. An expert judgement about the strengths and weaknesses of the securities available is a good starting point for the portfolio selection.

Although the capacity to generate revenues is essential for a good asset, another key principle in the selection among the different options is the correlation between their performances. The correlation coefficient measures how two investments vary according to the different possible futures and it spans between 1 and -1, where 1 is the perfect correlation, 0 represents an uncorrelation and -1 a perfect negative correlation. If the securities vary in the same direction and with the same proportion, the correlation between them is perfect, whereas if they vary in the opposite way, with a strong relation between the values, they will be negatively correlated. Portfolio diversification is effective when it regards assets which are less correlated or negatively correlated, whereas when the correlation is perfect and the assets proportionally vary in the same direction, the diversification has no effects and the risk is not reduced in the portfolio. Usually securities are correlated but not perfectly correlated and therefore diversification is generally effective in reducing the risk of the investment. On the contrary, if the aim is the reduction of the risk of the investment, portfolios with highly correlated assets should be avoided (Markowitz, 1991). This is an essential basis for the MPT and a key step in the selection of the right assets, also in the case of climate change investments. This work will return on this topic later.

3.2.1.2 Estimating the economic performances of the assets selected

Once the assets have been identified, their actual and expected returns should be measured. The classic literature about MPT is basically focused on financial assets and therefore it considers simple market prices and their flows in the future, finding a discount rate to actualise the future performances to the present. However, as presented later in the case study discussion, in the last years the use of the MPT has been expanded to several other topics, like the land use choices or the biodiversity preservation field. These topics concerns the management of public goods and there are no markets where these goods are traded, complicating the evaluation of the benefits and costs of the measures. In some cases, indeed, benefits from natural resource management cannot be easily quantified in monetary terms. In these cases, it may be better for the portfolio manager to measure returns in terms of the service provided rather than attempt to monetise the service flows (Alvarez et al, 2017).

For instance, portfolio managers that seek to maximise yields can measure returns in terms of biomass while those whose objective is to maximise recreational use can measure returns in terms of visitor-days. In the review of Matthies et al (2019), they find that assets, and thereby expected returns, can be defined by some or all of the following key return components: i) access/ownership to the resource base/asset (e.g. land); ii) biological growth component (i.e. periodic growth increment); iii) growth in the unit value of the output of the asset (i.e. transition between timber assortments); and iv) changes in value (monetary or non-monetary) associated with the asset. Therefore, it is interesting that the MPT can be performed also in the presence of various other measures apart from the market value, giving effective results also in the complex field of the natural resource management. However, as presented by Ando and Mallory (Ando and Mallory 2012; Mallory and Ando, 2014) in their case study focused on the preservation of a natural reserve, the alternative benefits values not always lead to the same results of the economic assessment. They used both a particular index valuing the quality of an ecosystem and a willingness to pay estimate in the attempt to analyse the best land to be preserved for natural interest objectives. Analyst should use benefit indexes that proxy for monetised social conservation benefits with care. If monetised benefits are a linear function of the physical index used as proxy, then the results of a portfolio analysis are invariant to whether monetised benefits or the index are used in the study. However, if WTP for conservation benefits is not linear in the benefit index, portfolio recommendations can change dramatically if analysts use measures of benefits that are convenient indexes rather than true WTP (Mallory and Ando, 2014). Moreover, in the attempt to simplify the accounting of the performances of the assets, some studies looking at non-market benefits have focused only on the benefits side (e.g. Finger and Buchmann, 2015), thus ignoring the costs. However, Mallory and Ando (2014), again, suggest to use valuation based on benefit-cost ratios rather than such a “benefit-only” approach. In their analysis the portfolio analysis with the inclusion of the costs of the land preservation brings to a completely different result in comparison with the analysis made with just the estimate of the benefit.

Here there is a first relevant obstacle in developing the portfolio analysis and it regards the need of a big amount of data about the features of the asset, the evaluation of its costs and benefits, the variability of these values according to different future scenarios, some of them unpredictable (e.g. climate change), and the correlation between the performances of the diverse assets available. Thus, a key driver in defining assets and their weights is often data availability and quality and the presence of several different competencies about all the diverse dimensions involved in the analysis. For example, in the climate change field, various knowledges and skills are needed: i) knowledge about the functioning of the climate data; ii) knowledge about the natural processes, how they are influenced by the climatic variables and how they interacts with the economic and social environment; iii) economic skills in computing the costs and benefits of the natural resource management, quantifying natural services in monetary terms with market prices or other measures (e.g. willingness to pay). This may be one reason why MPT in environmental management has so far largely remained a scientific tool (Matthies et al, 2019).

Thus, following the traditional economic terminology of the Cost-Benefit Analysis framework, the second essential step of the MPT requires the calculus of the Expected Net Present Value (ENPV) of each asset, i.e. the forecasted economic return of the investment on each asset considered. The sum of the economic performances of the assets in each scenario is called Net Present Value (NPV), whereas the weighted sum of these NPV gives the overall economic performance of the asset (Expected Net Present Value), considering the whole spectrum of possible future conditions. The future outcomes of the assets are indeed usually uncertain and a probability distribution for the possible rates of return that can be realized must be defined and assigned to each NPV. The expected return of each asset is the sum of the performances of the assets in each possible future multiplied by their probability of occurrence. Probabilities are usually assigned considering the past trends of the returns of the asset and imagining a future pattern in some way related to these performances (Fabozzi, 2008). However, considering the framework of the climate change related decisions, the definition of probabilities about the future scenarios represents a tricky point of the analysis. As previously discussed, the greenhouse gas emissions modify the historical pattern of the climate, increasing the mean temperature and changing some key meteorological dimensions. Therefore, making assumptions about the future is complex, although it can rely on the studies of the scientific community, summarised by the IPCC climate scenarios. As a matter of fact, as discussed later in this work, the scientific knowledge is still insufficient for assigning likelihood to each scenario. Anyway, even if the scientific community will accomplish a refined and complete understanding about the functioning of the climate system and its connection to the local environments, an uncertainty about the future pattern of the greenhouse gas emissions will remain. The evolution of the pace of the emissions is indeed something unpredictable and it hampers the description of the expected future with an objective distribution of probabilities. However, Fabozzi et al. (2002) present some examples coming from the finance world, where the predictions made on the observations of the past trend conducted to wrong estimates, showing how the identification of the right value and risk of an asset is something complex also in other fields, as the finance sector. The information learnt from the historical performances might indeed conduct to fallacies in the beliefs about the future happenings, leading to a wrong set of probabilities for each possible scenario. This is why, expert personal judgments are accepted in estimating the performance of the asset classes depending on the own understanding of the factors which influence the returns on asset (the political stability, the monetary and fiscal policies, the business cycles of sectors) and what is their impacts (Fabozzi et al, 2002).

However, according to Markowitz (1952) the ENPV is not enough for the identification of the best assets. Investors are usually risk adverse and between two securities with the same economic return but with two different level of risk, they will choose the one with the lower risk. Therefore, the analysis of the risk connected to the investment is the other essential step in the MPT framework and it relies on the statistical concept of variance. This measure represents the dispersion or variability of the possible outcomes around the expected value. Talking about the finance sector, variance might show the range of the possible returns of a bond or a portfolio of securities around the mean value according to different possible future economic scenarios. When the decision-maker has instead to deal with the management of natural resources, even the natural processes influence the variance of the portfolio performances. For example, in the decisions about the protection of a natural reserve, the effects of climate change on the land should be considered. Here the variance tells how the different possible outcomes of the conservation policy might vary according to the plausible futures. In the next chapter, which present the case study, the variance will measure how the outcome of the adaptation policy could vary according to the different possible climate futures (i.e. scenarios). In statistical terms, variance (σ^2) is the weighted sum of the square of the deviations from the arithmetic mean and the formula for the calculus of the variance of the asset i considered is the following:

$$Var(R_i) = p_1[r_1 - E(R_i)]^2 + p_2[r_2 - E(R_i)]^2 + \cdots + p_n[r_n - E(R_i)]^2$$

Where:

i = hypothetical asset

p_n = probability of scenario n

r_n = economic return of asset i in the scenario n

$E(R_i)$ = ENPV of asset i

$Var(R_i)$ = is the variance of the asset's ENPV

When the variance is 0, the investment is riskless and its outcome has no variability in the different possible futures, although this situation is obviously uncommon.

Another opportunity in representing the variability of the revenues is the standard deviation, which is the square root of the variance. The unit of measure of the standard deviation is the same of the outcome (the variance is a square unit) and it might simplify the comprehension and the discussion of the results of the analysis. Obviously the greater the variance and the standard deviation are, the bigger is the risk of the investment (Markowitz, 1952; Fabozzi, 2008). However, both variance and standard deviation may not be an appropriate measure for risk in context far from the classical financial environment for which the MPT was originally developed. These parameters contain both negative and positive deviations from the expected return, whereas sometimes just the negative value are relevant. In some cases, deviations in return are desired rather than be avoided when considering questions of ecological resilience. Alternatives to variance are the use of semi-variance or indicators which combine financial return and risk into one index (e.g. lower partial moments, LPM, or Value at risk, Var). These measures punish deviations below a defined threshold more than valuing options above this threshold (Matthies et al, 2019). This can be suitable when focusing on extreme but rather rare events.

However, the previous formula is focused just on a single asset, whereas usually, in the MPT, the portfolios are made by at least two different assets. Considering a combination of two assets, the calculus of the variance is more complex, and it depends also upon the relation between the assets. The information needed is the degree to which the economic performance of the two assets change together according to the different possible futures. In statistical terms this is the covariance. Hereby, the formula for the calculus of the variance of the return of a portfolio P, composed by two asset *i* and *j* is the following:

$$Var(R_p) = w_i^2 var(R_i) + w_j^2 var(R_j) + 2w_i w_j cov(R_i, R_j)$$

where *w* represents the weight of the asset in the portfolio and $cov(R_i, R_j)$ is the covariance of the two assets. Considering the two assets *i* and *j*, their expected return and *i'* and *j'* the deviation of the asset *i* and *j* from their expected value, the covariance, $cov(R_i, R_j)$, is the product between the expected value of *i'* and *j'*. The covariance is the measure of the extent to which two sets of numbers tend to move up and down together.

When both *i* and *j* are above their expected value, *i' * j'* is positive; when both *i* and *j* are below their expected value, *i' * j'* is also positive; when one variable is above and the other below its expected value, *i' * j'* is negative. Thus, if *i* is usually above its expected value when *j* is above its expected value, and below its expected value when *j* is below its expected value, then the covariance of *i* and *j* is positive. If *i* is usually above its expected value when *j* is below its expected value, and vice versa, then their covariance is negative. If the outcome of *i* has no influence on the outcome of *j*, then their covariance will be zero. As previously discussed, the correlation might be used besides the covariance. Correlation is similar to the covariance and it is estimated dividing the covariance of two assets by the product of their standard deviations. The correlation coefficient is a standardized number and it is comparable across different assets. It varies between +1.0, which represents the perfect co-movement in the same direction, and -1.0, the perfect co-movement in the opposite direction. If the correlation is 0, means that the economic performances of the assets are uncorrelated. Moreover, since the standard deviation is always a positive number, the mathematical sign of the correlation depends exclusively on the sign of the covariance. Markowitz discovered that finding investment with a small or negative correlation, the expected net present value of an investment might remain unchanged, but the standard deviation of this value could be considerably reduced (Fabozzi, 2008; Ringer et al, 2007).

Markowitz explains his approach to diversification as follows (Markowitz, 1952):

> *Not only does portfolio analysis imply diversification, it implies the "right kind" of diversification for the "right reason". The adequacy of diversification is not thought by investors to depend on the number of different securities held. A portfolio with sixty different railway securities, for example, would not be as well diversified as the same size portfolio with some railroad, some public utility, mining, various sorts of manufacturing, etc. The reason is that it is generally more likely for firms within the same industry to do poorly at the same time than for firms in dissimilar industries. Similarly, in trying to make variance [of returns] small it is not enough to invest in many securities. It is necessary to avoid investing in securities with high covariances [or correlations] among themselves.*

Therefore, the second essential step of the MPT requires to estimate the economic performances of the assets available. The key information needed are:

i) the ENPV of the various assets;

ii) the variance of these ENPV in the different scenarios;

iii) the correlation among the performances of the different assets.

The assets with good economic return, low variance and which have the economic performances not perfectly correlated are the ones to be selected for the portfolio analysis. In the climate change framework, they should be specialised in different scenarios, possibly having a very low correlation among them. Some of the adaptation policies should be perfectly suited for a no/low climate change scenario, whereas other adaptation policies considered for the portfolio analysis should be suited for scenarios with severe climate changes. Thanks to this diversification, the portfolio can be effective in reducing the risk of investing all the resources available in just one adaptation policy perfectly suited for just one possible future.

3.2.1.3 The aggregation of the assets in portfolios and the evaluation of their performances

The following step of the MPT methodology is the aggregation of the selected assets in portfolios. Portfolios are made by different shares of the available assets. The aim of the portfolio is to find investment solutions with a better trade-off among economic return and risk, through the mix of securities which are not perfectly correlated.

When the portfolios have been identified, their expected returns (or expected net present value) and variances have to be estimated. The expected return of a hypothetical portfolio P is the sum of the return of the portfolio in each possible scenario multiplied by the probability of occurrence of the scenario:

$$E(R_p) = p_1R_1 + p_2R_2 + \cdots + p_nR_n$$

Where,

$E(R_p)$ = expected return of the portfolio

R_n = is the n_{th} possible expected return for portfolio P

p_n = is the probability of obtaining the expected return N for portfolio P

n = is the number of possible outcomes for the rate of return

Portfolios are usually made by a plurality of assets and the variance must include the co-variance between each couple of assets which composes the portfolio. Thus, the formula for three assets becomes the following one:

$$Var(R_p) = w_i^2 var(R_i) + w_j^2 var(R_j) + w_k^2 var(R_k) + 2w_iw_jcov(R_i, R_j) + 2w_iw_jcov(R_i, R_k) + 2w_iw_jcov(R_k, R_j)$$

Therefore, as previously discussed, diversification is not always an effective strategy in the attempt to reduce the risk of an investment. The covariance or correlation between the assets included in the portfolio tells something about the possibility to obtain a less risky outcome thanks to the mix of these assets in a portfolio. Hereby, the standard deviation (and the variance) of a portfolio basically depends on three key dimensions (Markowitz, 1991):

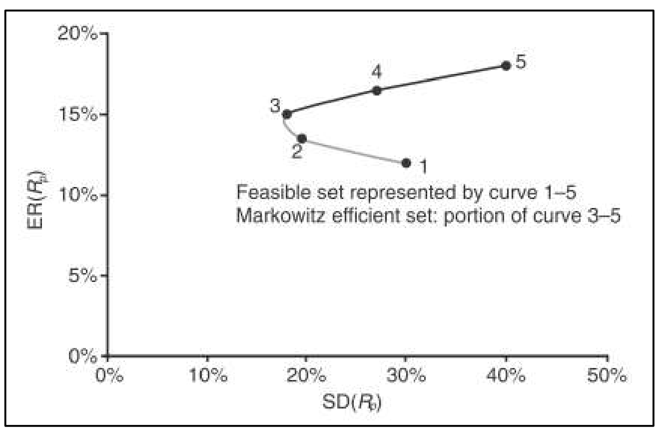
i) the standard deviation of each asset
ii) the correlation between each asset
iii) the amount of the investment assigned to each asset

Assuming the same value of standard deviation and the same amount of investment assigned to the securities, the correlation between the options is the essential value which determines the effectiveness of diversification in reducing the risk of the investment. As it will be discussed later in this work, in the case of climate change investments, MPT is effective when measures with different performances according to the different climate scenarios are considered. The diverse assets of the portfolios should be alternative between them, meaning that each one should be specialized for few scenarios and not for the entire spectrum and just the combination of them might guarantee robust outcomes (Crowe and Parker, 2008). Let's suppose to have two independent policy options and that two extreme scenarios are considered in the analysis (e.g. RCPs 2.6 and 8.5). In the attempt to reduce the risk of the investment, the decision-maker is going to split the resource available on both the solutions. Following the theory of the MPT, the risk will be reduced and the diversification strategy will be effective just in the case of non-perfectly correlated measures. If the two solutions increase or decrease their performances in the same way and with the same proportion according to the two extreme scenarios, the diversification will be useless, whereas in the opposite situation, where each one performs well in a different scenario, mixing the investment on the two policies in the portfolio will considerably reduce the risk of the investment.

3.2.1.4 The efficient frontier

When the economic return (or the ENPV) of the portfolios and the variances of these returns are estimated, the last two steps of the MPT require the presentation of the results on a diagram and the selection of the optimal portfolio. MPT calls "feasible portfolio" every portfolio that an investor can construct given the assets available. The results can be showed on a graph, having on the x-axis the values of the variance (or standard deviation) and on the y-axis the economic returns. Considering a portfolio with just two assets, all the results will fall on a line.

Figure 3.1: Efficient frontier considering portfolios with just two assets

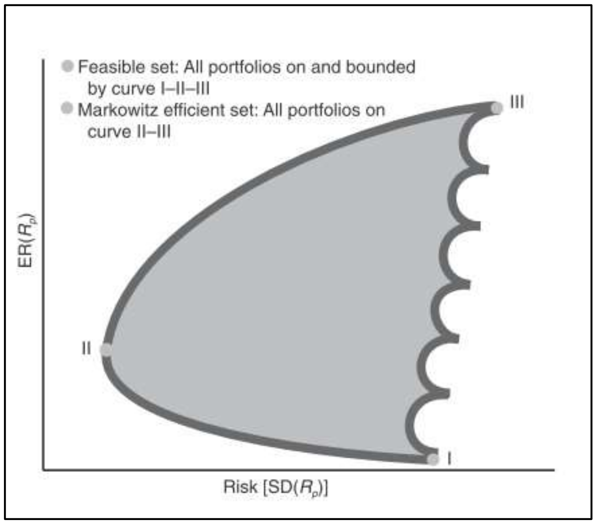


Source: Fabozzi et al, 2008

In this figure five possible combinations of the two assets are shown. Points from 1 to 5 represent possible feasible portfolios, but just the portfolios 3, 4 and 5 are the ones on the efficient frontier. The efficient frontier is the curve which contain all the efficient portfolios, the portfolios which have the highest expected returns among the all feasible that have the same risk. Therefore, the portfolios 1 and 2 are not efficient, due to the presence of other combinations of assets between 3 and 5 which have the same standard deviation but a higher economic return. The efficient frontier can be identified by finding all the possible portfolios which maximise the expected return given a particular value of standard deviation. An efficient portfolio is also called mean-variance efficient portfolio.

If a combination of more than two assets is considered, the figure on the graph will not be a line anymore but an area, collecting all the possible combinations between the assets.

Figure 3.2: Efficient frontier considering multiple assets portfolios



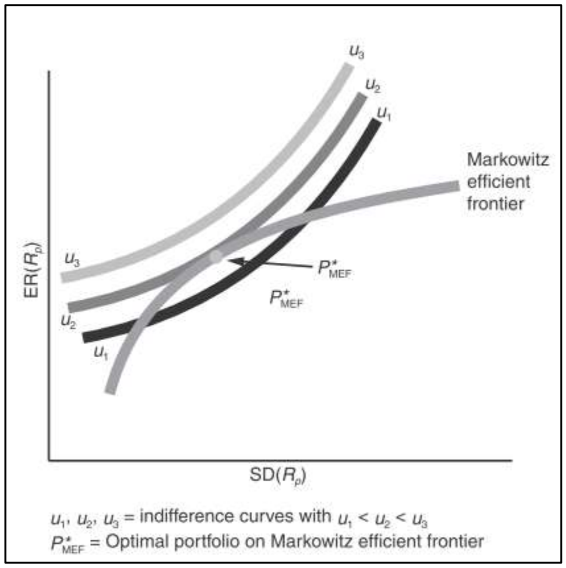
Source: Fabozzi et al, 2008

In this figure the possible portfolios are not just the ones on the line connecting the points I, II and III, but they can be any point inside the coloured area. However, the recommended portfolios are again the ones on the efficient frontier, the boundary line between the point III and II. There are no other portfolios which have a higher expected net present value with the same risk. The diagram with risk and revenues and the efficient frontier can be considered an effective representation of the investment solutions available. Both in a private investment context or in a public decision environment, this figure could easily show the characteristics of the options available, effectively presenting the trade-off between revenues and risk.

3.2.1.5 Portfolio selection

The last step of the analysis is the choice of the optimal portfolio. Every portfolio on the efficient frontier can be considered an optimal solution. The choice depends indeed on the utility function of the investor, which take into account her risk attitude also. Utility measures the relative magnitude of satisfaction someone derives from something; it is a subjective index of preference. If a person is faced with a decision, the alternative with the highest utility is the preferred choice. The investor's utility can be represented on an indifference curve, which collects all the combinations between economic return and risk which have the same utility for her. The grade of the curve is influenced by the attitude to risk of the investor. If the curve is more parallel with the x-axis, it means that she is risk seeking, because she is available to incur in a significantly higher risk of her investment even for a small increase in the economic return of his portfolio. Whereas, the more the line is vertical, the more the investor would have required a high economic return compensation for a little loss in the standard deviation. Thus, she is risk adverse. The following figure represents three indifference curves of the same investor and an efficient frontier of possible portfolios. The upper indifference curves collect points with a better welfare. The portfolio chosen will be the one where the indifference curve is tangent to the efficient frontier and it represents the one which maximize the utility of the investor.

Figure 3.3: Portfolio selection



Source: Fabozzi et al, 2008

A more risk seeker investor will have an indifference curve flatter and the preferred portfolio will be on the right part of the efficient frontier starting from the P^*_{MEF}. Whereas, a more risk adverse investor will choose a portfolio on the left part of the efficient frontier, where there are portfolios with lower level of standard deviation.

3.3 Portfolio analysis in practice

The power of diversification has been widely recognized by the financial literature, which focused on the opportunity to reduce the risk of an investment thanks to the aggregation of diverse assets in portfolios. Distributing the investment on securities with a low or negative correlation between them can reduce the variance of the investment, without sacrificing the economic revenue. Several contributions have been written in the last sixty years, starting from the seminal work of Markowitz (1952).

However, the management of risk in an uncertain context is not just an issue of the financial market. The natural resource management is steadily hampered by uncertainty, due to the presence of several unknown variables, e.g. the evolution of the climate conditions, the pattern of the human settlements, the scientific uncertainty about the interaction of the species. This is why some elements coming from the financial sector entered in the scientific framework of the natural resource management, with the aim to conduct the interventions to more efficient results.

Starting from the beginning of the twenty-first century, many articles have been written on the possible usages of the portfolio analysis in many different areas of the natural resource management. Due to the increasing relevance of the climate change issue and the difficulties in planning effective adaptation policies, diverse research works have oriented their focus on these topics. As previously discussed in this thesis, climate change introduces a deep and unprecedented level of uncertainty about the future environmental conditions, impeding several long-term irreversible decisions (Ando and Mallory, 2012). For example, the decision about the conservation of a natural land depends on the suitability of that area in providing a safe and appropriate space for the life and the breeding of some animal species at risk. Due to climate change these characteristics of the land available are no longer fixed and the ecology managers can no longer rely on the past trends of the environmental conditions of that area. Therefore, the conservation decision becomes particularly demanding, leading to a stuck of the decision process or to an un-optimal conservation plan with highly variable effects. Hereby, researchers are trying to assess the potentials of the portfolio analysis instrument, in the attempt to find investment solutions which can bring more robust outcomes, considering a plurality of possible climate and environmental conditions.

3.3.1 Portfolio analysis in the natural resource management

Modern Portfolio Theory originally comes from the finance sector but its use has been extended to several other fields with the attempt to face complex decisions in contexts with a widespread uncertainty. Initially the MPT was applied at the local or site level to determine the benefits associated with the diversification and hedging of management activity portfolios for a single or group of decision-makers in general investment decisions. Early studies found numerous benefits from applying MPT to diversification questions, included, but not limited to, agricultural inventories, crop allocation alternatives, and forward and credit contracts (Heifner, 1966; Johnson, 1967; Scott and Baker, 1972; Buccola and French, 1977). Then, the strengths of this instrument have been recognized also in natural resource management and biodiversity conservation choices and in the land-use decisions, helping the policy makers in identifying optimal solutions with a plurality of objectives and a longer planning horizon. In these contexts, portfolio selection has been considered a tool that can aid natural resource managers in their decision making by weighting returns and risks of different strategies to find the actions that optimize the provision of ecosystem service flows (Alvarez et al, 2017).

Going in depth with this recognition of experiences, a first interesting contribution about MPT in the biodiversity sector in proposed by Figge (2004). He presents the problem of the biodiversity conservation, in a context where the choices of a decision-maker are constrained by a limited budget and the knowledge about the future outcomes is scarce. He describes two different feasible approaches: the cost-benefit approach, which tries to find the solution that maximize the expected return, and the portfolio approach, which aims to identify portfolios that offer more return for a given amount of risk or less risk for a given return. Portfolio theory here focuses on the return that is lost by insufficient biodiversity. Figge (2004) presents again the three pillar elements to be considered in the portfolio analysis problem: i) the return and risk of an asset A; ii) the return and risk of an asset B; iii) the relation between the variation in return of the two assets. This last dimension determines the variation of the whole portfolio and the sign of the correlation between the assets is again essential. Some key elements of the portfolio theory return in the article. Figge (2004) states that mixing two perfectly correlated assets will have no positive effects on the variance of the portfolio. Anyway, although some assets might be positively correlated (as the crops yields to average temperature and precipitations), they are seldomly perfectly correlated and the diversification effort is often effective. For example, the crops yields can both increase or decrease depending on the climate variables, but different variety of plants have different ecological functioning and different sensitivity to temperature and precipitations. Then, the role of the portfolio manager is discussed. His goal is radically different from the analysis of single assets. In this case, the performances of the single securities have to be estimated, finding the pattern of their return during the time frame of the project, whereas the portfolio manager should consider the relations between the elements and their relative weights inside the portfolio.

Loss of biodiversity is one of the unsolved environmental problems and researcher slightly focused on the importance of the degree of diversity and they pay attention just on the quantity of species, genes or ecosystems. The connection between diversity and stability in ecology has been widely discussed, however the systematization of the relation between diversification of securities and the resilience of a system has been scarcely developed. The article presents also the differences between the MPT in the context of the financial market and the biodiversity management. In the natural environment the assets have relations between them. If a close symbiotic relationship exists between two organisms, and if an organism is “disinvested”, the expected return from the second organism necessarily falls. This can be faced considering the symbiotic assets as a unique element. Another difference regards the irreversibility of the decisions in the biodiversity management, where non preserving a species might lead to the extinction of that species, compromising future investments on that asset (whereas the investment in the financial market can be usually changed year by year).

Even Koellner and Schmitz (2006) present the concept of biodiversity as an issue of portfolio management, showing that the increased level of biodiversity can improve the yield-to-variance ratio and increase the marginal benefit of adding biodiversity to a portfolio. Yield, in the sense of the article, refers not only to direct financial performance but also to any type of service provided by ecosystems (e.g. biomass production in agriculture and forestry, carbon dioxide sequestration, flood mitigation). Risk refers to the unpredictability of future yields and is determined by the variance in space and time. Systems with many species can buffer the disturbance better than systems with fewer species, because the probability is greater that some species will be able to maintain certain level of ecosystem services, even though others may fail to function. The paper shows how the improved biodiversity can have a powerful effect in achieving better mean-variance performances. However, they point out how portfolio analysis requires a rich amount of data, starting from a deep understanding of the mean level of an ecosystem service but also its variability in time and space.

Beside its use in the biodiversity management field, MPT has been employed also in other natural resource management fields. Some authors used the portfolio analysis in the fishery sector, in the attempt to find harvesting strategies that increase the revenues while reducing the variability of the catchments. Sylvia et al (2003) develop optimal portfolio frontiers for the pacific whiting fishery using three alternative benefit functions representing the objectives of different interest groups (seafood brokers, seafood processors, resource managers). The analysis generates risk return frontiers for all of them, considering different mixes of fish harvested. They compare the actual mix of species caught with the optimal portfolio efficient frontier for each actor and they find that the actual portfolio is sub-optimal for every point of view considered. They state: “*a portfolio approach provides industry and resource managers with a potentially valuable framework to evaluate complex natural resources issues and develop management strategies best suited to balancing multiple objectives*”.

Edwards et al (2004) consider again the fishery sector, in the attempt to find better management strategies, more robust to the plausible expected futures. The predominant approach the governments use to regulate harvests of fish and invertebrate resources treats species in isolation from each other, the so called single-species approach. This approach, based on the maximum sustainable yield (MSY) for each species separately has been criticised by the scientific literature. Therefore, they recommend a portfolio approach as a conceptual model to optimally combine stocks of wild fish species that ecologically interact when jointly caught. A similar aim has been settled in the analysis made by Sanchirico et al (2008). The goal of their work is the use of the portfolio theory in setting catchments level for fishery. They demonstrate that this strategy can improve the yield while diminishing the variance of the fish available. The urgency of this new approach comes from the collapse of some fish stocks in the previous years. They considered the Ecosystem-based fishery management (EBFM) which requires recognition of system component interactions in determining management targets. Thus, they define an efficient frontier with different mixes of total available catches (TACs) for each species, considering the natural relations among them.

In the natural resource management framework, MPT has been used also for the decisions regarding the investments in the forest sector. Knoke et al (2005) develop a portfolio analysis with the aim to identify the better share of different tree species looking at their economic performance and its variability. Historically, in this sector, classical economic calculus leads to a superiority of the profitability of single species coniferous forest management. However, Knoke et al (2005) state that this strategy conducts to an increase of the vulnerability of the forests and a variability of the revenues, due to the loss of biodiversity and a severe reduction in the resistance against storm, snow, ice, drought and insects damage of the forest stands. Moreover, growing trees is an extremely long-term investment in central Europe. Production times of 100 years and more are common and during its lifetime there are several risks that can considerably reduce the expected yields. This is why an investment in this field should be carefully planned, considering also that making changes to the investment during the lifetime of the forest is quite complex and, thus, the robustness of the initial decision is crucial. They consider the work of a Bavarian silviculturalist, Karl Gayer, who claimed, in the 1886, that the forest condition must be able to deal with the uncertainty of future development and recommended the use of “mixed forest”. Starting from this theory, they use a portfolio analysis to compare the performances of a mixed forest management with single species forest management. They demonstrate that mixed forests decrease the risk, even if also the profitability of the forests fall. Risk adverse decision-maker can choose this kind of forest management strategy, due to a significant risk attenuation. They find that the mix between the spruce and beech investment can lead to a less risky strategy (the lowest variability is with 20% spruce and 80% beech). Knoke (2008) come back on this issue in another article with the aim to present different possible decision criteria for the assessment of the portfolios. He discusses three possible rules: i) the mean/variance; ii) the stochastic dominance criterion; iii) the information gap approach. He finds that these different decision rules have different data requirements and therefore they can be used accordingly to the information available. These topics have been discussed also by other contributions: Knoke et al (2015) and Hildebrandt and Knoke (2009; 2011).

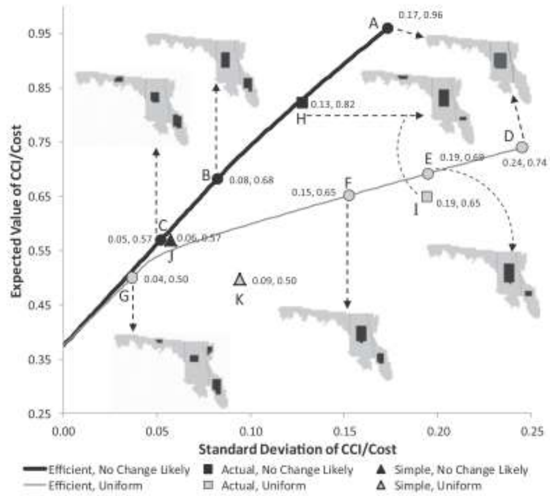
Another interesting perspective comes from Castro et al (2015), who uses the portfolio analysis in the attempt to find the right balance between organic and conventional banana in Ecuador, using the organic one in reducing the volatility of the investments made. The organic cultivation is described as more costly due to more labour contained in the process, but it doesn’t necessitate fertilizers and pesticides, thus, finally, the overall cost results similar. The conventional production is more productive but it is also more volatile, due to the general impoverishment of the soil, the losses of biodiversity and the contamination of the water resources. Moreover, consumers are willing to pay more for the organic products and the prices for these goods are usually more stable, as emerges from an analysis of historic data. Therefore, there is an interesting relation among the two different production alternatives, suggesting the possibilities to explore the portfolio analysis framework in the attempt to identify the opportunities made by mixing the organic and traditional production. In summary, although organic banana appears less attractive as a single option, this option, when embedded in a land-use portfolio together with other crops, may improve the economic return of the Ecuadorian banana farms (Castro et al, 2015). Conclusively, they suggest the general importance of diversification in the management of a farm, even if with wealthier farmers, the attitude toward risk increases. “More intensive diversification is probably more important for poorer farmers, who are both more exposed to and more adverse to risk, and they usually lack strategies to hedge against risks. Ultimately, wealthier farmers can afford better technologies and have better access to information” (Castro et al, 2015).

3.3.2 Portfolio analysis in the climate change framework

Even if the practice of the portfolio analysis in the natural resource management is becoming rich, the experience of this instrument in the climate change field is limited to few examples, focused on the biodiversity management and land-use allocation.

Ando and Mallory (2012) experiments the Modern Portfolio Theory to optimal spatial targeting of conservation activity, using wetland habitat conservation in the Prairie Pothole Region (PPR). The entity responsible for the management of the protected area is the Fish and Wildlife Service and it seeks to quadruple the amount of habitat protected in the PPR. The lands have a different performance in the Cover-Cicle Index (CCI) a measure of wetland habitat quality which creates an order of land with different conservation priorities. The authors identify three different sub-regions of this reserved area in the North of the United States: Western, Central and Eastern. Under historic conditions, modellers find that the best wetland habitat is in the Central subregion and therefore the conservation efforts should be concentrated mainly on this site. However, the quality of the natural environment in that lands is highly influenced by the mean temperature and the distribution of the precipitations. Thus, climate change considerably changes the quality of these areas, eventually compromising the initial investment choices made. In the attempt to find an investment solution more robust to the different possible futures, they structure a portfolio analysis considering the design of different portfolios with different shares of the amount of land in each of the three parts available. The climate change scenarios considered are four (no climate change, +2°, +4° and + 4° C with precipitation increased by +10%) and they test two different distribution of probabilities for these futures. Due to the high uncertainty connected to climate change they consider two sample probabilities distributions to demonstrate the sensitivity of optimal portfolio analysis to assumptions about outcome probabilities: i) the first distribution is called “no change likely” and is weighted heavily toward historic conditions, whereas the other is called “uniform” and assumes that each climate scenario is equally likely to occur. They consider as costs the value of the lands that must be purchased and as benefits the suitability of the land due to the Cover-Cycle Index. They structure two different analysis one just focused on the benefits and another one considering a ratio between habitat quality and land cost.

Figure 3.4: Efficient frontier of the land-use decisions



Source: Ando and Mallory (2012)

The figure presents the analysis considering both benefits and costs. The two lines present the two different distribution of probabilities. The thicker one assigns a higher weight to the no climate change scenarios, whereas the narrower one is focused on the uniform weighting. Points A and D are the portfolios with the higher expected return but higher variability and with a prevalence of the central area, whereas, moving to the left parts of the efficient frontiers is possible to find solutions with lower variance, with target lands progressively shifted to the east. Four main conditions are identified for an effective use of the MPT: i) climate change raises a considerable uncertainty in the benefits and costs of a resource management policies; ii) adaptation decisions have to be made much time before this uncertainty might be resolved; iii) the policy is focused on a spatial region over which the outcome of interest is somewhat fungible; iv) although the MPT can be used in vary circumstances, the best results of the diversification exercise emerge when the performances of the different assets are negatively correlated.

Mallory and Ando (2014) presented another work on this case study, developing some key dimensions connected to the counting of the economic benefits of the preserved lands. They suggest to use the economic value of the land in the case that economic value is not perfectly correlated with the parameter which measure the quality of the land. To generate plausible monetary values for the benefits associated with conservation of habitat which varies in quality, they use estimates of willingness to pay for wetland retention and restoration from a study in a Canadian portion of the PPR that borders the US. The analysis makes also assumptions about the possible evolution of the benefits according to the impacts of climate change. However, both the cost of the land and the willingness to pay could vary according to climate change and the scarcity of the land in the future and these values are essential in finding the correct shape of the efficient frontier. Therefore, an accurate analysis of these parameters is highly recommended.

Ando et al (2018) work again on the MPT in the natural conservancy context and they make a comparison between three portfolio analysis case studies in the United States, with the aim to find key characteristics which are good indicators of the suitability of the portfolio analysis: many negative correlations among the ecological returns in different assets; a second-best asset that has expected ecological returns almost as good as the returns in the best asset; and many assets that have little uncertainty in their ecological outcomes across climate scenarios. Those three characteristics are intuitive, so resource-investment planners can anticipate whether a case is likely to have any of those features and thus whether MPT is likely to have any of those features and thus whether MPT is likely to provide low-cost environmental risk reduction.

Another climate change case study is proposed by Crowe and Parker (2008), who show how MPT can use the results of a climate change impact model to select an optimal set of seed sources to be used in regenerating forests of white spruce in an environment of multiple, equally plausible future climates. This study shows that components of solutions are not selected to perform equally well across all plausible futures; but rather, that components are selected to specialise in particular climate scenarios. The negative correlation between the performances of the assets in the portfolios makes the investment more stable. Here, MPT is again recognized as a powerful instrument in dealing with uncertainty, helpful in taking robust decisions.

Dittrich et al (2017) present instead an analysis of the adaptation strategies suggested for the livestock sector, and they recommend the portfolio analysis for the economic appraisal of long-lifetime measures in the attempt to combat heat stress in livestock. Their approach to address heat stress in livestock is to diversify the breeds in a particular herd to reduce the risk of heat stress while trading off some productivity. Having a number of high-productivity animals in the herd with low heat tolerance levels and a number of lower-productivity animals with high heat tolerance will achieve this objective. It should be noted that this is not an adaptation to long-term temperature changes (as the productive lifetime of a dairy cow usually does not exceed 5 years); rather, it is an adaptation to increased variability in climate due to climate change.

Conclusions

The Modern Portfolio Theory is fundamentally based on the seminal work of Markowitz (1952), which started to systematise some key concepts of this discipline and started the use of this methodology in the finance sector. This instrument has the capacity to help the decision-makers, both private and public, in planning investment in an uncertain framework, giving them the opportunity to find ways to reduce the variability of the expected outcomes, without losing economic returns. This is why MPT overcame the boundaries of the finance sector and it has been widely used also in other fields: energy sector, fishes harvesting decisions, biodiversity conservation, forest management, agriculture, water resource management, invasive pest and disease surveillance, spatial planning and conservation under climate uncertainty. Ecologists have also recognised a positive effect of the diversification in natural systems, similar to the one of the portfolio management, by which communities with high diversity tend to produce more stable streams of ecosystem services.

The starting point of Markowitz's research is the refusal of the idea that the goal of the investor is the maximization of the discounted expected revenues of his investment. Investment decisions are made in a context of uncertainty about the future conditions and outcomes, therefore there is no perfect knowledge about the investment revenues. The investor surely considers the expected revenues as a desirable thing, but he looks also at the variability of this amount according to the plurality of possible futures. The aim of the investor, and the reason why he decides to diversify his investment in a portfolio, is the maximization of the expected return given his tolerance of risk. Alternatively stated, an investor seeks to minimize the risk at which he is exposed given some target expected return.

Therefore, the two decisive decision criteria are: i) the economic return (usually represented by the Expected Net Present Value); and ii) the variance or standard deviation of the economic return. The key insight of the MPT is that the diversification of the investment along different assets allows the decision-maker to find portfolios which can improve the performance of his investment strategies. The risk of the portfolios, i.e. the standard deviation, essentially depends on three main dimensions:

i) The standard deviation of each security
ii) The correlation between each asset
iii) The amount of the investment assigned to each security

The methodology of the portfolio analysis is composed by various important steps, which have been discussed in detail in this part of the thesis:

i) Firstly, the portfolio manager, i.e. the decision-maker, has to be identified, analysing its fundamental goals and exploring its available solutions;
ii) Then, the assets, e.g. the adaptation measures, have to be carefully analysed, describing their essential characteristics and the trends of the past performances (in economic terms or as a specific service produced);
iii) Another preliminary step regards the identification of the possible future scenarios (e.g. the climate change scenarios) and the description of their principal features, the scientific sources available, the predicted increases of the average temperatures and the variability of the other weather components;

iv) In the fourth step the economic performances of the assets have to be identified, considering all the scenarios previously selected: their economic return (ENPV) and the variance of this value along the different scenarios;
v) Then, the analyst should value the statistical correlation coefficient among the economic performances of the assets in the various scenarios, selecting the assets which are not perfectly correlated (correlation < 1);
vi) In the sixth step the assets selected have to be aggregated in the portfolios, dividing the whole investment in the assets, representing all the possible shares;
vii) Then, the ENPV and the variance or standard deviation of each portfolio have to be estimated;
viii) After that, the portfolios should be represented on a diagram, with the economic return on the y axis and the standard deviation on the x axis;
ix) The portfolios with the best trade-offs among the ENPV and the standard deviation are the ones on the efficient frontier; The efficient frontier is defined as "*the curve which contains the portfolios that have the highest expected return among the all feasible that have the same risk*";
x) Lastly, the decision-maker can choose her preferred portfolio, looking at the ones on the efficient frontier and deciding on the basis of her utility function.

The application of this methodology has been effective in several analytical frameworks, with the goal to identify economically efficient investments in various uncertain contexts. According to the literature review, the MPT has the following key strengths:

i) It is a strong analytical tool for the inclusion of the uncertainty and of a plurality of possible scenarios in the economic analysis;
ii) It demonstrates the power of diversification for the reduction of risk and to increase the performances of a natural site or a natural resource;
iii) It can be used in different contexts, due to its versatility and its capacity to deal with different kinds of data and measurements;
iv) The results are presented on the efficient frontier, an effective instrument for the communication of the performances of the different investments, collected in the various portfolios

However, even some limits emerge from the literature review made in this dissertation:

i) In some cases, portfolio analysis requires a significant amount of data and information;
ii) Natural performances and services provided could be used instead of economic values in the attempt to extend the number of interventions that this tool can evaluate. However, in some cases the use of economic data leads to completely different results. Therefore, portfolio analysis seems to remain in the boundaries of an economic analysis, with the strengths and weaknesses of this field. It should be integrated with other inquiries: e.g. an analysis of the preferences of the local stakeholders, an extended analysis of the environmental or social effects of the project;
iii) Portfolio analysis still relies on probabilities for the evaluation of the ENPV;
iv) It requires good computational skills and it is highly time consuming.

4 Case study: Portfolio analysis of adaptation measures in the tea sector in Rwanda considering the expected impacts of climate change

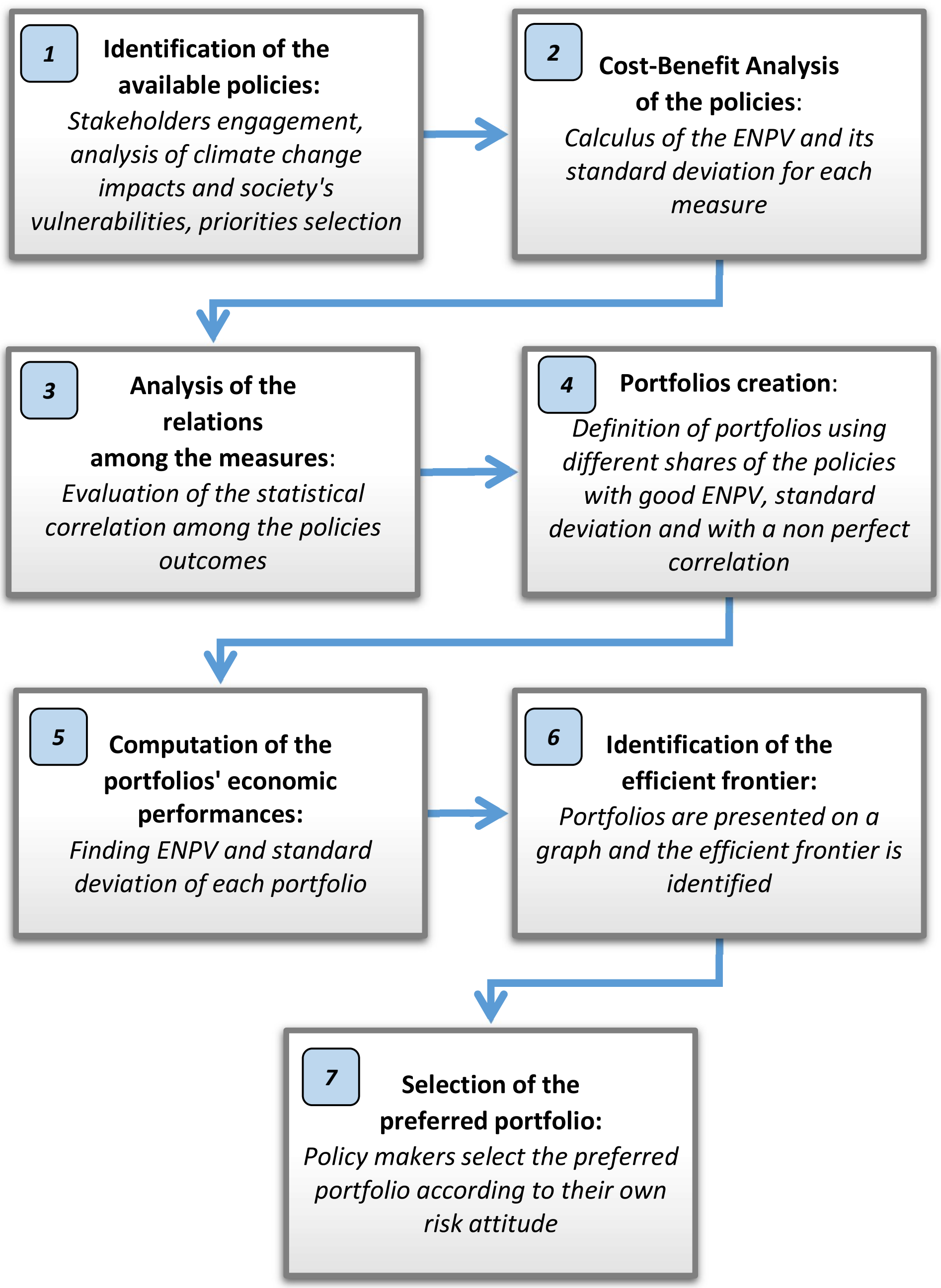
Introduction

Climate change is a key challenge for our societies (IPCC, 2014; United Nations, 2015; UNFCCC, 2015). Every public or private decision influenced by or regarding climate sensitive dimensions has to deal with this crucial issue. The rise of the temperature influences several natural aspects, like the pattern of the precipitations, the length of the dry periods, the frequency and intensity of the extreme events in general. The intensity of these changes and the scientific knowledge about climate are continuously evolving. It is possible to recognize changes in the present, i.e. trends, comparing the climate of the beginning of the XX century with the last thirty years. However, the rate of these changes will not probably remain the same in the future. As discussed in the first chapter, these changes could be stronger or weaker depending on various aspects, some of them connected with our mitigation efforts and other ones related to natural processes which are still not perfectly known (Pindyck, 2006; Markandya, 2014; Heal et al, 2002; Schneider and Kuntz-Duriseti, 2002; Schneider, 2004; UKCIP, 2003; Heal and Millner, 2017; Hallegatte, 2012). Therefore, considering the framework of the public policy decisions, climate change represents a new and consistent element of uncertainty (Watkiss et al., 2015, Jones et al., 2014; Heal and Millner, 2014), it produces new significant obstacles for the decision-making processes and it complicates the economic analysis of the public investments. Hereby, a common question in the climate change adaptation literature is (Wilby and Dessai, 2010): how can we ensure that adaptation measures realize societal benefits now, and over coming decades, despite the uncertainty about climate variability and change?

This chapter presents the application of the Modern Portfolio Theory (MPT) methodology in a case study about agricultural investments in a developing country, Rwanda, including in the analysis the expected effects of climate change. It tries to test this economic tool with the aim to identify useful insights, in the attempt to enrich the scientific literature on the climate change adaptation practices and decisions. The analysis made in this chapter is fundamentally based on economic values, using the economic efficiency criteria as a guiding principle for the selection among measures. However, it is evident that the adaptation policies are complex and multidimensional, requiring more than economic indications about the efficiency of development investments. As highly argued in the scientific and institutional literature, a public adaptation policy should engage the local community in the identification of needs and vulnerabilities, looking at the local values and priorities. Furthermore, there are several, multifaceted, approaches for climate change adaptation in the agriculture sector. Various techniques, technological solutions, early warning instruments and new efficient irrigation practices have been developed, and analysed by the literature, for the adaptation of the farmers to climate change. However, this study has not the ambition to exhaustively provide recommendations and instruments for the development of a climate change resilient agriculture in developing countries. Following the indications coming from the most relevant scientific literature on adaptation, this research starts from the assumption that new decision support tools should be tested and disseminated, with the aim to help the decision-makers in identifying the costs and benefits of the adaptation policies, clearing the way for the implementation of concrete and effective measures.

The portfolio analysis is here tested, looking at the strengths and weaknesses of this tool in designing good adaptation investments and in facing the wide uncertainty generated by climate change. The key steps of this analysis are the same presented in the previous methodological chapter. Firstly, a Cost Benefit Analysis of the available adaptation investments will be performed, finding the Expected Net Present Value and the Standard Deviation of these measures. Then, the statistical correlation among the investments will be estimated, with the goal to exclude from the analysis the solutions that are perfectly correlated. As discussed in the methodology, the mix of perfectly correlated measures does not reduce the risk of the investment, which results as the sum between the risks of the two measures. In the next step, the selected measures will be mixed in portfolios and their ENPVs and Standard Deviations will be estimated. Lastly, the portfolios will be presented on a diagram and the efficient frontier will be identified, leaving to the decision-makers the selection of the preferred solutions according to their own risk attitudes.

Figure 4.1: Key steps of the portfolio analysis



Source: personal elaboration

There are two main reasons why we think that the application of this decision support tool to agriculture in a climate change framework is important.

Firstly, MPT has been applied several times to agriculture but there are no examples of the application of this tool with the inclusion of the climate scenarios. In this research work we instead experiment the strengths of this instrument in finding good investment solutions taking into account the possible uncertain effects of climate change, even the ones in the distant future.

Secondly, agriculture is a pillar of the development of poor countries and, at the same time, it is one of the most affected sectors by the current and expected impacts of climate change, thus requiring new and urgent strategies for the identification of adaptation solutions. In developing countries, agriculture employs large part of the population and it produces key assets for the wellbeing of the people and for the growth of the foreign trades. As indicated in the SDG 1 "End poverty in all its forms everywhere" and SDG 2 "End hunger, achieve food security and improved nutrition and promote sustainable agriculture", agriculture is essential for the achievement of the basic needs of the population. However, climate change is already having a dramatic impact on this sector. The Paris Agreement (2015) recognizes in its Preamble "*the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse effects of climate change*". Climate change might compromise the efforts made by these countries in pursuing a sustainable development, worsening the key meteorological components needed for efficient crops investments. Agriculture is thus highly considered in the scientific and institutional literature about climate change. The UNFCCC explicitly mentions the agriculture both in the mitigation and adaptation sections. Article 4 (1)(c) requests Parties to "*Promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases*". In this section, agriculture (and forestry) is mentioned alongside all other sectors. Article 4 (1)(e) commits instead Parties to cooperate in preparing for adaptation to the impacts of climate change. Here, agriculture has a more specific role: "*the development of appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas affected by drought and desertification, as well as floods*", are emphasized. Agriculture is an important topic also in the other key documents produced by the UNFCCC, as the Cancun Adaptation Framework (2010), and it is now reaching a central role thanks to the Koronivia Joint Work on Agriculture (in force in 2020), a thematic panel of the Convention which has the goal to identify the vulnerabilities of agricultural systems to climate change and possible responses both in the field of mitigation and adaptation.

4.1 The Rwanda case study

The case study is fundamentally focused on the development of the tea sector in Rwanda, through the selection of locations for the plantation of new tea plants that are robust to all the possible expected climate change scenarios.

Tea is one of the most important cash crops worldwide and it plays a significant role in rural development, poverty reduction and food security in developing countries (FAO, 2014). Tea is planted in 58 countries in all 5 continents with Asia having the largest area dedicated to tea leaves production, followed by Africa. In 2012, the total land under tea cultivation was 3.36 million hectares, whereas the production was 4.78 million tons (FAO, 2015). Rwanda is highly reliant on the agriculture sector and especially on tea, and the government is trying to implement his new development strategy, the Economic Development and Poverty Reduction Strategy II 2013-2018 (Republic of Rwanda, 2013), in the attempt to reach the status of middle developed country by the 2020. One of the key interventions of this strategy is the expansion of the tea plantations, in order to increase the tea leaves production, a key element of the trade relations with the foreign countries. The Rwanda government wants to identify the best locations for these investments, providing the local investors the information about the suitability of a specific site to the growing of tea. Tea is particularly sensitive to weather conditions and temperature, which influence the quality and quantity of the tea leaves production. This is why a specific site might be highly appropriate for the growth of tea in the present but, in the case of severe climate changes, it might become not suitable and inefficient compared with other sites. Moreover, tea plants are considered a perennial crop, requiring 7/8 years to reach the maximum production possible, and the investment has high sunk costs, necessitating several years to refund the initial outflow. Therefore, the investment decision should be carefully planned, considering the expected climate characteristics of the site in the coming decades. The farmer cannot ignore that the climate is no longer stable, and it might significantly change in the future. In Kenya, tea's optimum altitude band is currently between 1,500 mt and 2,100 mt (CIAT, 2011). However, the International Centre for Tropical Agriculture (CIAT, 2011) projects that this optimal band will shift to between 2,000 mt and 2,300 mt by 2050 as a result of climate change. Given the proximity of Rwanda to Kenya, locations in Rwanda that are suitable to grow tea today may not be suitable in future climate scenarios.

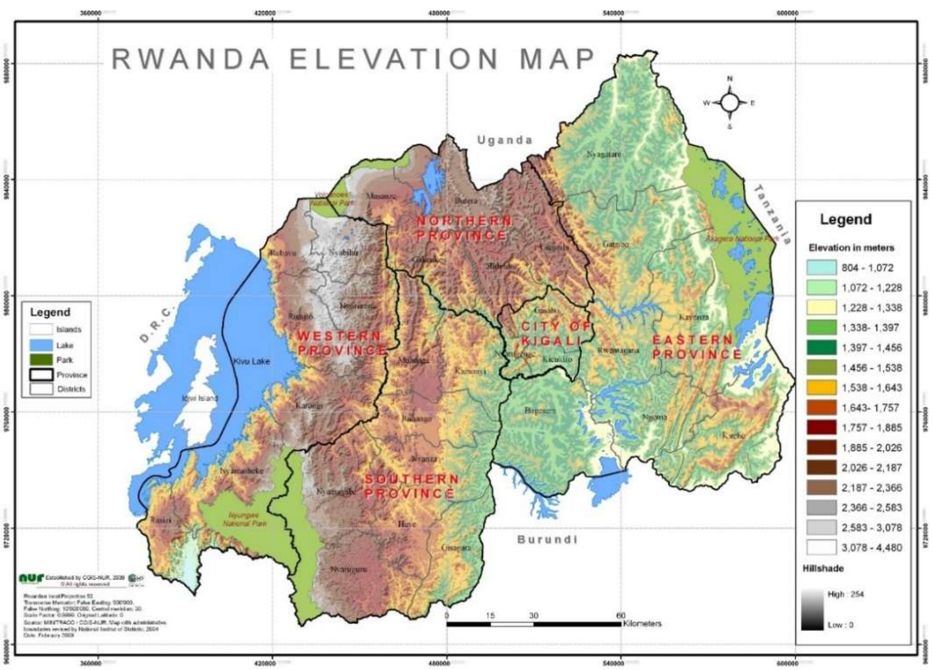
However, although the potential for private self-adaptation is high, especially in the agriculture sector (Fankhauser 2017), dealing with long-term investments could be confusing because an effective private action depends on good information on both the nature of risks and the related adaptation measures (Tietenberg, 2018). However, most of the data about climate change risks is a public good, hereby it will be undersupplied unless the government provides it or cooperates in its supply. In this case study, the Rwandan farmers would probably choose locations that are currently suitable for the tea investments without considering the possible effects of climate change in the future. The information about climate change cannot be easily found by the private investors, especially when they have no access to the complex scientific data of the local or international meteorological institutions.

Due to these key findings, there is a strong need of climate information and economic analysis of adaptation in the agriculture sector, especially in the case of perennial crops, such as tea, where the initial investment decision implies high costs which cannot be recovered in the short period. The information about the performances of the various tea expansion sites is essential in the attempt to find an effective investment, considering the changes of the climate. Thus, the aim of this case study is to experiment Portfolio Analysis as an economic tool able to deal with deep uncertainty, giving important insights to the investors and helping them in making good decisions, robust to all the possible climate futures.

4.1.1 Rwanda country framework

Rwanda is located in the tropical Great Lakes region of East-Central Africa between latitudes 10°S and 30°S, and longitudes 29°E and 31°E. Rwanda is basically a mountainous country: the altitude considerably varies between the East part, where the lowest point (950m) is located and the west part, where the Albertine Rift Mountains dominates, with the Mount Karisimbi, part of the Virunga Volcano, which reaches 4,500 mt.

Figure 4.2: Rwanda elevation map



Source: University of Rwanda, GIS Centre, http://cgis.ur.ac.rw/content/rwanda-elevation-map

Rwanda has a population of 12.2 million[7], 70% concentrated in rural areas, observing an increase of 2,5% every year during the last fifteen years, the same rate of the whole East Africa. It is a small country and the population density is high, reaching 471 persons each square kilometre in 2015, higher than the average of the Eastern African Countries, i.e. 199 (the most densely populated area in Africa) (UNDESA Population Division website). According to FAO (Faostat)[8], besides the increase of the population, there has been an increase of the undernourished people also, mainly because the occurrence of severe droughts in 2015 and 2016. Between 2010 and 2014 the number of undernourished people remained stable at 3.5 million, whereas it has significantly risen at 4.3 million in the three years period 2015-2017, reaching a share of 36.1% of the entire population (the first inversion of the decreasing tendency which characterised Rwanda since the beginning of the twenty-first century). The population of Rwanda will more than double in 2050, passing from 11 million today to 26 million. The urbanization will increase too, at a

[7] United Nations Department of Economic and Social Affair, Population Division - https://www.un.org/en/development/desa/population/index.asp
[8] http://www.fao.org/faostat/en/#country/184

significant rate, i.e. +4.4% per year. Therefore, the pressures on the environment and on the natural resources will probably rise, because of climate change and human activities. As mentioned in other official documents, Rwanda is highly reliant on rain-fed agriculture, both for households' everyday consumption and as a driver of the international trades. Rwanda also depends on hydropower for half of its electricity generation. The country is highly dependent on external imports of oil-based products, which sustain the 39% of the electricity generation and the whole transport sector. Moreover, Rwanda is one of the less responsible countries for the current climate changes, since its greenhouse gas production is among the lowest in the world (0.4 tCO_2e/person compared to a global average of 6.7 tCO_2e/person), fundamentally caused by agriculture and energy production.

Rwanda's economy has been growing steadily for most of the past decade, at rates ranging between 6-7% and often exceeding double digits (11.8% in 2008). In the third quarter of 2014, the economy grew at an impressive 7.8%, although it slowed in 2015 and 2016, growing with a slower pace, i.e. 3.3% and 2.4%, because of the occurrence of an extended drought. Then, the economy restarted to grow with high rates, reaching the 7.8% in 2017 (World Bank). This rate makes Rwanda one of the fastest growing economies in the world. This growth is the result of steady and consistent investments in areas that drive the economy, such as infrastructure (mostly roads and electricity), agricultural production, tourism promotion, and more recently, mining.

According to the Statistical Update of the UNDP (2019), Rwanda has an HDI value of 0.536 (in 2018), positioning it at 157 out of 189 countries and territories, in the category of the low human development nations (but above their average value of 0.504). However, again, between 1990 and 2010, Rwanda has registered a considerable increase in all the components of the HDI (life expectancy, education, GNI) and the overall score almost doubled, passing from 0.245 (among the worst nations) to 0.488. Rwanda has reached and exceeded most of the Millennium Development Goals targets, although, as we mentioned earlier, malnutrition or stunting are still a consistent problem for the country and the overall economic performance still considerably relies on the agriculture sector.

Agriculture is still highly dependent on the weather conditions, which are a constant risk element to the growth outlook, as was made clear when a drought slowed the growth in 2016 and the first half of 2017 (World Bank Group, 2018). Rwanda still depends heavily on rain-fed agriculture with just the 4.6% of the intensive croplands irrigated. Therefore, climate changes could be particularly dangerous for the country. Global warming is going to modify the pattern of the precipitations, the length of the dry periods and the average degree of the temperature. These dimensions might compromise the efforts made by the country in the last years, producing consistent shocks to the economy. However, The Government of Rwanda is still relying on the agriculture sector in its second Economic Development and Poverty Reduction Strategy (EDPRS II). The main aim of this strategy is to move towards a middle-income country status, continuing the work made for the achievement of the Millennium Development Goals. Rural Development is one of the thematic priority areas and it is considered a key asset for a sustainable poverty reduction as it engages the vast majority of the population (EDPRS II).

Moreover, in 2007, Rwanda signed the Comprehensive Africa Agriculture Development Programme (CAADP). Following the CAADP recommendations, the share of the national budget allocated to agriculture increased from 3% in 2006 to 10.7% in 2013.

Table 4.1: Rwanda development indicators

	Selected indicators		2007	2009	2011	2014
SOCIO-ECONOMIC	GDP (current billion US$) *		3.8	5.3	6.4	7.89
	GDP per capita (current US$) *		380.3	504.2	574.9	695.7
	Agricultural value added (% of GDP) *		35.1	33.9	32.3	33.1
	Agricultural value added (annual % growth) *	(average 2007-2013)	5.18			
		(2013)	5.3			
	Total population (thousand)		9 481.1	10 024.6	10 556.4	11 341.5
	Rural population (% of total)		82.6	80.9	79.3	77
	Agricultural labour force (% of total labour force)		89.9	89.6	89.2	88.9 (2013)
	Human Development Index **	(2014)	0.483			
AGRICULTURAL PRODUCTION & TRADE	Per capita cultivated land (ha)		0.14	0.14	0.13	0.13
	Area equipped for irrigation (ha)		96000 (2012)			
	Value of total agriculture (current million US$)		1 783.5	2 788.1	3 339.4	4 377.7 (2013)
	Value of cereals production (current million US$)		145.9	322.8	388.0	4 74.3 (2013)
	Yield for cereals (hg/ha)		10 136.5	17 479.0	2 1062.3	2 1718.2
	Cereal import dependency ratio (%, average 2009-2011)		23.7			
	Top 3 commodities	Production quantity	plantains; cassava; potatoes (2012)			
		Production value	plantains; potatoes; cassava (2012)			
		Import quantity	wheat; maize; sugar raw centrifugal (2011)			
		Import value	wheat; palm oil; sugar raw centrifugal (2011)			
		Export quantity	tea; coffee, green; potatoes (2011)			
		Export value	coffee, green; tea; flour of wheat (2011)			
	Top 3 trade partners (2011)	Import value	Uganda; Kenya; Italy (2011)			
		Export value	Kenya; Switzerland; Democratic Republic of the Congo (2011)			
FOOD SECURITY & NUTRITION	Top 3 commodities available for consumption		Plantains; Cassava and products; Beans (2011)			
	Per capita food supply (kcal/capita/day)		1 997	2 128	2 148	NA
	General (g) and Food (f) CPI (2000=100)		NA	96.7(g), 96(f)	104.1(g, 103.3(f)	124.0(g), 135.0(f)
	People undernourished (million)		4.5	4.4	4.2	4.0
	Proportion of undernourished in total population (%)	(2008-2010)	45.2	42.8	40.1	37.3
	Prevalence of underweight children under 5 years of age		11.7 (2010)			
	Global Hunger Index ^	(2015)	30.3 (serious)			
	Access to improved water sources (% of population) *		71	72	74	76

Sources: FAOSTAT; *WB; **UNDP; ^ IFPRI (accessed on day, month, year)
Note : Food CPI 2009 and 2012: Index base 2008=100

Source: FAO (2016)

Rwanda is recovering from the 1994 genocide, which severely impoverished the population and stalled the country's private and external investments. This made the country highly dependent on external aids. The Government of Rwanda (GoR) has embraced an expansionary fiscal policy to reduce its external reliance by improving education, infrastructure, foreign and domestic investments and pursuing market-oriented reforms (FAO, 2016).

The Rwandan economy is primarily based on rain-fed agriculture, with coffee and tea as the major cash crops. Farms are small, fragmented, and semi-subsistence oriented. Agriculture accounts for 35% of gross domestic product (GDP) and almost 90% of total employment (FAO, 2016). Rwandan agriculture has made major advances in the last decade. Productivity for a number of crops has sharply improved (and therefore, rural incomes) due to significant interventions regarding land consolidation, expansion of areas under irrigation and protected against soil erosion, increased cultivated terraces and improved use of inputs. Access to agricultural finance and microfinance services has sharply increased, playing a key role in risk reduction and investing in many farms along the country (FAO, 2016). Since 90% of domestic cropland is on slopes ranging from 5% to 55%, investing in land management and related training to farmers has been essential in improving productivity. Rwanda has been intensifying production in marshlands and hillsides with the support of the World Bank (WB) since 2001 through the Rural Sector Support Project (RSSP). Since 2010, support is also provided through the Land Husbandry Water Harvesting and Hillside Irrigation (LWH) Project. So far, over 7,200 hectares of marshlands and nearly 30,000 hectares of hillsides have been sustainably rehabilitated.

This has directly contributed to increases in maize yields from 1.6 tonnes hectares to nearly 5 tonnes hectares, potato yields from 7 tonnes ha to 20 tonnes ha and rice yields from 3 tonnes ha to 7.9 tonnes ha.

The trade sector has an important role for the Rwandan economy. Rwanda started to develop its trade policy in 2010, releasing the National Export Strategy. Rwanda is a member of the East African Community (EAC), the Common Market for Eastern and Southern Africa (COMESA) and the Commonwealth. The country has also signed international agreements which permit it to enjoy duty-free and quota-free access to the EU and US markets. Although it still faces a trade deficit, exports are steadily increasing, and the government has the objective to move from subsistence to commercial agriculture.

Tea is an essential asset for the economy of Rwanda and an expanding commodity on the international markets. World tea production increased by 4.4% annually over the last decade to reach 5.73 million tons in 2016. China had the leading role in this growth, doubling its production from 1.17 million tons in 2007 to 2.44 million tons in 2016, entirely due to the increase of the domestic demand (FAO, 2018). This amount of production places China at the first position in the global production of tea, reaching the 42.6% of the world tea production. India holds the second place, with a domestic production of 1.27 million tons. Export earnings at the global level increased by 75% over the 10 years, from USD 3.12 billion in 2007 to USD 5.46 billion in 2016, contributing to improved rural incomes and household food security in tea producing countries. Between 2007 and 2016 the significant increase of the exports has been absorbed by the impressive growth of the internal demand of Africa and Asia, whereas the consumption in the European countries decreased by 17%. Rwanda is among the countries with the highest increase, with a rate of 110.2% (Malawi had a growth of 565.2% and China grew by 128.6%). The African countries are expected to lead the increase of consumption forecasted for the next decade. Rwanda internal consumption will rise by 9%, Uganda 5% and Kenya 4.4%. Asian countries internal consumption will grow slowly, apart from China, with its 5.9% of annual expected increase (FAO, 2018). The exports of both black and green tea will grow in the next decade, with Kenya keeping its leading role in the black tea international market, whereas China is expected to continue to dominate the green tea export. Rwanda is expected to become one of the ten most important countries for the export of black tea, reaching the 8^{th} place by 2027.

Table 4.2: Black Tea - Actual and Projected Production

Countries / Regions	PRODUCTION			
	Estimated 2017	Projected 2027	Growth Rates 2008/2017	2018/2027
	Tons		Percent per year	
WORLD	**3333316**	**4420015**	**3.1**	**2.2**
Africa				
Kenya	439850	605915	3.4	2.7
Malawi	43127	42833	-1.5	-0.3
Zimbabwe	8500	9848	0.7	1.4
Rwanda	24000	30942	2.1	2.5
South Africa	2400	5177	4.2	7.6
Uganda	61411	82426	2.6	2.6
Tanzania United Rep	34000	42770	0.5	2.3
Other	42715	53448	2.1	2.1
Latin America and Caribbean				
Argentina	79000	100782	-0.4	2.2
Brazil	7000	7009	-2.0	-0.1
Other	9710	11228	1.7	1.2
Near East				
Iran, Islamic Republic of	26000	36430	-5.0	3.4
Turkey	310500	429308	4.9	3.2
Far East				
India	1260000	1617871	3.4	1.4
Sri Lanka	305000	370379	0.0	1.6
China	310000	554331	19.1	5.6
Vietnam	86000	100564	-3.7	1.3
Bangladesh	78659	96696	3.6	1.9
Malaysia	13000	10850	2.2	-1.8
Nepal	24264	29309	5.2	1.8
Indonesia	110195	108673	-1.7	-0.6
Other	42870	50064	1.4	1.3
CIS				
Russian Federation	3800	4349	2.7	1.2
Other CIS	4500	12416	1.1	10.1
Oceania	**6800**	**6382**	**-0.8**	**-0.7**

Source: FAO (2018), Intergovernmental Group on Tea, 23rd Session, Current Market Situation and Medium-term Outlook

Tea has indeed an important role in the trade development strategy of the Government of Rwanda. Since its introduction in the 1950s, tea has been one of the Rwanda's strongest sectors, growing until almost the 35% of the whole national exports. Now the areas planted are approximately 24 thousand ha. The seeds are planted in deep, well-drained, fertile soils with a pH level of between 5.0 and 5.6 and at a minimum depth of two meters. The plants grow best in areas where the rainfalls range between 1,200 to 1,400 mm each year and are evenly distributed, alternating with long sunny days. Rwanda, located in the tropic zone, has the ideal climate to grow tea year-round with minimal seasonal variation in terms of quality. Tea plucking usually continues throughout the year (due to the lack of a cold season), with two peak seasons, between March and June and between October and December (FAO, 2015). Tea production has increased steadily, from 5.909 tonnes of black tea in 1980, to 12,854 tonnes in 1990. In 1994, during the genocide, tea plantations and factories were abandoned, and tea production decreased to 4,136 tonnes of black tea. From 1994 many efforts were made, and tea production increased to 14,874 tonnes in 2000, 15,483 tonnes in 2003, 20,478 tonnes in 2007 and to a peak of 24,066 tonnes in 2011 of black tea, 22,562 tonnes in

2012 and 22,184 tonnes in 2013 (FAOSTAT). The government privatized the tea sector in 2006 and the Rwanda's tea industry is now directly employing approximately 600,000 people, many of them smallholders. Export value increased form US$ 57.8 M in 2014 to US$ 73.5 M in 2016 (UN Comtrade, 2018). Although these significant progresses, Rwanda struggled to compete on the international tea markets (even though it is among the ten best countries for the export of black tea), mainly due to high production and transport costs. In 2008 the Ministry of Trade and Industry published the Revised Tea Strategy for Rwanda, identifying the key steps to develop the sector within the 2020 and a series of measures as improving fertilizer efficacy, training in plucking and pruning, improving transportation, consolidating land plots and promoting the processing of higher value and organic teas.

Table 4.3: Black Tea - Actual and Projected Exports

Countries / Regions	EXPORTS			
	Estimated	Projected	Growth Rates	
	2017	2027	2008/2017	2018/2027
	Tons		Percent per year	
WORLD	**1348512**	**1658514**	**0.8**	**1.2**
Africa				
Kenya	400000	524140	3.5	2.8
Malawi	29290	22814	-5.3	-3.1
Zimbabwe	5800	6390	1.7	0.9
Rwanda	23500	24647	2.2	1.5
South Africa	4510	4781	-1.5	0.0
Uganda	55589	71723	2.5	2.4
Tanzania United Rep	30000	37035	1.5	2.4
Other	25234	20287	2.8	0.0
Far East				
India	240680	362932	2.8	-1.2
Sri Lanka	281840	335522	-0.2	1.4
China	35000	24236	-2.6	-0.8
Vietnam	61850	72315	-4.4	2.8
Bangladesh	650	910	-20.2	0.0
Malaysia	1293	1421	7.7	0.0
Nepal	10334	10835	5.1	-0.7
Indonesia	43338	22969	-8.3	7.5
Other	10903	7292	10.8	0.0
Near East				
Turkey	6117	2191	13.1	0.0
Other	0	0	-	-
Latin America and Caribbean				
Argentina	72693	93766	-0.4	2.3
Brazil	19	2119	-71.3	0.0
Other	972	994	1.9	0.0
CIS				
Russian Federation	0	0	-	-
Other CIS	2500	2300	2.3	0.0
Oceania	6361	6847	-1.8	0.0

Source: FAO (2018), Intergovernmental Group on Tea, 23rd Session, Current Market Situation and Medium-term Outlook

Therefore, the agriculture sector and especially the production and trade of tea are an essential asset for the socio-economic development of Rwanda. The country concentrated substantial efforts in improving the tea yields and their share of the international markets. Furthermore, the tea sector is also employing a consistent part of the society, sustaining the welfare of various households. This is why the development of the tea sector is important for Rwanda and why these new tea plantation investments are essential for the welfare of the country.

Agriculture and land availability were a delicate issue also in the past history of Rwanda. Some researchers have studied the relations among agriculture development, the growth of the population and the social equilibria in the country. These studies should be carefully taken into account, because climate change might exacerbate these challenges, leading the country to new undesired risks. Marijke Verpoorten (2011) studied the Rwanda genocide (April 1994 – June 1994; 800.000 Tutsi died, 75% of the Rwanda's Tutsi population) and found that in the years preceding the genocide, the Rwandan rural population was fighting an uphill battle against land scarcity and soil degradation. In the previous years there has been a significant expansion of agriculture investments and intensive farming techniques, while the space for other activities like the pasture was heavily declining. No significant progresses were made towards modern agricultural intensification, leaving the use of improved seeds and fertilizers in Rwanda well below that of the Sub-Saharan average. The productivity of the lands was drastically decreasing. Thus, there have been a correlation between the mass genocide and the failure to keep the pace of the population increase with the growth of the per-capita food production. Several studies highlighted this correlation. Moreover, authorities offered incentives to the participants, e.g. the fields left vacant by Tutsi victims. Therefore, even though the most important elements for the Rwandan genocide were the ethnic polarization and the elite insecurity, the struggle over the control of scarce resources has been a key factor too (Verpoorten, 2011). Various researches have then been written about the relations between climate change, environment degradations, social conflicts, migrations and struggles for the acquisition of scarce natural resources. However, this is not the principal goal of this dissertation and this analysis might be further developed in an eventual next version of this research work.

4.1.2 Rwanda policy framework

This dissertation is focused on the evaluation of a specific adaptation measure: the integration of climate change predictions in the development of new tea plantations, in the attempt to consider the wide uncertainty about the future climate conditions. Although this is an important adaptation measure, especially for a country highly reliant on tea production and export, a proper adaptation policy requires an overarching adaptation strategy, which should be strictly connected to the general development goals of the country. This is why this dissertation focuses now on the policy framework produced in the last years by the Rwandan Government. The analysis starts from the two essential development documents of the Rwandan public administration: The Vision 2020 and the Economic Development and Poverty Reduction Strategy. Then, other secondary political strategies are assessed. Lastly, the climate change official strategies are described, in particular the NAPA, the National Strategy for Climate Change and Low Carbon Development and the Nationally Determined Contribution (NDC), with the aim of depicting a comprehensive policy framework of the Rwandan climate change planned policies. This analysis is essential for the understanding of the adaptation needs and strategies of the country, designing a coherent and straightforward picture of the policies and priorities of Rwanda. This framework will give the opportunity to better understand the priorities of the country, presenting the background of the adaptation policies discussed in detail in the portfolio analysis developed in this work.

4.1.2.1 National policy documents

Vision 2020 (2012)

The first key document, which is inspiring the development of the country, is the Vision 2020. Vision 2020 aims to transform Rwanda from a subsistence agriculture economy to a knowledge-based society, making Rwanda a middle-income country by 2020. It is a country-driven strategy, i.e. the outcome of a national consultation process, which engaged public and private stakeholders. The first document was published in 2000, whereas the second edition was released in 2012. The strategy identified a series of challenges for the development of the country: low agricultural productivity and dependency on the exports of coffee and tea; the presence of natural barriers to trade (long distances from oceans ports, lack of a link to the regional railway network and poor quality of the roads which connect Rwanda with the other countries); low level of human resource development; low infrastructure development. Due to these persistent problems, a series of key development priorities has been designed (table 4.4).

Table 4.4: Key pillars of the Vision 2020

<table>
<tr><th>Pillars of Vision 2020</th><th>Cross-cutting areas of Vision 2020</th></tr>
<tr><td>1. Good governance and a capable state</td><td rowspan="2">1. Gender equality</td></tr>
<tr><td>2. Human resource development and a knowledge-based economy</td></tr>
<tr><td>3. A private sector-led economy</td><td rowspan="2">2. Protection of environment and sustainable natural resource management</td></tr>
<tr><td>4. Infrastructure development</td></tr>
<tr><td>5. Productive and market-oriented agriculture</td><td rowspan="2">3. Science and technology, including ICT</td></tr>
<tr><td>6. Regional and international economic integration</td></tr>
</table>

Source: Government of Rwanda, 2012, Vision 2020 (revision)

The Economic Development and Poverty Reduction Strategy II (2013-2018)

The Economic Development and Poverty Reduction Strategy II (EDPRS) is the operational instrument for the achievement of the Vision 2020 and it follows the first EDPRS (2008-2012). The strategy is declined over four main thematic areas, each of them characterised by various priorities.

The first pillar is dedicated to the economic transformation, which is mainly aimed at accelerating the economic growth with an increasing role of the services and the industrial development. Five priorities have been designed: increasing the domestic interconnectivity of the Rwandan economy; increasing the external connectivity (a new airport and appropriate railway connections) and boosting exports; helping the private sector in pursuing long-term investments, raising the accessibility to international financing; promoting infrastructure and investments for the development of Kigali and of secondary cities, in the attempt to foster the growth of non-agricultural activities; pursuing a “green economy” approach to economic transformation. The second thematic area regards the rural development, with the essential goal of reducing the poverty to below 30%. Four priorities have been identified:

ensuring that rural settlements are revisited to ensure greater access to economic opportunities and basic services; increasing the productivity in agriculture (irrigation, advisory services and farmers closer to agrobusiness); providing services to the poorest and monitoring their progresses outside the extreme poverty; connecting rural communities to economic opportunities. The third thematic area is dedicated to productivity and youth employment. The main objective is the creation of at least 200,000 new jobs annually moving towards the Vision 2020 objective of 50% of the workforce engaged in off-farm sectors. The priorities designed for this area are: promoting new national education curricula, internships, courses and short training skills in the attempt to develop new competencies and attitudes; promoting technology with a focus on accelerating innovation and improving ICT skills; stimulating entrepreneurship, access to finance and business development; labour market interventions, especially focused on the development of Employment Service and Career Advisory Centres. The last thematic area is focused on increasing the quality and reliability of the services provided by the government, rising also the participation of the citizens to the government of the country. Two main priorities have been defined: strengthening media and ICT mechanisms to promote the engagement of the communities in the development of the country; improving the quality of the services provided by the public administration, with a customer-centred service delivery culture.

4.1.2.2 Climate change policy documents

Rwanda National Adaptation Program of Action (2006)

NAPAs are tools for Least Developed Countries (LDCs) to identify urgent activities that are considered particularly relevant to adapt to the most immediate consequences of climate change. NAPAs have been established by the UNFCCC in 2001 and their development makes a country eligible under the Least Developed Countries Fund (LDCF) of the Global Environmental Facility (GEF). The NAPA of Rwanda constitutes an integration of the EDPRS I (2008-2013). The document has been developed with the financial and technical support of GEF and United Nations Environmental Programme (UNEP). In its NAPA, the Rwandan government highlights that the country is with no doubt vulnerable to the negative effects of climate change, mainly because its economy depends on rain-fed agriculture. Moreover, with a rate of 60% of the population below the poverty line, its adaptive capacity to impacts related to extreme meteorological events is very low.

Thanks to this document, Rwanda has analysed the present vulnerabilities to climate change, the most vulnerable groups of population, the most vulnerable regions and sectors, the adaptation priorities and the immediate activities and projects to be implemented. The document identified a strategy for the adaptation to climate change, which is composed by six priority adaptation options: i) an integrated water resource management; ii) an information system to early warning of hydro-agro meteorological system and rapid intervention mechanisms; iii) promotion of non-agricultural income generating activities; iv) promotion of intensive agro-pastoral activities; v) introduction of species resisting to environmental conditions and climatic pressures; vi) development of firewood alternative sources of energy. Starting from these key needs, 7 high primary projects, hence urgent and immediate, have been selected and their profiles developed: land conservation and protection against erosion and floods; installation and rehabilitation of hydrological and meteorological stations; development of irrigated areas by gravity water systems; planning and implementing measures and techniques related to conservation and water harvesting and intensive agriculture and promoting existing and new resistant varieties of crops adapted to different bioclimatic soils; increase the adaptive capacity of vulnerable communities, improving the access to drinking water, sanitation and alternative energy services and the promotion of non-agricultural jobs; increase the supply methods for food and medicine during the extreme events and the stocking and conservation of agriculture products; preparation and implementation of woody combustible substitution national strategy to combat the deforestation and erosion as well. These projects were launched in the 2007.

Green Growth and Climate Resilience, a National Strategy for Climate Change and Low Carbon Development (2011)

This strategy has been produced thanks to the collaboration between the Government of Rwanda, the Smith School of Enterprise and the Environment of the University of Oxford and the UK Department for International Development. This is the second key document on Rwandan climate change policies. The purpose of the strategy is identified by three main pillars: i) guiding national policies and planning in an integrated way; ii) mainstreaming climate change into all sectors of the economy; iii) increasing the ability of Rwanda to access international funding in order to achieve climate resilience and low carbon development. The strategy imagines the country in 2050, a nation with a strong service sector, low unemployment and low levels of poverty, where agriculture and industry have a minimal negative impact on the environment. By 2050 development is expected to be achieved with low carbon domestic energy resources and the country will develop a local and regional knowledge hub for the improvement of the climate awareness and the dissemination of scientific information.

The strategy is an overarching document on the challenges posed by climate change, and it includes both mitigation and adaptation actions that should be mainstreamed into the Vision 2020 and the EDPRS II 2013-2018. Three key goals have been defined: i) energy security and a low carbon energy supply that supports the development of green industry and services; ii) sustainable land use and water resource management that results in food security, appropriate urban development and preservation of biodiversity and ecosystem services; iii) social protection, improved health and disaster risk reduction that reduces vulnerability to climate change. These overarching objectives are then declined in 14 Programmes of Action (e.g. low carbon energy grid, climate data and projections, sustainable land use management, …) which can be pursued through 5 Enabling Pillars (i.e. institutional arrangements, finance, capacity building and knowledge management, technology innovation and infrastructure, integrated planning and data management).

The implementation of these programmes will be realized thanks to 7 fundamental actions, which are called “Big Wins”. These solutions are the ones with the most significant return for the investment and they will have a long-term effect on the future human development of the country. Three of them are mitigation measures: i) the growth of the geothermal energy production; ii) the application of an integrated approach to soil fertility and nutrient management, instead of relying on inorganic, imported, fertilizers; iii) the development of high-density walkable cities, where pedestrians, cyclists and green spaces are the pillars for the urban life. On the other hand, the Big Win measures selected for adaptation are: i) the improvement of the infrastructure for irrigation (which also allows the cultivation of different crops and the agriculture diversification); ii) the building of a robust road network, able to deal with floods; iii) the development of a Centre for Climate Knowledge for Development, which faces the lack of sufficient and reliable data that affect the African countries; iv) the development of agroforestry, that will give wood for cooking, a new source of income and a good protection against erosions and floods.

Besides these seven big long-term measures, a series of immediate tasks have been identified: i) integrate the diverse sector of the administration in the implementation of climate resilient low carbon development in rural areas; ii) operationalise the National Fund for Climate and Environment (FONERWA) to facilitate the access to international climate finance; iii) implement regular measuring and reporting of greenhouse gas emissions; iv) review and expand the Technical and Vocational Educational and Training programme, to develop skills needed for the strategy implementation; v) set up a climate portal in the attempt to promote the National strategy for climate change; vi) use the strategy to complete the UNEP Technology Needs Assessment, to speed up the technology transfer; vii) implement resource efficient design in the Special Economic Zone (SEX) in Kigali. The National Fund for Climate and Environment was created in May 2012 and it is now the key financial instrument for the green development of the country and for the funding of climate change policies. It invests in public and private projects in the attempt to build a strong green economy. There are four priorities through which the fund provides investment: i) conservation and sustainable natural resources management; ii) research and development and technology transfer and implementation; iii) environment and climate change mainstreaming; iv) environmental impact assessment monitoring and enforcement. This institution is accredited to the Green Climate Fund.

UNFCCC Rwanda Nationally Determined Program (NDC) (2016)

The next essential document for the climate change action of the Rwandan Government is the UNFCCC NDC, submitted in 2016. During the run-up to UNFCCC COP21 in Paris 2015, Rwanda submitted its Intended Nationally Determined Contribution (INDC) which remained unchanged when Rwanda ratified the Paris Agreement in 2016. The NDC is based on the 2011 Green Growth and Climate Resilience Strategy (GoR 2011) and contains a long list of measures addressing mitigation of and adaptation to climate change to be implemented in the period between 2020 and 2030. Many of the specific adaptation activities that are proposed in the NDC are identical with those listed in GoR (2011) but with different targets and timeframes. The Detailed Implementation Plan for the Nationally Determined Contribution of Rwanda was developed in 2017, after a stakeholder engagement, and it contains the classification of the NDC’s measures according to their urgency and cost. Milestones and timelines for the implementation of the measures have been indicated and the timeframe used in the document reaches 2030. For each measure, co-benefits with the Sustainable Development Goals, barriers and risks for the implementations, competencies needed and strategies to mobilise the investments were identified.

Table 4.5: Adaptation policies contained in the Rwanda's NDC

Agriculture
Programme 1: Sustainable intensification of agriculture
Action A1.1: Mainstreaming agro-ecology techniques using spatial plant stacking as in agroforestry, kitchen gardens, nutrient recycling, and water conservation to maximize sustainable food production
Action A1.2: Utilizing resource recovery and reuse through organic waste composting and wastewater irrigation
Action A1.3: Using fertilizer enriched compost
Action A1.4: Mainstreaming sustainable pest management techniques to control plant parasites and pathogens
Action A1.5: Soil conservation and land husbandry
Action A1.6: Irrigation and water management
Programme 2: Agricultural diversity in local and export markets
Action A2.1: Add value to agricultural products through processing to meet its own market demand for foodstuffs
Forestry
Programme 3: Sustainable Forestry, Agroforestry and Biomass Energy
Action A3.1: Promote afforestation/reforestation of designated areas through enhanced germplasm and technical practices in planting and post-planting processes
Action A3.2: Employ Improved Forest Management for degraded forest resources
Tourism
Programme 4: Ecotourism, Conservation and Payment for Ecosystem Services Promotion in protected Areas
Action A4.1: Maximize business tourism (the largest source of export revenues) through strategic conference management in order to maximize the distribution and volume of business travellers throughout the year
Water
Programme 5: Integrated Water Resource Management and Planning
Action A5.1: Establish a national integrated water resource management framework that incorporates district and community-based catchment management
Action A5.2: Develop water resource models, improved meteorological services, water quality testing, and improved hydro-related information management
Action A5.3: Develop a National Water Security Plan to employ water storage and rain water harvesting, water conservation practices, efficient irrigation and other water efficient technologies
Land use
Programme 6: Integrated approach to Sustainable Land Use Planning and Management
Action A6.1: Employ an integrated approach to planning and sustainable land use management
Action A6.2: Improve spatial data by harnessing ICT and GIS (Geographic Information System) technology
Cross-cutting
Programme 7: Disaster Management
Action A7.1: Conduct risk assessments and vulnerability mapping
Action A7.2: Establish an integrated early-warning system, and disaster response plans
Action A7.3: Employ community-based disaster risk reduction (DRR) programmes designed around local environmental and economic conditions, to mobilize local capacity in emergency response and to reduce locally specific hazards
Programme 8: Climate data and projections
Action A8.1: Improve observation facilities to provide all climate information necessary for future monitoring, climate trend detection, management of climate variability, early warning and disaster management

Source: Detailed Implementation Plan for the Nationally Determined Contribution (GoR, 2017)

Since this dissertation focuses on the agriculture sector, more about the adaptation policies in this specific field should be presented. The first agriculture measure is labelled "sustainable food production". The selected technique to make Rwanda's agricultural sector more sustainable is agroforestry, which is a production system that combines elements of agriculture with elements of forestry. It integrates trees among or around croplands in order to create a healthier, ecologically sound and productive farming system. The strategy states that agroforestry has the potential to alleviate poverty through income generation and diversification, production of energy and improvements in water security and biodiversity management. The NDC sets out the target of increasing the share of households applying agroforestry to 100% by 2030, whereas Vision 2020 predicts to achieve 85% agroforestry by 2020 already, which would require a national tree coverage of 30%. In order to realise this goal, Rwanda would need to more than double its efforts to increase agroforestry (GoR 2011). The stakeholder consultation has assigned a high priority to this measure.

The second agriculture policy is composed by two adaptation measures and it is focused on the production of organic fertilizers through composting the organic wastes. This measure aims at restoring the soils fertility, using organic waste and wastewater and decreasing the dependency of Rwanda from foreign inorganic fertilizers. "*The country is dependent on imported inorganic fertilisers for its agricultural activities. In 2014, 36,000 tons of fertilizer were imported, a number that is likely to increase in subsequent years. While they are suitable for increasing the productivity, intensive use of inorganic fertilizer has adverse impacts on environment and climate change*" (GoR, 2017). Several adaptation benefits have been highlighted for this measure, ranging from the improvement of the production especially in the more vulnerable farms, to a considerable reduction in organic waste and the enhancement of water resources and soils with better natural properties. Even this measure has been classified as high priority.

The third agriculture policy is aimed at the improvement of the management of wastewater, in the attempt to disseminate the practice of using this resource for irrigation purposes. The volume of wastewater is increasing due to the growth of the population and the economy; thus, this resource could become a sustainable and affordable solution for the irrigation of the crops and the enrichment of the soils. A medium priority has been assigned to this policy.

Other agricultural measures are dedicated to the integrated land use planning. Due to the expected increase of the population and the growth of the economic activities, there will be a competition among the different interests and aims of the Rwandan society. Furthermore, the document emphasizes the role of climate change (as droughts, floods and other extreme events) in worsening the quality of lands. This is why the NDC sets the goal of an integrated land use planning, in order to find a good balance among the competing objectives, finding development solutions that are aligned to the country's priorities. There are two leading targets for these interventions: i) a planning and zoning regulatory framework, land registration and land tenure regularization reform; ii) a National Spatial Data Infrastructure (SDI) that will provide access to key information about the land. These measures are predicted to reduce the uncontrolled land development, the overutilization of water and sanitation systems and the loss of biodiversity. Furthermore, it would have significant benefits for other sectors, e.g. Disaster Risk Reduction. A medium priority has been assigned to this policy.

Another measure regarding the lands' management is the one about soil conservation. Land degradation is presented as a recurring problem in many Sub-Saharan countries, mainly because the increased agricultural pressures to meet the food demand of the growing population and due to climate change impacts. This high priority measure is especially aimed at increasing the terrace agriculture, which is considered particularly useful because of the presence of several areas that are characterised by steep slopes (the majority of Rwanda's crop land, 90%, is located at slopes which have a gradient of 5% - 50%). The increasing of extreme events caused by climate change could be disruptive for these steep soils, provoking landslides and permanent fertility losses.

The last two adaptation policies for the agriculture sector are dedicated to pest management and irrigation. The first one has a medium priority and it regards the dissemination of sustainable methods for the intensification of agricultural activities without the need for synthetic pesticides. These integrated pest management strategies could also be more economic efficient, due to savings coming from the reduction of synthetic pesticides. The last measure is a key policy for Rwanda, because of the dependency of this country on rain-fed crops. Only 4% of land with irrigation potential had been equipped with irrigation technology by 2012 (GoR, 2015). Rwanda's target is to ramp up investments in irrigation infrastructure in order to increase agricultural yields and improve food security. To achieve this result, a "district irrigation master plan" will be established in conjunction with small scale schemes based on available water catchments. The target is to increase the land under irrigation to 11% by 2030.

National Environment and Climate Change Policy (2019)

Promoted by the Ministry of the Environment, this strategy is designed to give responses and a policy framework to the environmental and climate change issues. The document has been developed through a consultative process involving all the stakeholders and it is an update of the National Environment Policy issued in 2003. The key policy goal is: "*to have a clean and healthy environment resilient to climate variability and change that supports a high quality of life for its society*". The seven objectives of the policy are: (i) Greening economic transformation; (ii) enhancing functional natural ecosystems and managing biosafety; (iii) strengthening meteorological and early warning services; (iv) promoting climate change adaptation, mitigation and response; (v) improving environmental well-being for Rwandans; (vi) strengthening environment and climate change governance; (vii) promoting green foreign and domestic direct investment and other capital inflows. To implement these policies, 22 policy statements and 127 policy actions have been identified. One policy statement is specific for adaptation: "*strengthen adaptation mechanism in planning and implementation*". The policy actions connected to this areas are: mainstreaming of green, ecological and climate resilient practices in the development sectors; promotion of resource recovery and reuse; integration of weather and climate information into infrastructure planning and development; improvement of water storage and management; promotion of ecosystem-based approaches to climate change adaptation; promotion of afforestation and reforestation of critically-degraded and residential areas. The climate change policies are although extended to the whole document and mainstreamed into the general environmental strategy

4.1.2.3 International and regional policy documents

The work of the FAO Intergovernmental Group on Tea

The FAO Intergovernmental Group (IGG) on Tea is a forum for international consultation and exchange on trends in production, consumption, trade and prices of tea, including regular appraisals of the global market situation and short-term outlook. Every two years there is a plenary session of members, the last one in May 2018, at Hangzhou, China. Even though Rwanda is not a member of this Group, the work of this organisation is significant for the scope of this review.

Various indications about climate change implications for tea production all over the world have been made in the last meetings. In 2014 meeting of Bandung (Indonesia), the impacts of climate change on the global tea production were presented. The increased temperatures could dry the soils, with significant effects on tea yields. Hotter temperatures could lead to increasing of pests and diseases that attack bushes. In extreme cases, temperature becomes too high for the actual tea plantations locations and production needs to be shifted at higher elevations. Finding new locations could be a conflicting action with the mitigation targets, since it will require deforestation. There is less knowledge about the expected pattern of precipitations. In the Naivasha (Kenya) 2016, 22nd, meeting, "Possible Strategies to Address Socio-Economic Adaptation Policies" have been developed and a series of adaptation practices have been recommended: "*Replanting drought- and stress-resistant tea varieties; Planting shade trees to protect the tea bushes; Diversifying crop production in low-yielding, poor-soil tea areas with crops that do not require rich soil conditions for optimal growth; Improvements in efficient water management; and Investing in climate-resilient infrastructure, including, inter alia, drainage and irrigations systems and adapt national public infrastructure to climate change*". *Policymakers should bear in mind that integrating traditional knowledge and practices with new climate-smart technologies could be an important adaptation measure in designing infrastructure and developing new techniques. Furthermore, at the design stage of a new development, planners and designers should consider climate forecasts and projections.*

Research should be supported, especially on new stress and drought tea varieties, integrated soil nutrient management and ecological pest management and better water management. The report highlights that the production of tea requires large quantities of water; therefore, an essential branch of the adaptation policies should consider the strengthening of watershed management: investments in rural infrastructure to improve drainage and irrigation; increasing water storage capacity; improving washing techniques; better recycling and more effective water management methods; promotion of efficient water use; pricing reforms to support efficient water use. Another key adaptation driver regards the crop diversification, in the attempt to reduce the dependency of the farmers to the tea production, especially risky in a climate change framework. The plantation of rubber plants on the boundaries of the fields could then be considered another crop diversification strategy. These trees provide shade that is vital for tea bushes during rising temperatures, and they also reduce water losses. The latex of the tree could be sold and becomes an additional source of revenues for the farmer.

Tea mono-crop farm should be mostly avoided. *Poor smallholder tea growers could enhance their food security and improve their own nutrition by farming crops that can thrive in harsher climates, such as certain varieties of pulses. This could also provide higher economic benefits that could help them address the negative impacts of climate change.* A recommended mitigation practice is the labelling of products with the carbon footprint, which can aware the consumers about the sustainable and organic practices used in the tea production. A chapter of the policy brief is dedicated to the access to credit, a problem that severely limit the capacity to adapt of farmers, which cannot purchase quality inputs to improve productivity in a sustainable manner. Therefore, government policies are required to improve access to credit by tea smallholders, improving the functioning of micro credit schemes.

FAO Strategy on Climate Change (2017)

The Strategy was adopted by the 40th FAO Conference in July 2017 with the goal of enhancing support to Member Nations in achieving their commitments to face climate change. The Strategy is structured around three mutually reinforcing outcomes to this end: i) Outcome 1 - enhanced capacities of Member Nations on climate change through FAO assistance as a provider of technical knowledge and expertise; ii) Outcome 2 - improved integration of food security and nutrition, agriculture, forestry and fisheries considerations within the international agenda on climate change through reinforced FAO engagement; iii) Outcome 3: Strengthened coordination and delivery of FAO work on climate change.

Koronivia Joint Work on Agriculture

At COP23 (November 2017), Parties reached a decision on next steps for agriculture within the UNFCCC framework, known as the Koronivia Joint Work on Agriculture. This decision is the first substantive outcome and COP decision in the history of the agenda item on agriculture, which has been under negotiation since 2011. The decision requests the Subsidiary Body for the Implementation (SBI) and the Subsidiary Body for Scientific and Technological Advice (SBSTA)[9] to jointly address issues related to agriculture, including through workshops and expert meetings, working with constituted bodies under the Convention and taking into consideration the vulnerabilities of agriculture to climate change and approaches to address food security. The Koronivia Joint Work on Agriculture (KJWA) represents an important step forward in the negotiations on agriculture with the UNFCCC and emphasizes the importance of agriculture and food security in the climate change agenda. By mainstreaming agriculture into the UNFCCC processes, the KJWA want to drive transformation in agricultural and food systems, and address the synergies and trade-offs between adaptation, mitigation and agricultural productivity.

The African Union Agenda 2063 and its First 10-Year Implementation Plan (2014-2023)

Adopted in 2013, the African Union Agenda is dedicated to building an integrated, prosperous and peaceful continent, driven by its own citizens and representing a dynamic force in the international arena. It represents the African strategic view for the next fifty years, in the attempt to identify a self-determined pattern to inclusive and sustainable development. The goal 7, is the most specific objective dedicated to climate change policies and it is aimed at growing climate resilient economies and communities.

The East African Community (EAC) Vision 2050 (2016)

The Vision 2050 lays out a broad East Africa's perspective in which the region optimizes the utility of its resources to narrow the gap in terms of social wellbeing and productivity. It focuses on environment protection by prioritizing development enablers which are integral to long-term transformation, value addition and acceleration of sustained growth.

The EAC Climate Change Policy (2010)

[9] These two entities have been created in 1995 by the first Conference of the Parties of the UNFCCC and they are permanent bodies of the Convention. The SBI supports the COP through the assessment and review of the effective implementation of the Convention, whereas the SBSTA provides information and technical advices on scientific and technological issues that emerge during the works inside the UNFCCC.

The EAC CCP guides the Partner States of the East African Community on the preparation and implementation of collective measures to address climate change in the EAC region while ensuring sustainable social and economic development. The policy prescribes statements to guide adaptation and mitigation actions to address climate change.

The EAC Climate Change Master Plan (2011–2031)

The purpose of the Master Plan is to provide a long-term vision and a basis for the member states to operationalize a comprehensive framework for adapting to and mitigating climate change in line with the EAC Protocol on Environment and Natural Resources Management and with international climate change agreements. The Master Plan's Vision is to ensure that: "*The people, the economies and the ecosystems of the EAC Partner States are climate resilient and adapt accordingly to climate change*"

4.1.3 Rwanda climate analysis and uncertainties

Coming back to the economic analysis of the tea investment in a climate change framework, an essential input is the inquiry of the climate information available. Usually, the investors rely on the analyses about the past trends of the climate and of the weather dynamics. However, as we discussed in the first part of this work, climate change completely changes the pattern of the climate, modifying some key essential components, like the average temperature, the length of dry periods and the distribution of rainy days. Therefore, the knowledge of current climate should be integrated with considerations about possible expected climate scenarios.

Climate models are essential instruments for the collection of information about the expected climates. They have been developed with the aim to aware people and institutions about the possible local impacts of climate change. These models have been accurately refined in the last decades, leading to more affordable results and more location-specific information. However, there have been an incredible proliferation of these models. There are now several models, developed with their own methodology, using their personal parameters about the biological relations between climate and nature and working at a specific geographical level (e.g. a grid of 5 or 10 or 20 kilometres, depending on the accuracy of the model). The Intergovernmental Panel on Climate Change periodically produces important analyses about climate, possible future scenarios and expected impacts. These pillar works are produced by hundreds of scientists coming from various parts of the world and they are called Assessment Report (AR). The last AR was published in 2014/15 and it was the fifth. The next one is expected in 2021/22. Despite the presence of these important and reliable reports, which identify the possible expected increases of the temperatures, the evaluation of the local impacts of climate change remains a complex issue. IPCC AR reports contain information about the greenhouse gas emission future trajectories, the effects on the global average temperature and the possible connected impacts. However, for detailed, site-specific, climate data about the various weather components, the climate models have to be considered.

In this specific case study, the climate data about Rwanda is collected thanks to the Climate Change Knowledge Portal 2.0 by the World Bank. This tool presents climate data downscaled for each country, using the Coupled Model Intercomparison Project, Phase 5 (CMIP 5) and assembling together 16 different models. CMIP is a standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models; CCKP uses the current fifth project phase. All data is presented at a 1°x1° global grid spacing. Hereby, the data is recent, updated and it includes a wide variety of predictive models. The baseline period is the climate trend between 1986 and 2005, whereas the projections are produced for the following years: 2020-2039, 2040-2059, 2060-2079 and 2080-2099. For this research the forecasts for 2040-2059 and 2060-2079 have been considered. For the first scenario of this case study the 10^{th} lowest percentile of the RCP 2.6 has been used. In the two middle scenarios the average temperature increases of the RCP 4.5 and 6 has been considered. For the last one, the RCP 8.5 highest 90^{th} percentile has been considered, trying to include in the analysis the widest range of possible future scenarios.

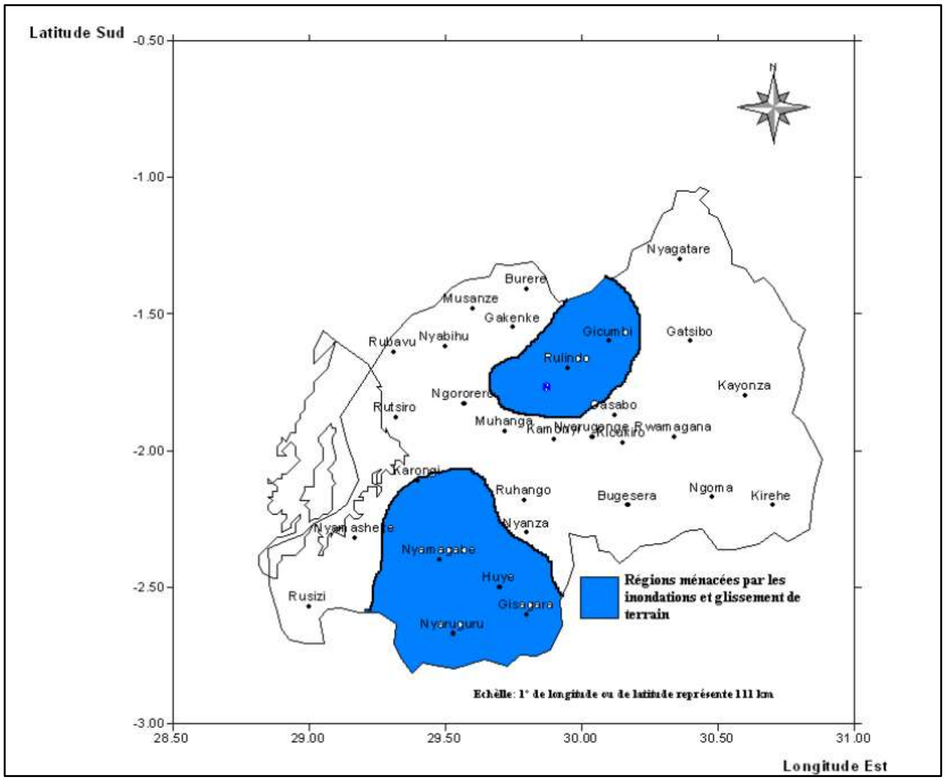
Table 4.6: Expected evolution of the average temperatures

		Scenario RCP 2.6	Scenario RCP 4.5	Scenario RCP 6	Scenario RCP 8.5
Baseline – Kigali (1500 mt), 19.8°C average temp.	2050 increase	+0.78°C	+1.39°C	+1.24°C	+2.57°C
	2070 increase	+0.64°C	+1.72°C	+1.8°C	+3.96°C

On the contrary, the projected changes in average and seasonal rainfalls are more intricate, because of the high levels of current rainfall variability, but also due to the greater uncertainty over the exact change that may occur. Rwanda has two rainy seasons, a main season from March to May and a short season from mid-September to mid-December, and the trend of the precipitation highly varies over the different parts of the country. The yearly amount of rainfall in the site of this project is approximately 1,200 mm. However, there is no clear trend about the influence of climate change on precipitations, as there is for temperature. Rainfall projections for most of East Africa, and in particular for Rwanda, are usually unclear, as models' agreement is low. Some models suggest that there will be an increase in rainfall while others suggest a decrease. The average change from the models indicates that rainfall may increase slightly in Rwanda, particularly in the East, but the high uncertainty makes the use of the average particularly misleading, because of contradictory messages from the models and from observational data in the region (Watkiss, 2016).

Although the estimates about the expected evolution of the rainfalls are partially absent or contradictory, some of them, e.g. the one made for the official NAPA of Rwanda, present the area of Nyaruguru (i.e. the lands of this case study) as very vulnerable to negative effects caused by heavy rains. They are particularly exposed to destructive erosion, considerable soil degradation, landslides and landslips. These tendencies are expected to get worse in the coming decades due to climate change.

Figure 4.3: Regions threatened by floods and landslides



Source: Rwanda National Programme of Action (2007)

Rwanda is evaluated as a highly vulnerable country to the effects of climate change. The Notre Dame Global Adaptation Initiative (ND-GAIN)[10] develops an index score, composed by a Vulnerability score and a Readiness score. Vulnerability measures a country's exposure, sensitivity and ability to adapt to the negative impact of climate change. ND-GAIN measures the overall vulnerability by considering vulnerability in six life-supporting sectors – food, water, health, ecosystem service, human habitat and infrastructure. Rwanda ranks 153rd among 181 countries. The worst performances are in the health index (especially in the adaptive capacity: medical staff - number of medical staff per 1,000 people) and in the food index (especially because of the presence of high share of rural population - 90% - and low values in the agriculture capacity, measured as the use of fertilisers, irrigation and the frequency of tractor use). Looking at the exposure value, which measures the extent to which human society and its supporting sectors are stressed by the future changing climate conditions, Rwanda is the 160th worst nation among 192. If we consider the sensitivity parameter, i.e. the measure of the degree to which people and the sectors they depend upon are affected by climate related perturbations, Rwanda is 163rd among 171 countries assessed. Despite these alarming performances, the Readiness score shows better results. This is the measure of the predisposition to make effective use of investments for adaptation actions thanks to a safe and efficient business environment and it is composed by three key dimensions: i) Economic Readiness (the investment climate that facilitates mobilizing capitals from private sector); ii) Governance Readiness (the stability of the society and institutional arrangements that contribute to the investment risks); iii) Social Readiness (social conditions that help society to make efficient and equitable use of

[10] https://gain.nd.edu/our-work/country-index/rankings/

investment and yield more benefit from the investment). Thanks to good results in Economic and Governance Readiness, Rwanda ranks 114th among 181 countries in the general ND-GAIN index. Therefore, the country has a high level of vulnerability to climate change and a good level of readiness. ND-GAIN states that, "*in these countries, the need for adaptation is large, but they are ready to respond. The private sector may be more likely participate in adaptation here than in countries with lower readiness*".

The WorldRiskIndex[11] is another important international index. It analyses the risk of disaster in consequence of extreme natural events, such as earthquakes, cyclones, floods, droughts and sea-level rise. A total of 13 of the 15 most vulnerable countries in the world are located in Africa. Here the hotspots are in Central Africa, Chad, Congo, Eritrea, Niger. However, the islands of the Caribbean Sea and of the Pacific Ocean have got very high values in the exposure parameter and thus they generally reach the first positions in the overall index. Rwanda ranks 75th among 180 countries (the first countries have the highest risk), inside the group of the nations with medium risk, with again high values of sensitivity to the impacts of the extreme events. In the comparison with the other African countries, Rwanda is 39th among 53, a relatively good performance, mainly due to better results in exposure and coping capacity (i.e. an aggregation of various abilities of societies to be able to minimize negative impacts of natural hazards and climate change through direct action and the resources available).

Although the relative performances of the country in these indexes are not dramatic in comparison with other African countries, the impacts of climate change on Rwanda are expected to be severe, limiting the capacity to develop the agriculture sector and the economic growth. Climate change temperatures and precipitations extremes will be particularly relevant in the agriculture field and probably they will have a key role in the future agricultural production. On the steep slopes that dominate much of the country, floods, landslides, and soil erosion already impact agriculture, infrastructure, and services. Heavy rains in 2012, for example, led to extensive flooding and an estimated loss of 1.4% of GDP. In 2016, floods and landslides blocked roads, destroyed bridges, and damaged 1,425 homes in Gakenke district. In rapidly growing urban areas, there is increasing concern about water shortages during longer dry spells and the impact of flooding and landslides on expanding informal settlements in risk-prone areas like steep slopes and flood plains (USAID, 2019). The USAID (2019) Rwanda Climate Change Risk Profile contains other information about the expected impacts of global warming whereas, in the following chart, GIZ (2015) presents the key potential risks produced by climate change to the tea production.

[11] https://weltrisikobericht.de/english-2/

Table 4.7: Most significant climate change risks for tea plants

Climate change problem	Impact
Increased temperatures	Drying of the soils causing reduced water content in the tea and decreasing quality
	Drying of the soils causing increased soil erosion
	Arrival of new pests and diseases not previously present
	Changes in the suitability of existing tea growing areas
	Sun damage decreasing quality
Reduced water content of tea crop	Decreases leaf quality
	Reduces resilience of tea crops
Changing rainfall patterns	Uncertainty in when to apply fertilisers
	Water scarcity and drought
	Extreme rainfall events
Increase in extreme weather events such as hailstorms, floods, landslides	Crop damage and failure
	Increased financial vulnerability of tea farmers
	Soil fertility loss through erosion
	Frost
Reduced productivity of subsistence crops for tea farmers	Increased vulnerability of tea farmers through food insecurity

Source: Giz, 2015

These are the most important impacts of climate change on the tea plants recognized by the scientific literature. Unfortunately, most of these considerations remain basically qualitative, without reliable and recurring quantitative estimates that can be included in the evaluation of the expected future tea production. This is why the study considers just the average temperature predictions, ignoring the variations of the other weather components. This is an important assumption of this analysis, due to the importance of various other climate change impacts, e.g. the pattern of the precipitations, the occurrence of extreme events (deluges, landslides …) and the losses in soils humidity.

However, this work is not focused on a detailed analysis of the expected climate and, at least at this initial stage, it will not give concrete advices to the Government of Rwanda for the plantation of the tea plants. The work is aimed at the evaluation of the portfolio analysis as a useful tool for guiding climate change adaptation decisions, and, at this initial stage, the variation of the average temperature is the essential climate information needed. However, a further improvement of this work could be interesting, maybe with new reliable and more precise data about the expected pattern of the precipitations and the evolution of the extreme events.

4.1.4 A portfolio analysis of investments in the tea sector

As a part of EDPRS II, the Government of Rwanda decided to make further investments in agriculture and in the tea sector in particular. One of the areas involved in this development plan and the site chosen for this analysis is the Nyaruguru District, where The Wood Foundation Africa and smallholders will manage this agricultural project. Nyaruguru is a district in Southern Province and Kibeho is its capital. The district is the most southerly in Rwanda, lying between the cities of Butare and Cyangugu and along the Burundian border. It is mountainous, containing part of the forest of Nyungwe, one of Rwanda's most popular tourist destinations, which also provides cooking charcoal for much of the Southern region. This is one of the last remaining forest areas of Rwanda.

As a guide for the development of new tea plantations, the Government designed tea expansion maps, trying to identify the most suitable areas for the tea production. However, these maps did not include climate changes in their considerations, thus giving a partial information, especially short-sighted for a long-term investment, like the planting of tea plants.

This analysis starts from this research question: is it possible to include climate information in these maps, giving economic indications based on different climate scenarios? Would the decision-maker change her choice if she can consider climate change forecasts also?

Thus, in the attempt to find an answer to these queries, the analysis is here structured in two main parts:

i) firstly, a Cost-Benefit Analysis (CBA) of the tea investment in various locations will be developed, aimed at finding significant economic considerations about the profitability of the tea plants in these settings. The locations for the investment have been identified in ten altitude bands, 100 meters each one, starting from 1,500 mt to 2,500 mt. This first step will give us the Net Present Value of planting the whole 3.5 thousand hectares of tea in each altitude bands. The NPV will be estimated on the basis of four climate scenarios plus a +0°C scenario, representing the whole possible set of futures. The variances and the standard deviations of these NPVs will be estimated, as well the correlation coefficients among the different locations, showing the relations among the variations of the different altitudes in the various scenarios. The locations which are not perfectly correlated can be mixed in the Portfolio Analysis in the attempt to reduce the variability of the investment, giving more robust investment solutions;

ii) secondly, the Portfolio Analysis (PA) will be developed, considering just the altitude bands which are not perfectly correlated or, possibly, negatively correlated. The Efficient frontier will be designed, and the possible efficient investment choices will be identified according to the possible risk preferences of the public decision-makers.

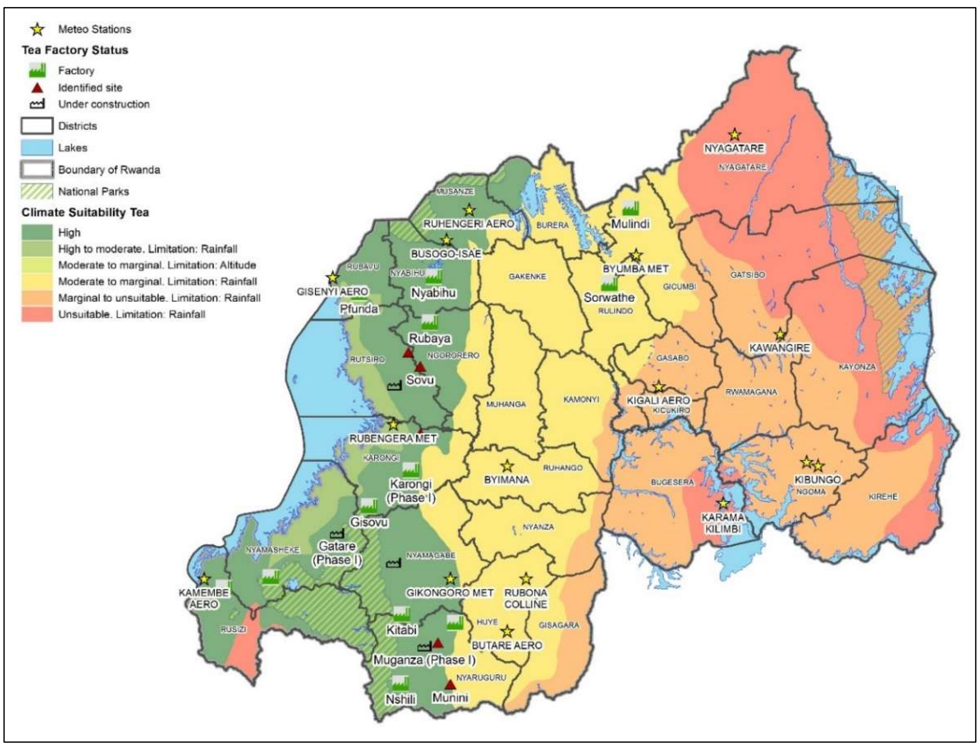
The decision criteria enrolled in this research work are the economic efficiency and its variance. Other criteria, as the values and the preferences of the local farmers or the adaptability of the investment choice to the Rwandan government's goals, are not included in this analysis. However, a refined version of this work might be interesting, and the information could be integrated in this more comprehensive analysis.

4.1.4.1 Cost-benefit analysis of tea plantation investments

The CBA developed in this thesis starts from the cooperation between the ECONADAPT project (founded by the European Union Seventh Framework Programme, FP7), the Government of Rwanda and the local stakeholders, which gave the opportunity to collect a large amount of data about the agriculture sector and the tea plantations investments and revenues. The information arriving from the project have been essential for this work, especially because they were able to describe the relation between the different locations, their climate and the tea yields connected with them. This correlation is the essential engine of this analysis and it gives the opportunity to connect the expected climate changes with the expected outcome of the agricultural investment.

There is a big correlation between climate and tea yields and leaves quality indeed, although the weather and the average temperature are not the only dimensions which have an influence on the overall production. Soil type, nutrient, water availability, vegetative cover, cultivar and management, they all influence the speed of the tea plants growth, which has strong effects on both the quantity and quality of the leaves (FAO, 2015). However, the temperature remains one of the most important drivers, showing a clear and direct correlation with the tea yields. At high average temperatures there is a faster maturing rate, higher amount of tea leaves, but lower quality. With lower temperatures, the tea leaves grow slowly, and tea can mature in a better way, usually rising the quality of the production. These relations have been carefully analysed by the ECONADAPT project, which took the key information from FAO (2015). Tea can grow between 12^{o}C and 30^{o}C, with a maximum production at 19.2^{o}C. In Rwanda, the ideal growing conditions for tea are for average annual temperatures of 18-20°C.The tea yield has been assumed to be zero above the upper and under the lower boundaries whereas the gradient of the function, connecting these three-average temperatures, was funded in FAO (2015). Reflecting this temperature profile, most Rwandan tea is grown at the height of 1,600 to 2,100 meters above sea level which is predominantly in the west and north west of the country, where it is cooler (as higher) and wetter (ECONADAPT, 2016).

Figure 4.4: Climate suitability for tea plants



Source: Watkiss, 2016

Then, the project has analysed the tea auction in Mombasa, Kenya, collecting data from the last 30 years, in the attempt to find information about the tea prices. Yearly average tea prices and yearly average temperatures have been gathered and a strong correlation between these two values has been found. Fundamentally, at higher average temperatures, the tea leaves quality, and thus the price, were lower, whereas the tea leaves have been sold at higher prices in the years with a lower average temperature. While approximate, there is thus a clear relationship between elevation (temperature) and price. While management and other factors are clearly important, the temperature effect on the speed of the leaves' growth seems decisive. The information has been enough for designing a correlation between the yearly medium temperature and the expected tea yield (in Kg) and price (in Rwandan Francs – RWF).

Another important correlation, and a key assumption of this analysis, connects the different altitude bands (100 meters each) with an average temperature. As discussed earlier, the locations where to build new tea plantation have been characterized by different altitudes, each one with a yearly medium temperature. The surface available for new tea plants is between 1,500 and 2,500 meters above sea levels. Hereby, this work has divided this 1-thousand-meter gap in 10 different altitude bands, 100 meters each one. Every band has been characterized by an average temperature, where the main reference point has been identified in Kigali (1497mt), with an average temperature 19.8°C during the last thirty years. Then, a decrease of 0.65°C every 100 meters above Kigali has been assumed, characterizing all the locations with an average temperature and defining a basis for the application of the climate change scenarios. As previously discussed, the Climate Change Knowledge Portal 2.0 by the World Bank has been used to collect data about the expected climate scenarios. Four scenarios (RCP 2.5, RCP 4.6, RCP 6, RCP 8.5) and a no climate change scenario (+0°C) have been considered, with the aim to look at the most comprehensive representation of the plausible futures. According to the scientific literature (IPCC, 2014) a no climate change scenario is highly unlikely, due to the persistence of the greenhouse gas in the atmosphere once it has been produced; however, the use of this scenario can be a useful assumption of this work basically due to two main reasons: i) it can show the impact of climate change, i.e. the economic losses connected to it; ii) the analysis has not the goal to concretely inform the Rwanda's government decisions, therefore experimenting the portfolio analysis on a wider range of scenarios seems an interesting features even though the no climate change scenario is apparently not likely. Moreover, this solution in coherent with the papers by Ando and Mallory (2012) and Mallory and Ando (2014), where they perform a portfolio analysis about land use decisions in a climate change context and they consider four climate scenarios: a no climate change scenario, 2 light climate change scenarios and one high climate change scenario.

Linking the production of tea, both the quality and the quantity, just to the average temperature is a strong assumption of this work. This assumption has been made in the attempt to simplify the analysis, making easier the calculus of the expected production in each site. The analysis is an experimental test of the possibility to use the portfolio analysis for the evaluation of agricultural investments in a climate change framework, helping the decision-makers in including the wide climate uncertainty in their investment choices. The essential goal of this work is the key reason for the simplification of the analysis in some technical parts. However, there are several other dimensions which can influence the tea yield, e.g. the characteristics of the soils, the humidity of soils and air, the gradient of the soils which can affect the exposition to the sunbeams. For example, a study (Mupenzi et al, 2011) about the suitability of the Rwandan soils to the tea plants has highlighted some interesting insights. The soils in the valley regions of the country have good physical characteristics, great depth with excellent porosity, good permeability and high infiltration rates and it is easy to work. However, in the mountainous tea-growing regions (e.g. Kitabi, a location very close to the site of our analysis) the study identified that the dry and stony soils make it difficult for the tea bushes to access water and other nutrients. Therefore, in these areas a rising shortage of precipitations due to climate change could be a critical issue for the growth of tea plants. Consequently, the quality of the soil might be a limiting factor to the plantation of tea at the highest elevations, balancing the positive effect of the colder temperatures. This might be a decisive element in the choice of the most suitable areas, and it should be introduced in a hypothetical refined version of this study.

The first essential step of the Cost-Benefit Analysis (CBA) has been the development of the tea plantation investment financial analysis, considering the economic performance of one hectare of tea plants, with no climate changes. In the financial model, land is assumed to have an economic life of 50 years (Wintgens, 2009; Bunn et al, 2014; Republic of Rwanda, 2016) whereas agricultural tools and materials are assumed to have an economic life from 1 to 10 years. These assets are depreciated over their economic life and then incurred as a reinvestment cost when fully depreciated. Thanks to an accurate survey mainly produced by the ECONADAPT project in 2016 with an engagement of the Rwanda Government and local stakeholders, the main data about the investment and running costs and the revenues have been collected. ECONADAPT has also developed the preliminary financial analysis, generating the essential structure of the CBA for the single elevations.

In the next stage of this study, the financial analysis has been converted in economic values, with the aim to consider the costs and benefits from a social perspective, looking at the welfare of the society. Thanks to the presence of the investment there will be a positive effect on the job market and positive side effects on the food security, health and education, due to the increase of the wage of the local communities. Therefore, the following shadow prices (figure 12) has been considered in the analysis, converting the purely financial values in economic terms.

Table 4.8: Shadow prices for the economic analysis

Shadow prices	**Assumptions**
Capital goods	0.7139 of market prices[12]
Unskilled work	0.8600 of market prices[3]
Skilled work	0.7692 of market prices[3]
Income multiplier	1.053 – conservative multiplier of Rwanda to reflect preference for receiving goods and services today rather than tomorrow (HM Treasury, 2015). In Rwanda these positive externalities include food security and higher investments into human capital e.g. health and education

In the quantitative analysis of this project no other externalities have been considered due to the lack of evidence. Other possible social or environmental externalities might be connected to the impact of the project on biodiversity, to the carbon sequestration or to the impact of the soil-erosion, basically depending on the characteristics of the field where the tea plants are planted. This point might be further developed in a future version of this work, trying to better understand the whole environmental and social impacts of this investment, not a focus of this specific study.

The analysis has been designed assuming that there is just one decision point, where the tea plants are planted all together. However, planting all the 3.5 thousands of hectares in just one solution is probably not feasible. In the original project developed by the government, 12 years are needed for the complete development of the tea plantation. Nevertheless, this work considers just one decision point, trying to make the portfolio analysis simpler and

[12] Shadow price assumptions for financial inputs and outputs taken from World Bank (2013) Rwanda Second Rural Sector Support Project (RSSP2) Implementation and Completion Report.

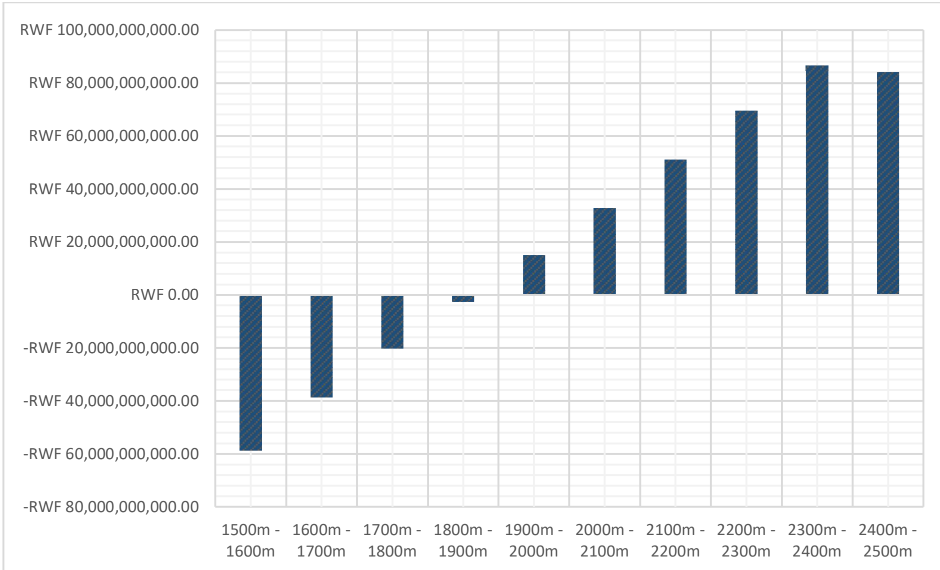
straightforward. However, introducing a sequence of decision points might be interesting as well, considering the effects of learning new information in the future. Although the whole uncertainty cannot be resolved in the future, there is surely an opportunity to learn from newer and more accurate climate scenarios, thanks to refined climate models and a better understanding of natural processes. For example, IPCC is going to publish the 6th Assessment Report in 2021, showing new trustworthy and significant climatic data, probably with a better comprehension of the climate characteristics. This analysis might introduce considerations about the quasi-option value of limiting the investment now, without compromising the opportunity to change the investment strategy due to new information.

In the following step, the economic performance of each altitude bands has been assessed assuming that all the tea plants, 3.5 thousands of hectares, are settled at just one elevation. The possibility to place the plantations in just one altitude is another assumption of this work and it has to be verified, especially at the highest altitudes.

Afterwards, trying to assess the Expected Net Present Value (ENPV) of each altitude band, the uncertainty about the future must be included in the analysis. Climate change produces a great variability of future environmental conditions, increasing the complexity of this analysis. As mentioned before, although considerable improvements have been done in the climate change science, we still don’t have precise information about the climate we are going to have in the future. The further we go with the analysis, the less the forecasts are affordable. We explained that there are reasons why these forecasts are probably going to remain uncertain also in the future, although more reliable models will be developed in the next years. However, attempting to design a coherent and comprehensive CBA, it is important to consider the possible uncertainties connected with the key variables of the analysis. In this specific case study, the performance of the tea plantations highly depends on the climate. Following the recommendations of the CBA manual (Boardman et al, 2017), the first step of the uncertainty analysis is to identify a set of contingencies. These chances must be exhaustive and mutually exclusive. According to the exhaustiveness need, the Expected Net Present Value should consider all the possible climate scenarios available. Hereby, all the four climate scenarios designed by the IPCC, i.e. RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5. and a no climate change scenario have been included in this work. To be coherent with the assumption that the five scenarios taken together are exhaustive and mutually exclusive, the probabilities that we assign must be nonnegative and sum to exactly 1. Usually the probabilities must be based on historically observed frequencies or on subjective assessments by the analysts or the clients, based on their own experience and expert knowledge. As we mentioned before, climate change complicates this step of the analysis, as it is a new phenomenon and diverse dimensions are still unknown. There are also exogenous variables that are difficult to forecast, reducing the possibility to learn and improve the information in the future. Hereby, as a first approximation, the probability has been distributed equally to each scenario (20% each one). This assumption seems to be reasonable, because of the deep uncertainty connected to climate change forecasts. In the sensitivity analysis other distributions of probabilities will be assessed.

In the following figure the Expected Net Present Values (ENPVs) of the single altitude bands are presented.

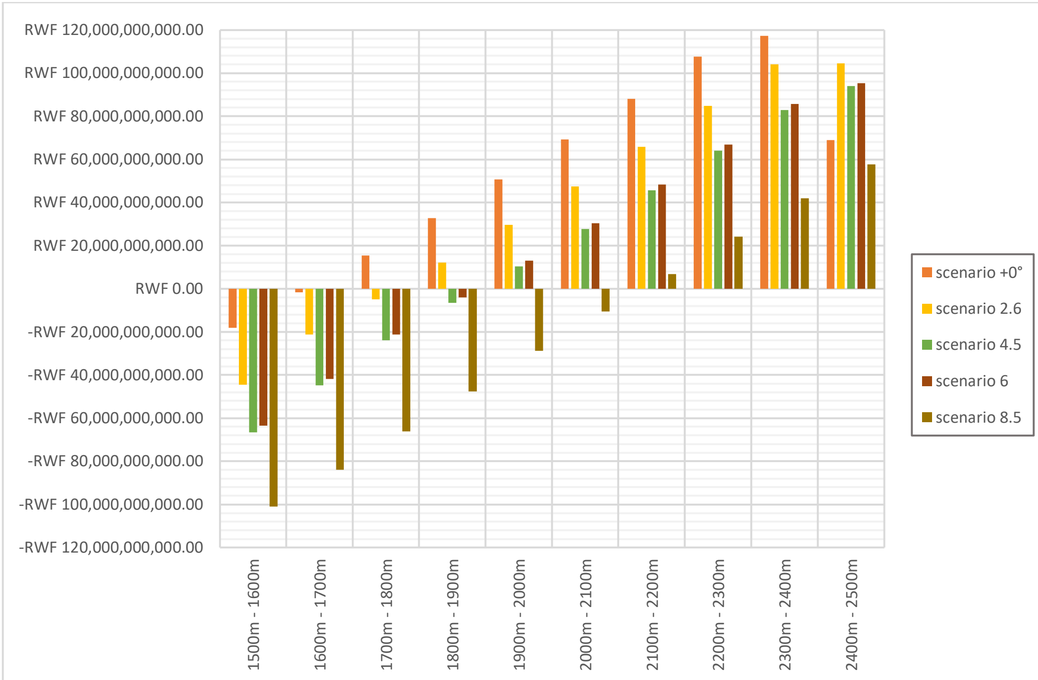
Figure 4.5: Altitude bands ENPVs considering a 0% discount rates (20% assigned to each climate scenarios)



The economic analysis of the altitude bands shows these following results. Firstly, the higher the elevation of the investment is, the higher is the economic performance too, except for the last one. This result is connected just to the temperature effect. There are colder temperatures at higher elevations and thus the climate change effects are more easily faced, giving more efficient outcomes in scenarios with climate change. The data collection has found that there are no significant variations on costs at higher altitudes in this specific case study. Therefore, this study assumes just a 5% increase of the costs for each altitude. The rising costs are the ones related to the building of the plantation, the management costs and the costs for the harvest. The costs of the materials and the seeds remain identical, because they are not affected by the increase of the altitude and the distance of the villages from the plantation sites. However, although there is an increase (even if only slightly) of the investment and running costs, planting at higher elevations is reasonable most of the time, because in the higher altitudes the average temperature is more suitable for the tea plants, especially in the most severe climate change scenarios, where the temperature might reach almost +4°C. This is a fist interesting result of the analysis. In the presentation of the case study, the ideal temperature for the growth of tea in Rwanda has been identified between 18°C and 20°C, with the maximum production at 19.2°C. In the no climate change scenario, the first two elevations 1,500-1,600 mt and 1,600-1,700 mt are the ones with the average temperature which is closer to the optimal values (19.8°C and 19.15°). Probably, according to the analysis of the past trend of the climate, the farmers would settle the tea plants at this elevation. However, the economic analysis show that there is an important impact of the prices of tea on the final economic performances of the different altitude bands. Considering both the quantity and the quality of tea (according to the correlation formulated in this work), the highest altitudes (except the last one) should be preferred instead of the lowest ones. Then, considering the climate change scenarios, the ideal temperature is no longer at the lowest elevations, but it goes at the upper ones. The lowest elevations become highly unsuitable for tea plants, especially in the most severe climate scenario, where their average temperatures reach 23.76°C and 23.11°C.

The next figure shows the pattern of the NPVs considering the occurrence of a no climate change scenario (+0°C) and then a 100% likelihood assigned to each one of the four scenarios respectively.

Figure 4.6: A comparison between five different scenarios



Even in the no climate change scenario, going at higher elevations generally brings higher revenues. In this business as usual framework, just the first two elevations have a negative NPV, whereas the last altitude (2,400 to 2,500) is considerably less economically efficient compared with the previous two. Here the 2,300-2,400 m band has a better economic output, which is the best performance among all the different altitude bands in all the scenarios available (i.e. 117 billion RWF)

Table 4.9: elevations' NPVs in the five scenarios (0% SDR) – data in Rwandan francs

	scenario +0°	***scenario 2.6***	***scenario 4.5***	***scenario 6***	***scenario 8.5***
1500m - 1600m	-18,106,762,369.81	-44,398,057,806.18	-66,551,851,601.54	-63,552,178,853.81	-100,979,080,998.04
1600m - 1700m	-1,629,348,693.65	-21,351,617,124.16	- 44,885,008,250.14	- 41,726,218,549.78	-84,053,687,398.53
1700m - 1800m	15,362,324,597.46	-4,806,808,895.27	- 24,004,151,894.29	- 21,293,865,852.79	-66,097,675,867.69
1800m - 1900m	32,850,527,781.18	12,132,322,454.66	- 6,569,762,059.39	- 4,009,998,702.34	-47,589,195,392.09
1900m - 2000m	50,820,902,367.83	29,564,603,494.08	10,352,304,387.72	12,982,196,297.61	-28,871,326,287.69
2000m - 2100m	69,263,207,972.92	47,476,162,483.07	27,763,775,788.67	30,462,375,997.23	-10,539,034,090.19
2100m - 2200m	88,172,170,107.40	65,857,298,460.70	45,651,622,025.35	48,417,959,688.21	6,811,756,799.94
2200m - 2300m	107,548,639,641.14	84,703,440,567.14	64,007,214,223.60	66,840,866,117.61	24,170,384,151.56
2300m - 2400m	117,292,077,948.34	103,980,176,737.12	82,808,568,956.89	85,709,813,281.33	41,992,231,849.57
2400m - 2500m	68,840,661,492.72	104,605,894,766.32	94,004,717,671.78	95,330,888,483.83	57,686,456,165.82

In the 2.6 scenario there is immediately a big change in the relationship among the performances of the elevations. The last band, previously 48 Billion RWF less profitable than the lower one, is now the most efficient site for the tea plantation investment. The investment in the highest altitude is recommended even in the other scenarios, with an increase in the gap between the economic performance of this highest elevation and the outputs of the lower ones.

In the 8.5 scenario, the difference between the 2,400-2,500 m band and the lower one approximately reaches 16 Billion RWF.

Thanks to this CBA, the evaluation of the economic impact of climate change is here possible. In the 8.5 scenario, six altitude bands, among ten, have negative ENPVs and in some cases the economic losses are significant. Looking at the actual average temperature, investing at 1,700-1,800m might be economic efficient, giving back an economic return of approximately 15 Billion RWF. However, the worsening of climate change generates considerable economic losses and in the RCP 8.5 scenario there is a considerable decrease of the outcome of approximately 81 Billion RWF, and the NPV in this scenario reaches a severe negative amount (-66 Billion RWF). Apart from the highest elevation (where climate change generally brings benefits), in every altitude there is a loss in the occurrence of climate change. Therefore, even if this work just looks at the increase of the medium temperature, climate change brings considerable economic losses to the tea investment in every altitude bands, leading to negative performances. In the 2.6 scenario, the lightest one, the average economic loss (considering the first nine bands) is roughly 20 billion RWF, whereas in the other ones the average losses are respectively: 41 billion, in the RCP 4.5; 38 billion RWF in the RCP 6; and 81 billion RWF in the RCP 8.5. Converting these values in US Dollars (850 RWF every 1 Dollar), the losses respectively accounts for: 25 million $ (RCP 2.6), 49 million $, 45 million $ and 95 $. It is interesting to note that the economic performances in the RCP 4.5 are worsen than the ones in the RCP 6. Looking at the climate projections, in the RCP 4.5 there is a stronger increase of the average temperature in the first decades, then the peak is rapidly reached, whereas, in the RCP 6, in the far future the growth of the average temperature is continuously and strongly rising. This probably happens because in the RCP 4.5 there is a rapid increase of the greenhouse gas emissions in the first years, then followed by a peak and a strong decrease of the emissions in the following years. In the RCP 6, there is probably a constant growth of the emissions and the peak is very far in the future, leading to a slower but more intense growth of the average temperature in the far future.

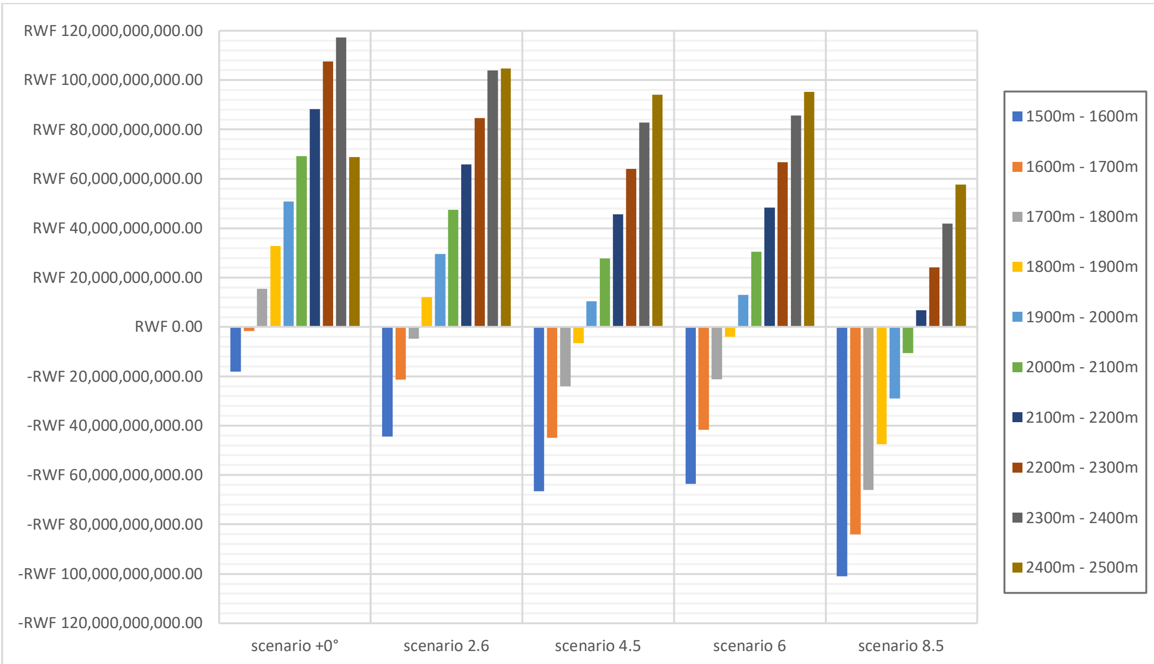
Table 4.10: Economic losses caused by climate change (temperature effect) – (in RWF)

	BAU - scenario 2.6	***BAU - scenario 4.5***	***BAU - scenario 6***	***BAU - scenario 8.5***
1500m - 1600m	- 26,291,295,436.37	- 48,445,089,231.73	- 45,445,416,484.00	- 82,872,318,628.23
1600m - 1700m	- 19,722,268,430.51	- 43,255,659,556.50	- 40,096,869,856.13	- 82,424,338,704.88
1700m - 1800m	- 20,169,133,492.73	- 39,366,476,491.75	- 36,656,190,450.25	- 81,460,000,465.16
1800m - 1900m	- 20,718,205,326.53	- 39,420,289,840.57	- 36,860,526,483.52	- 80,439,723,173.27
1900m - 2000m	- 21,256,298,873.75	- 40,468,597,980.10	- 37,838,706,070.21	- 79,692,228,655.52
2000m - 2100m	- 21,787,045,489.85	- 41,499,432,184.25	- 38,800,831,975.69	- 79,802,242,063.12
2100m - 2200m	- 22,314,871,646.70	- 42,520,548,082.05	- 39,754,210,419.19	- 81,360,413,307.45
2200m - 2300m	- 22,845,199,074.00	- 43,541,425,417.54	- 40,707,773,523.53	- 83,378,255,489.58
2300m - 2400m	- 13,311,901,211.23	- 34,483,508,991.46	- 31,582,264,667.01	- 75,299,846,098.77
2400m - 2500m	35,765,233,273.60	25,164,056,179.06	26,490,226,991.11	- 11,154,205,326.89

These findings are particularly significant in the attempt to calculate the possible expected impacts of climate change on the agricultural investments in Rwanda. These economic estimates could also be a rough indication of the effects of climate change on the agricultural production in other African or developing countries with a similar climate;

although other climate change effects should be included in the analysis, like the pattern of the precipitations and of the extreme events (floods and droughts), in the attempt to perform a more realistic analysis.

Figure 4.7: NPVs of the different altitude bands divided in scenarios (0% SDR)



Even more significant is the comparison between the four cc scenarios ENPVs (considering the same probability for each scenario) with the no climate change framework. This analysis is more representative about the climate change effects because it considers all the climate change scenarios, not only the most severe ones. The economic loss in the tea plantation investment comparing the no climate change scenario and the ENPV in the four climate change scenarios is roughly between -51 and -39 billion RWF. Just the last altitude band gives a better result in the presence of climate change, which reaches a +19 billion RWF. It is evident that the global warming is going to have a sizeable impact on this specific investment, with considerable economic losses, pushing the farmers at higher elevations in the attempt to reach more robust yields.

Even though, in this case study, the economic analysis suggests to the investors to settle the tea plantations at the two highest elevations, the investment decision might be problematic. Climate change poses challenges to the agricultural investment especially in the far future and the increase of the temperature, even in the worse scenario, will probably be progressive, not immediate and abrupt. According to the data collected in the World Bank database, even in the worst scenario, the RCP 8.5, the initial expected increase of the temperature (approximately +1°C in 2030-2031, compared to the last 30 years average temperature), will not be enough for settling the investment at the highest altitude possible. The lower elevations remain recommended in the first years because they initially have a temperature more adapted for efficient tea yields. However, the tea plantation investment has a long life (40/50 years), and the highest altitude thus becomes the preferred, due to the expected increase of the temperature.

Therefore, looking just at the first years' outcomes of the project, going at higher elevations could seem a poorly performing decision, leading to lower economic revenues, compared to the lower altitudes, and requiring an apparently unreasonable effort to the farmers who have to reach very far locations every day. Moreover, the analyses about the past climate trends are still decisive in the evaluation of climate sensitive investments (as the Government of Rwanda has initially done with its tea plantations development strategy). This point could be decisive especially in a developing country context, where the immediate earnings might be privileged in comparisons with long-term outcomes. In the attempt to give some concrete illustrations about this relation, the economic performances of the ten altitudes could be compared. In the next three figures the revenues of the elevations are compared, looking at the performances in the RCP 2.6 scenario. The first table shows the NPV of the tea investment in the various bands, looking at the performances in the RCP 2.6 scenario; the second figure illustrates the cash flows of the sum between costs and benefits (for the RCP 2.6 scenario); whereas the third one presents the cumulative cash flows (for the RCP 2.6 scenario). As shown in the next table, the investment at the highest altitude bands is the most remunerative, whereas planting tea at the first two bands produces a negative economic outcome. Even with slight climate change, the last elevation is the recommended one, with +20 Billion RWF compared to the 2,200 – 2,300 mt band and +40 Billion RWF compared to the 2,100 – 2,200 mt.

Table 4.11: NPV of the tea investments considering an RCP 2.6 scenario (0% SDR) – (in RWF)

	scenario 2.6
1500m - 1600m	- 44,398,057,806.18
1600m - 1700m	- 21,351,617,124.16
1700m - 1800m	- 4,806,808,895.27
1800m - 1900m	12,132,322,454.66
1900m - 2000m	29,564,603,494.08
2000m - 2100m	47,476,162,483.07
2100m - 2200m	65,857,298,460.70
2200m - 2300m	84,703,440,567.14
2300m - 2400m	103,980,176,737.12
2400m - 2500m	104,605,894,766.32

Figure 4.8: Cash flow of the altitude bands

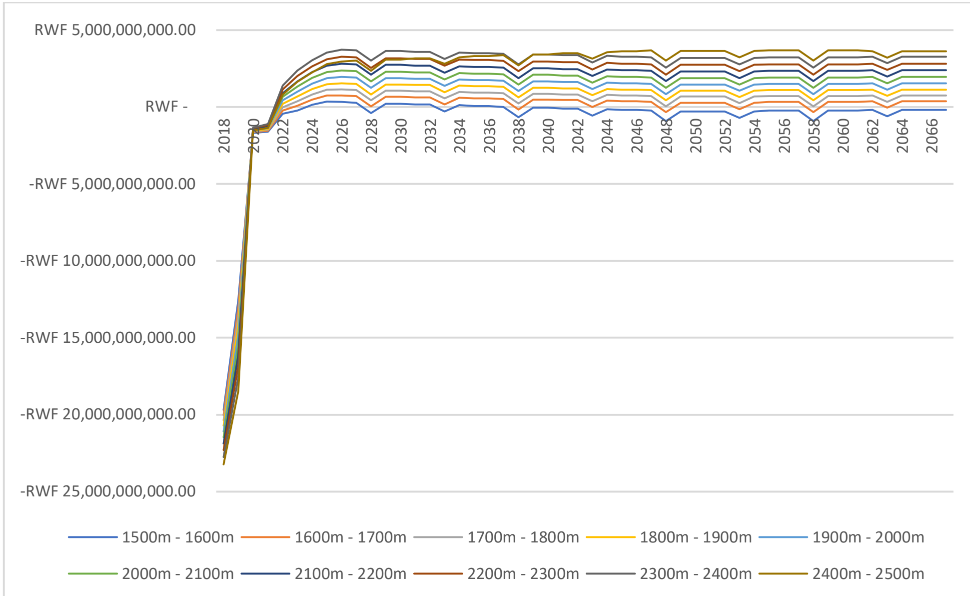
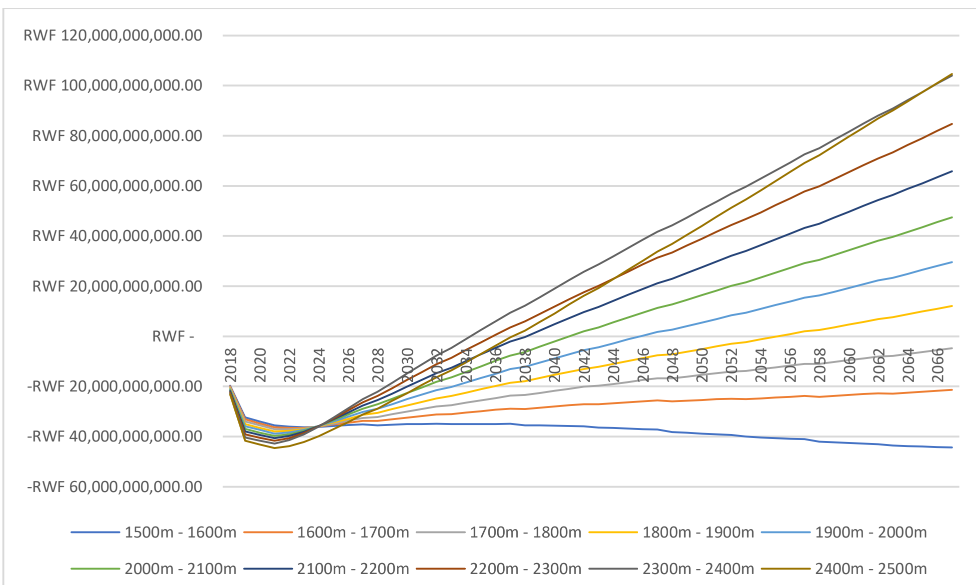


Figure 4.9: Cumulative cash flow of the altitude bands



However, the Figure 4.8 shows that the cash flow of the highest altitude is initially the worst one, requiring higher investment costs, due to the long distance of the investment site and primarily giving lower revenues due to the initial too cold average temperature. Then, the average temperature progressively rises, and the last bands becomes the most suitable for the tea plants, thus leading to better revenues. The last band thus passes the cash flow of the 2,100 – 2,200mt band in the 2025 and the one of the 2,200 – 2,300mt band in the 2031. Looking at the cumulative cash flow (Figure 4.9), the last altitude has the worst performance until the 2025 (eight years since the initial investment!). In the 2034, sixteen years after the planting of the tea, both the 2,100 – 2,200mt band and the next two ones (2,200 – 2,300mt, 2,300 – 2,200mt) still have a higher cumulative cash flow than the highest elevation. In 2066, the penultimate year for the evaluation of the investment, the last elevation surpasses the previous one (2,300 – 2,400mt), becoming the one with the best economic performance. Even if we consider the worst climate change scenario possible, the RCP 8.5, the investment at the highest elevation takes some years becoming the one with the best economic performance. In 2025 the highest band reaches the top cash flow among the other elevations, whereas we have to wait 2031 to see the cumulative cash flow of the highest elevation becoming the best. This distribution of costs and benefits over the duration of the project might lead to different results according to the use of different social discount rates (SDR). Higher SDR will give more weight to the benefits collected in the first years and it will discount the benefits which will occur far in the future, probably limiting the economic profitability of the highest altitude. The effects of different SDR will be discussed in a next section of this research work (paragraph on sensitivity analysis). This initial economic analysis thus leads us to some significant considerations about the effects of the climate change:

i) Even if the analysis just includes the effects of the average temperature, there is a significant economic impact of climate change on the revenues of the tea plantations investment anyway; in the worst climate scenario, six among ten elevations have a negative NPV; this result is coherent with the indications coming from the literature and, in particular, from the last climate risk assessment made by USAID (2019): "*rising temperatures compromise the quality and productivity of highly lucrative, temperature-sensitive tea and coffee (which account for more than 20 percent of export earnings) as agro-ecological zones shift to higher elevations with less arable land*".

ii) climate change pushes the farmers at higher elevations, in the attempt to find higher revenues and more robust investment solutions;

iii) going at higher elevations might be unfeasible in some cases, because there might be limited space, or it might lead to significant higher costs or higher efforts by the farmers;

iv) although investing at the highest elevation is probably the most sustainable solution from an economic point of view, the benefits of this investment choice will occur in the far future, whereas in the initial period the higher investment costs and the too much lower average temperature will have a negative impact on the short-term profitability.

As a conclusion of the CBA for the single elevation bands, the variance and the standard deviation of the ENPV must be identified, considering the NPVs of the elevations in the five scenarios considered. In this analysis the standard deviation is then considered instead of the variance, because it is easier to be analysed, having the same unit of measure of the ENPV. The standard deviation is an important information about the risk of the investment. A high standard deviation means that the return of the tea plantation investment can vary by a significant amount, giving back outcomes that could be either higher or lower. On the contrary, a low standard deviation means that the investment revenues are more robust to the various climate scenarios and therefore less sensitive to the variations of the average temperature.

Table 4.12: Altitude bands CBA results (in RWF)

	ENPV	Standard deviation
1500m - 1600m	- 58,717,586,325.88	27,294,947,696.10
1600m - 1700m	- 38,729,176,003.25	27,493,870,614.73
1700m - 1800m	- 20,168,035,582.51	26,921,697,267.21
1800m - 1900m	- 2,637,221,183.59	26,516,218,157.82
1900m - 2000m	14,969,736,051.91	26,251,194,328.56
2000m - 2100m	32,885,297,630.34	26,283,146,001.32
2100m - 2200m	50,982,161,416.32	26,796,943,382.43
2200m - 2300m	69,454,108,940.21	27,462,151,464.26
2300m - 2400m	86,356,573,754.65	25,490,383,565.68
2400m - 2500m	84,093,723,716.09	17,749,650,819.45

As a result of the cost-benefit analysis, there are two main results:

i) the 2,300 – 2,400mt elevation is the one with the best ENPV;

ii) nevertheless, the highest band (2,400 – 2,500mt) has the lowest standard deviation, meaning that its ENPV is more robust in the various possible scenarios and the investment is therefore less risky.

The difference between the ENPV of the last two altitudes is approximately 2 Billion RWF, whereas the difference in the standard deviation is roughly 7.5 Billion RWF, meaning that if the investor decides to sacrifice part of its expected revenue, he can reach a considerably less risky solution. Therefore, looking just at the expected economic outcome of the investment, the decision-maker will probably choose the penultimate elevation, whereas if the standard deviation criteria is introduced, the decision is going to be more complicated, and the investor will presumably choose the highest one, due to the better trade-off among ENPV and risk.

These are the results of the CBA. Now the analysis goes further, with the aim to test the portfolio analysis as an instrument able to deal with the deep uncertainty produced by climate change. Thus, in the next paragraph, this research work will try to answer to these key questions: i) Is the portfolio analysis useful in helping the decision-makers in the climate change/uncertain framework? ii) Does the PA lead to different investment solutions? iii) Can the PA find investment solutions with better trade-offs among ENPV and variance compared with investing in the single bands?

4.1.4.2 Portfolio analysis

The next step in the methodology used in this case study is the identification of the portfolios and the design of the efficient frontier, in the attempt to find investment solutions with a better trade-off between economic return and standard deviation. The final aim is helping the decision-maker in designing new adapted investments, aware of the possible effects of climate change and possibly more robust and less risky compared to investing the whole quantity of hectares on a single altitude band.

According to the methodology discussed in the second part of this thesis, not all the investment can be mixed in the portfolios in the attempt to find solutions with a better trade-off between ENPV and variance. The fundamental insight that emerge from the MPT framework is that the correlation between the investment is the key parameter in the selection of the assets for the portfolios. Correlation ranges from -1 to +1: -1 is a perfect negative correlation, where the assets revenues inversely vary with the same proportion; 0 means that there is no correlation; +1 means that there is a perfect positive correlation and the investments outcomes increase or decrease together, with the same proportion. If we mix investment which are perfectly correlated, there are no effects on the standard deviations in the portfolios. The risk results in the sum between the risks of the investments which compose the new portfolio. On the contrary, mixing assets that are not perfectly correlated can result in portfolios that have a new, lower, standard deviation and probably a better trade-off between economic return and risk.

Looking at the results of the CBA, the following insights can be highlighted:

i) the 2,300 – 2,400mt band is the elevation with the best ENPV

ii) the last altitude band (2,400 – 2,500mt) has the lower standard deviation

iii) As shown in the previous figure, all the elevations, except for the last one, vary in the same direction and with a similar proportion. This point has been verified looking at the correlations between the performances of the bands in the various scenarios. The correlation has been initially estimated for one altitude with the next higher one (

Table 4.14).

Table 4.13: The NPV of the elevations in the different scenarios (0% SDR) – (in RWF)

	scenario +0°	scenario 2.6	scenario 4.5	scenario 6	scenario 8.5
1500m - 1600m	- 18,106,762,369.81	- 44,398,057,806.18	- 66,551,851,601.54	- 63,552,178,853.81	- 100,979,080,998.04
1600m - 1700m	- 1,629,348,693.65	- 21,351,617,124.16	- 44,885,008,250.14	- 41,726,218,549.78	- 84,053,687,398.53
1700m - 1800m	15,362,324,597.46	- 4,806,808,895.27	- 24,004,151,894.29	- 21,293,865,852.79	- 66,097,675,867.69
1800m - 1900m	32,850,527,781.18	12,132,322,454.66	- 6,569,762,059.39	- 4,009,998,702.34	- 47,589,195,392.09
1900m - 2000m	50,820,902,367.83	29,564,603,494.08	10,352,304,387.72	12,982,196,297.61	- 28,871,326,287.69
2000m - 2100m	69,263,207,972.92	47,476,162,483.07	27,763,775,788.67	30,462,375,997.23	- 10,539,034,090.19
2100m - 2200m	88,172,170,107.40	65,857,298,460.70	45,651,622,025.35	48,417,959,688.21	6,811,756,799.94
2200m - 2300m	107,548,639,641.14	84,703,440,567.14	64,007,214,223.60	66,840,866,117.61	24,170,384,151.56
2300m - 2400m	117,292,077,948.34	103,980,176,737.12	82,808,568,956.89	85,709,813,281.33	41,992,231,849.57
2400m - 2500m	68,840,661,492.72	104,605,894,766.32	94,004,717,671.78	95,330,888,483.83	57,686,456,165.82

Table 4.14: correlation among the altitude bands revenues (in RWF)

Altitudes	Correlation coefficient
15-16/16-17	0,995062042
16-17/17-18	0,998089576
17-18/18-19	0,999922121
18-19/19-20	0,999728117
19-20/20-21	0,999871051
20-21/21-21	0,999994229
21-22/22-23	0,999999851
22-23/23-24	0,993461968
23-24/24-25	0,450328906

The first 9 altitude bands are all almost perfectly correlated, having a correlation coefficient close to +1. However, the last two bands have a correlation coefficient of 0.45, meaning that they are not perfectly correlated. This happens because climate change has a similar negative effect on the revenues of the first nine bands, whereas there is a positive impact of climate change on the highest elevation between the scenario with no climate change and the scenario RCP 2.6. As previously discussed, in the last elevation the temperature is initially too cold for the tea growth, but it becomes more suited in the climate change scenarios due to the increasing of the temperature. Therefore, the correlation coefficient between the revenues of the highest band and the other ones vary between +0.27 and + 0.45. Fundamentally, this means that the investment solution at the highest elevation is going to be the most economically efficient in the climate change scenarios, whereas the other ones (between 2,000mt and 2,400mt) have a better performance in the no climate change scenario. Thus, according to the MPT methodology, mixing the investment between the 2,400 – 2,500mt band and the other bands, will give a better trade-off between ENPV and risk. Nevertheless, the penultimate band has the best ENPV and the lower standard deviation among the first nine band. Therefore, mixing the investment among these bands will not give better results than investing 100% of the hectares in the penultimate band. This is why we have chosen to use just the two highest elevation (i.e. 2,300 – 2,400mt; 2,400 – 2,500mt) in the portfolio analysis.

In the next step, one hundred and one portfolios have been created mixing different percentage of the whole investment on the two highest bands. Every combination among these elevations has been tested, starting from 1% assigned to the 2,300 – 2,400mt and 99% to the 2,400 – 2,500mt, until 99% settled at 2,300 – 2,400mt and 1% at 2,400 – 2500mt. Using STATA procedures, the NPV of these portfolios in every scenario has been estimated. The values of the ENPV (20% likelihood assigned to each scenario) and the standard deviation have been calculated too and they are shown in the next figure[13].

[13] For calculation needs of STATA, the economic values have been divided by 1.000.

Table 4.15: ENPV and Standard deviation of the portfolios (thousands of millions RWF) – 0% SDR, equally likely scenarios.

Portfolio	2300-2400	2400-2500	ENPV	Standard Deviation	Portfolio	2300-2400	2400-2500	ENPV	Standard Deviation
1	100%	0%	85,366,666.25	25,704,743.09	**43**	58%	42%	84,827,814.09	19,294,976.97
2	99%	1%	85,353,839.48	25,523,604.49	**44**	57%	43%	84,814,984.05	19,182,234.64
3	98%	2%	85,341,008.12	25,343,493.13	**45**	56%	44%	84,802,155.24	19,071,909.22
4	97%	3%	85,328,177.90	25,164,427.57	**46**	55%	45%	84,789,326.96	18,964,045.50
5	96%	4%	85,315,344.72	24,986,434.92	**47**	54%	46%	84,776,495.04	18,858,682.68
6	95%	5%	85,302,516.34	24,809,536.72	**48**	53%	47%	84,763,665.26	18,755,865.98
7	94%	6%	85,289,691.97	24,633,757.16	**49**	52%	48%	84,750,836.23	18,655,636.61
8	93%	7%	85,276,858.54	24,459,117.92	**50**	51%	49%	84,738,005.82	18,558,034.56
9	92%	8%	85,264,030.65	24,285,644.63	**51**	50%	50%	84,725,176.97	18,463,104.06
10	91%	9%	85,251,197.75	24,113,362.97	**52**	49%	51%	84,712,344.05	18,370,883.55
11	90%	10%	85,238,370.89	23,942,301.24	**53**	48%	52%	84,699,514.45	18,281,417.14
12	89%	11%	85,225,540.64	23,772,480.00	**54**	47%	53%	84,686,686.99	18,194,743.86
13	88%	12%	85,212,706.33	23,603,930.38	**55**	46%	54%	84,673,857.03	18,110,904.65
14	87%	13%	85,199,880.51	23,436,679.60	**56**	45%	55%	84,661,028.59	18,029,938.86
15	86%	14%	85,187,046.61	23,270,751.21	**57**	44%	56%	84,648,196.85	17,951,883.09
16	85%	15%	85,174,218.50	23,106,181.71	**58**	43%	57%	84,635,365.97	17,876,779.12
17	84%	16%	85,161,394.72	22,942,997.13	**59**	42%	58%	84,622,537.72	17,804,662.52
18	83%	17%	85,148,559.08	22,781,220.22	**60**	41%	59%	84,609,708.72	17,735,569.08
19	82%	18%	85,135,734.27	22,620,890.68	**61**	40%	60%	84,596,876.81	17,669,535.62
20	81%	19%	85,122,900.71	22,462,033.98	**62**	39%	61%	84,584,044.61	17,606,594.42
21	80%	20%	85,110,071.43	22,304,684.08	**63**	38%	62%	84,571,215.59	17,546,781.23
22	79%	21%	85,097,243.29	22,148,872.16	**64**	37%	63%	84,558,389.14	17,490,129.03
23	78%	22%	85,084,408.20	21,994,630.96	**65**	36%	64%	84,545,562.76	17,436,665.70
24	77%	23%	85,071,581.11	21,841,994.38	**66**	35%	65%	84,532,727.79	17,386,419.55
25	76%	24%	85,058,746.36	21,690,993.72	**67**	34%	66%	84,519,895.27	17,339,421.91
26	75%	25%	85,045,925.30	21,541,671.32	**68**	33%	67%	84,507,069.80	17,295,700.81
27	74%	26%	85,033,096.39	21,394,051.78	**69**	32%	68%	84,494,238.40	17,255,275.41
28	73%	27%	85,020,261.00	21,248,174.46	**70**	31%	69%	84,481,413.37	17,218,173.00
29	72%	28%	85,007,436.46	21,104,079.53	**71**	30%	70%	84,468,579.33	17,184,414.81
30	71%	29%	84,994,597.50	20,961,794.71	**72**	29%	71%	84,455,746.30	17,154,016.81
31	70%	30%	84,981,774.62	20,821,369.92	**73**	28%	72%	84,442,920.94	17,127,001.87
32	69%	31%	84,968,945.20	20,682,833.57	**74**	27%	73%	84,430,088.72	17,103,384.02
33	68%	32%	84,956,110.86	20,546,223.22	**75**	26%	74%	84,417,262.30	17,083,177.58
34	67%	33%	84,943,283.00	20,411,584.43	**76**	25%	75%	84,404,429.20	17,066,395.15
35	66%	34%	84,930,450.97	20,278,950.77	**77**	24%	76%	84,391,598.38	17,053,043.41
36	65%	35%	84,917,623.87	20,148,364.80	**78**	23%	77%	84,378,772.90	17,043,136.67
37	64%	36%	84,904,798.06	20,019,866.84	**79**	22%	78%	84,365,941.07	17,036,675.56
38	63%	37%	84,891,965.45	19,893,493.72	**80**	21%	79%	84,353,114.10	17,033,667.34
39	62%	38%	84,879,133.45	19,769,288.78	**81**	20%	80%	84,340,282.56	17,034,110.10
40	61%	39%	84,866,301.59	19,647,292.93	**82**	19%	81%	84,327,446.47	17,038,007.43
41	60%	40%	84,853,476.17	19,527,549.02	**83**	18%	82%	84,314,624.70	17,045,354.57
42	59%	41%	84,840,646.57	19,410,096.08	**84**	17%	83%	84,301,790.74	17,056,148.30

85	16%	84%	84,288,963.40	17,070,383.14	**94**	7%	93%	84,173,494.22	17,351,194.40
86	15%	85%	84,276,130.77	17,088,047.24	**95**	6%	94%	84,160,666.07	17,399,030.39
87	14%	86%	84,263,298.26	17,109,130.77	**96**	5%	95%	84,147,832.96	17,450,103.53
88	13%	87%	84,250,475.14	17,133,624.41	**97**	4%	96%	84,135,002.17	17,504,388.80
89	12%	88%	84,237,640.22	17,161,509.49	**98**	3%	97%	84,122,173.94	17,561,860.68
90	11%	89%	84,224,817.40	17,192,773.82	**99**	2%	98%	84,109,341.13	17,622,480.43
91	10%	90%	84,211,982.62	17,227,392.29	**100**	1%	99%	84,096,516.50	17,686,218.11
92	9%	91%	84,199,151.94	17,265,351.58	**101**	0%	100%	84,083,686.45	17,753,041.52
93	8%	92%	84,186,323.17	17,306,627.30					

4.1.4.3 The efficient frontier and the decision-maker choice

Thanks to the data collected in the previous table, the efficient frontier is here identified (Figure 4.11). In the next figure (Figure 4.10), three key elements are presented:

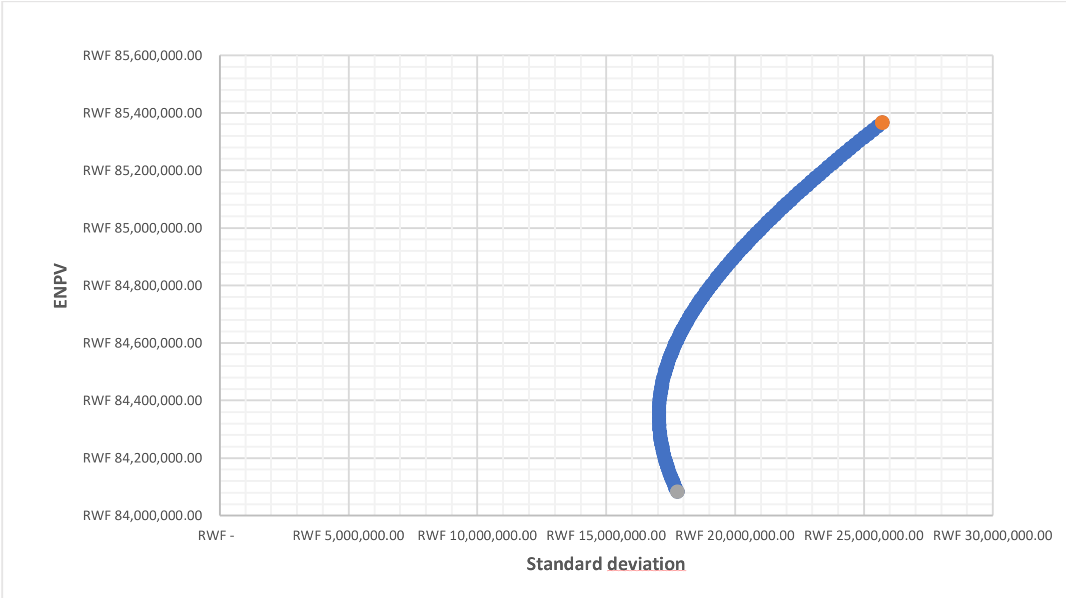
i) the orange point represents the 2,300 – 2,400mt elevation band, which has an ENPV of approximately 85 Billion RWF, but a great standard deviation too (more than 25 Billion RWF);

ii) the grey dot represents the performance of the highest elevation, which has a lower ENPV (a little bit more than 84 Billion RWF), but a very low standard deviation too (17 Billion RWF);

iii) the blue line is the set of the portfolios made by the mixes of the investment in the two altitudes. Due to the mixes are made just by two assets, the output has the shape of a line. If the assets involved were more than two, the portfolios would have defined an area instead of a line.

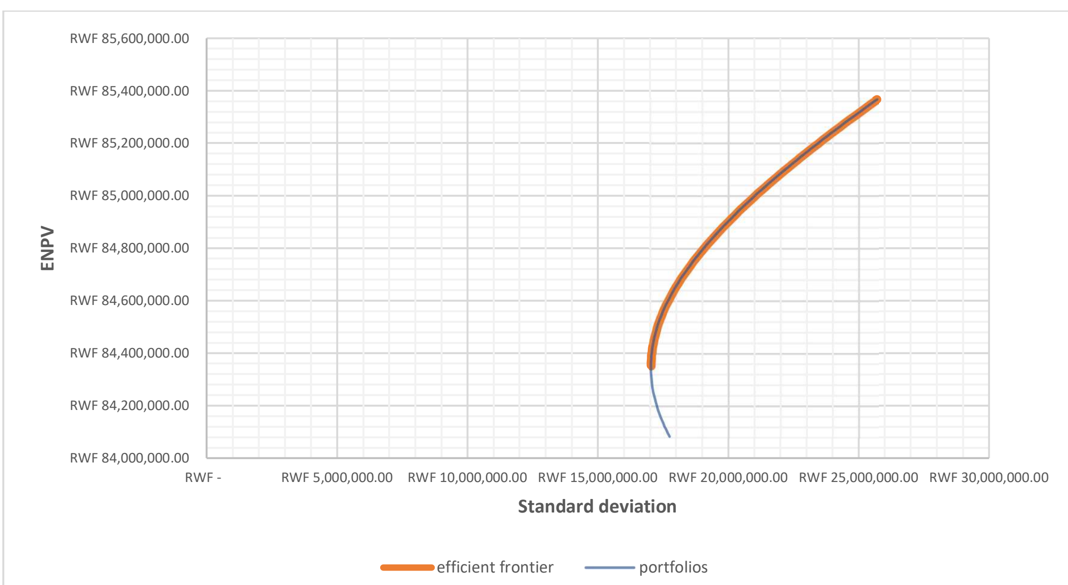
This figure immediately shows an interesting insight of the portfolio analysis. The mixing of the investment in portfolios gives alternative possible investment solutions, identifying a new frontier with a better trade-off among ENPV and standard deviations. For example, with these new sets of investment solutions, planting tea at the highest elevation (grey dot) is no longer a solution on the efficient frontier. There is indeed at least one new investment solution with the same standard deviation but with a better ENPV too.

Figure 4.10: The two highest altitude bands and their mix in portfolios



The new efficient frontier starts again from the 2,300 – 2,400mt band, but now stops at the portfolios which have the lowest standard deviation possible, which is the portfolio N.80, with 79% invested at the highest elevation and 21% invested on the penultimate one. That means: 2,686 ha invested in the 2,400 – 2,500mt band and 714 ha invested in the 2,300 – 2,400mt band. The portfolios with a bigger share of the highest altitude have got a standard deviation higher than the previous ones and a lower ENPV. Therefore, they are no longer on the efficient frontier, as there are other investment solutions with a better trade-off among ENPV and risk.

Figure 4.11: The efficient frontier (0% SDR, 20% likelihood to each scenario)



The efficient frontier here identified represents the key output of this portfolio analysis. This line collects all the investment solutions which have the best trade-offs among the economic return (the ENPV) and the risk (the standard deviation). The efficient frontier, the orange curve of Figure 4.11, has several important characteristics:

i) it collects a series of equally efficient investments, whereas there is not a single optimal investment solution;

ii) it identifies new interesting investment solutions which can significantly reduce the risk of the investment; the standard deviation of the portfolio with the lowest risk (N.80) is approximately 8 Billion RWF lower than the standard deviation of the 2,300-2,400mt elevation (the one with the highest ENPV); this great reduction in the risk of the investment coincides with a very low difference in the ENPV between these two investment solutions, i.e. approximately 1 Billion RWF. This might be a very important insight for the hypothetical decision-maker of our analysis. A sacrifice of 1 Billion RWF of expected economic return leads to a reduction in the risk of the investment of almost 8 Billion RWF. Probably the farmer will choose this new solution, in the attempt to guarantee a better and more robust revenue in every possible climate scenario.

iii) the decision-maker can choose the investment solution she prefers among the ones on the efficient frontier, according to his personal risk attitude; if she is risk seeker, she will choose the point of the efficient frontier with the best ENPV, even if it has the highest standard deviation; if she is risk neutral, she will probably choose again the point with the highest ENPV ("*a person has risk neutral preferences when he or she is indifferent between certain amounts and lotteries with the same expected payoff*" – Boardman et al, 2018); whereas if she is risk adverse, she will choose the solution with the lower standard deviation ("*a person is risk adverse if he or she prefers a certain amount instead of the lottery*" – Boardman et al, 2018).

4.1.4.4 Sensitivity analysis – the Social Discount Rate

The Social Discount Rate (SDR) is a key element in the evaluation of the public projects with the CBA methodology. This is even more crucial when the climate change policies have to be assessed, since the global warming impacts significantly rise in the future. There is a universally agreed need of weights to aggregate in one unique measure the costs and benefits emerging in the present with the ones which are going to occur in the future. However, there is less agreement about the specific values of that weights.

The SDR is needed due to two main motivations. Firstly, the society is expected to grow in the future, reaching wealthier conditions, caused by economic progress and social development (wealth effect). Through investment, a given amount of currently available resources can be transformed into a greater amount of resources in the future. Therefore, a dollar today is worth more than a dollar in the future, when higher incomes are going to be enjoyed and the revenues of an investment in the present might be collected. The second, and more controversial, reason refers to people's pure time preference (or impatience). People have the propensity to prefer income today rather than tomorrow, even if they are not expecting to be wealthier in the future. More formally, people have a positive marginal rate of time preference. These parameters are the engine of the so-called Ramsey's formula (Ramsey, 1928), an equation that relates the social discount rate to: i) a pure time preference rate; ii) the growth rate of per capita income/consumption; and (iii) the elasticity of marginal utility of income/consumption.

Ramsey's formula:

$$SDR = d + n * g$$

Where *d* is time preference, *n* is the elasticity of marginal utility of consumption and *g* is the grow rate.

The issue of SDR has been a central issue for many years but it now becomes even more complicated due to the need of assessing projects with long-lasting environmental effects. The increase awareness about current environmental problems leaded to a renewed attention to this key parameter, in the attempt to find a reasonable range of values which takes into account the possible intergenerational catastrophic consequences (Weitzman, 2001). The issue of the SDR has recently been a key topic of the debates about the Stern Review on the Economic of Climate Change (Stern, 2006). This widely reported study argues that current policies could lead to the cost of climate change amounting to 5% of Gross Domestic Product (GDP) each year. Thus, according to these estimates, the Stern Review suggests an immediate sacrifice of 1% of the global GDP. However, these dramatic results have been highly argued by various economists. One of them, William Nordhaus, stated that the conclusions of Stern were absolutely influenced by an "extreme assumption" about discounting (Stern used a symbolic 0.1% SDR), and he claimed that, using more conventional discount rates coming from the climate change scientific literature, the dramatic results of the review would disappear (Boardman, 2018).

In the last years an increasing part of the scientific literature has proposed a Declining Discount Rate (DDR) for the policies which have a long-term effect (usually projects that have an economic life longer than 50 years), affecting the life of the future generations (Arrow et al, 2013). Climate change produces new extreme challenges and risks to our society, thus leading the development of our communities on a perilous pathway. In the climate change mitigation framework, the present costs of the policies have to be compared with benefits which can occur in the late future (Arrow et al, 2013). Greenhouse gas emissions remain in the atmosphere for decades and they might provoke severe impacts in the distant future. Therefore, the decision of emitting or not a certain amount of CO_2 now should be evaluated considering its very long-term effects. This is also true for other long-term policies, like the building of a nuclear power station, the construction of a bridge or the plantation of perennial crops. However, the impacts of climate change are highly uncertain, and it is difficult to say how much the society is going to be badly affected, estimating the welfare of the future generations. More distant we go in the future, more the predictions about the impacts of climate change and the prosperity of the people become uncertain.

Boardman et al (2018) summarise the reasons why a decreasing SDR should be preferred in the place of a constant SDR: i) people appear to be "time inconsistent"; Laibson (1997) observed that individual discount functions are approximately hyperbolic, implying they engage in hyperbolic discounting. People recognise that if they are not committed to save money every day, they will never save as much as they know they should for the future needs (thus people are aware of their lack of self-control). Therefore, they tend to save big amount of money in long-term saving programs (such as government's bonds) with large penalties for early withdrawals, but, at the same time, the want to maximise their available credit in the present consumption and thus they borrow short-term on credit cards at a high real interest rate. These particular observed saving patterns are consistent with a time-declining discount rate.

ii) secondly, in the case of impacts that occur far in the future, such as some environmental problems, there are ethical dilemmas in the application of a constant SDR. Even if we use a low SDR (1% or 2%) the result of an economic analysis would suggest that it is not efficient to sacrifice even a small amount of consumption today in the attempt to avoid catastrophic environmental disasters in the far future. This problem could emerge in the case of mitigation policies, reforestation intervention and biodiversity conservation projects.

iii) thirdly, there should be some considerations about the well-being of the future generations. Therefore, the future of our sons and heirs is a part of our concerns.

iv) lastly, the further the projects produce effects in the distant future, the more there is uncertainty about the welfare of the society. Climate change increases the uncertainty about the future: there is possibility of catastrophic events, the average temperature could become unsustainable in some countries and some economic activity might be dramatically compromised by the future climate conditions. Therefore, especially in the distant future, there is a widespread uncertainty about the growth rate of the economy and the expected market rates of interest. “It is difficult to judge how fat the tail of catastrophic climate change might be because it represents events that are very far outside the realm of ordinary experience” (Weitzman, 2011).

Weitzman (2001) made a survey based on the opinions of 2,160 economists, asking them the correct SDR to apply to public projects. According to the paper, there were no declining SDR suggested, but the wide variety of the answers makes the effective SDR decline significantly over time. The research of Weitzman (1998 and 2010) shows that if there is uncertainty about the social discount rate to be used in the cost-benefit analysis, a declining social discount rate should be applied in order to represent this wide uncertainty. The essential reason is represented by a “fear factor” that derives from risk aversion to significant productivity shocks representing bad future states of the world (Weitzman, 1998). Furthermore, this uncertainty and the other significant uncertainties previously mentioned in this work (the magnitude of climate change, the equilibrium climate sensitivity, the local impacts, …) contribute to the difficulty to estimate the possible extraordinary impacts of catastrophic climate changes (Weitzman, 2011).

France and UK administrations use a DDR in the evaluation of their investment projects. In its Green Book for the Appraisal and Evaluation of the Public Interventions (2018), the UK HM Treasury suggests a declining SDR of 3.5% for the first 30 years, then decreasing to 3.0% from the 31st to the 75th and 2.5% from the 76th to the 100th year.

A completely different point of view comes from the developing countries. In these countries, people’s pure time preference is significantly focused on the current consumption and the discount rates are usually very high. For example, the African Development Bank has used a 12% SDR for the evaluation of a Road Rehabilitation Project (2016) in Kenya. In Rwanda, the SDR is published by MINECOFIN as Economic Opportunity Cost of Capital (EOCK) on their website[14]. The EOCK or SDR to be applied is 13%. Comparable SDR rates as in Rwanda have been found for other African countries, e.g. 11.08% for South Africa (Rwanda Ministry of Finance and Economic Planning, *Methodology for Project Appraisal*, 2018). There are no comprehensive surveys about the SDR in Africa and the theoretical basis of these high values. Zhuang et al (2007) presented a survey about the SDR used in various countries and they have identified different traditions in the use of this specific parameter. In Asia, the SDR adopted are generally high. The

[14] http://rwanda-cscf.cri-world.com/NationalParameters.php

Philippines and Pakistan use 15% and 12%, respectively, whereas India currently uses 12%. China suggests an 8% SDR for short- and medium-term projects and a lower than 8% discount rate for projects with a long-time horizon.

According to these two opposite views, the portfolio analysis is here tested using a declining 3.5%-3% SDR and a 13% SDR, in the attempt to assess the widest spectrum of possible assumptions.

Firstly, the sensitivity analysis of the SDR starts with the evaluation of the economic performances of the single altitude bands with this two SDRs. In the case of the SDR suggested by the UK HM Treasury, the discount factor has been identified with the following formula until the 30^{th} year of the project (2048):

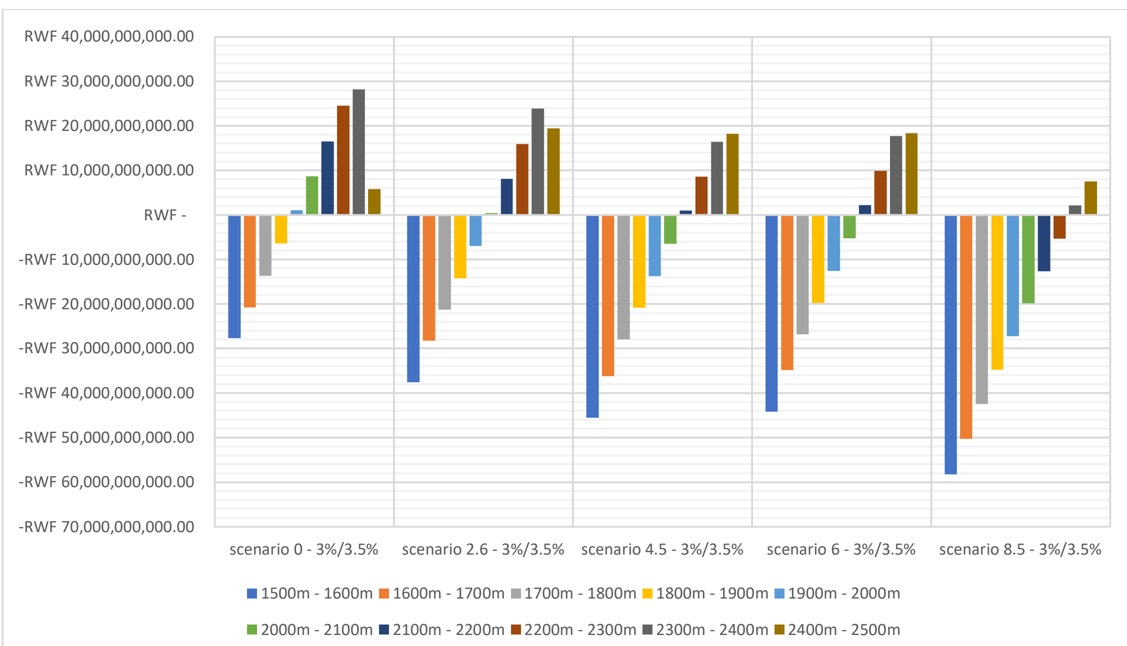
$$DF(t) = \frac{1}{(1 + 3.5\%)^t}$$

With the 31^{st} year (2049) the lower SDR is introduced:

$$DF(t) = \frac{1}{(1 + 3.5\%)^{30}} * \frac{1}{(1 + 3\%)^{(t-30)}}$$

The NPVs of the different elevations with the new SDR are shown in the next figure.

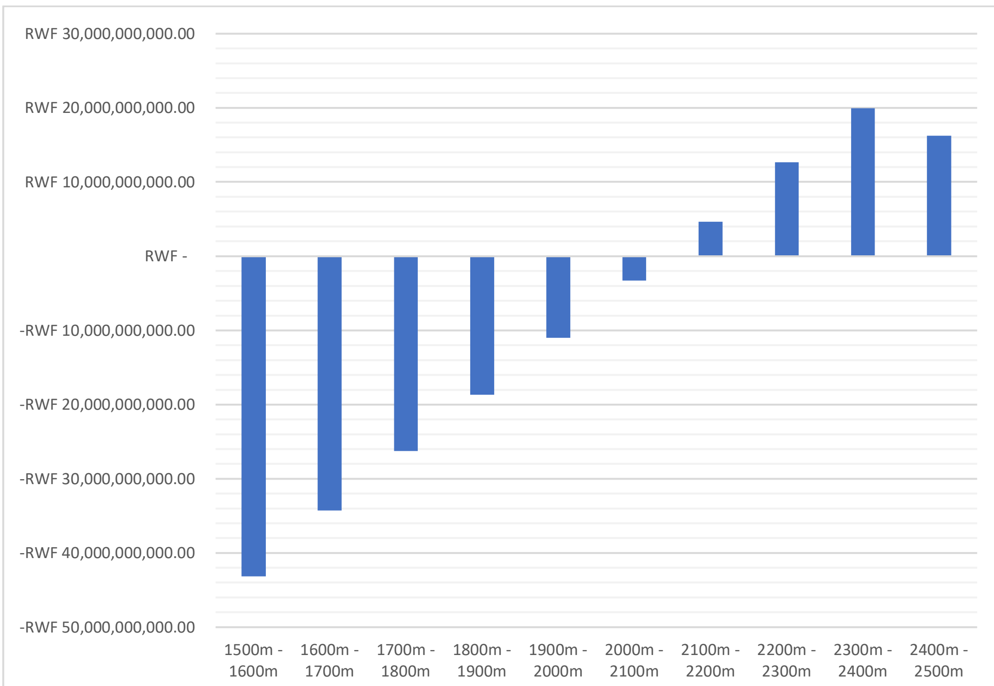
Figure 4.12: NPVs of the ten elevation bands (five scenarios, SDR 3.5%-3%)



The discount rate inevitably rises the relative weights of the initial investments for the plantation of the tea plants (remember, there is a +5% of the investment costs at each elevation, starting from the lowest one, i.e. 1,500 mt) and it decreases the benefits of planting tea at the highest elevation. As discussed in a previous section of this chapter, the benefits of going at higher elevations especially emerge in the future, due to the increasing of the climate change effects. The last elevation is indeed not perfectly suited for the tea investment in a no climate change scenario, due to the presence of a too cold average temperature. However, with the climate change scenarios the temperature rises, and the highest bands progressively becomes the best location among the other ones. Nevertheless, the SDR here introduced partially reduce the weight of the distant future, the moment where the climate change effects will be more severe. Therefore, now the last band is no longer the best solution in every possible climate change scenario. Now the highest elevation band remain in a secondary position even in the 2.6 scenario and it has almost the same NPV of the penultimate one in the 4.5 and in the 6 RCP scenario. In the worst climate change scenario, there are now just two altitude bands with a positive NPV, the lasts two.

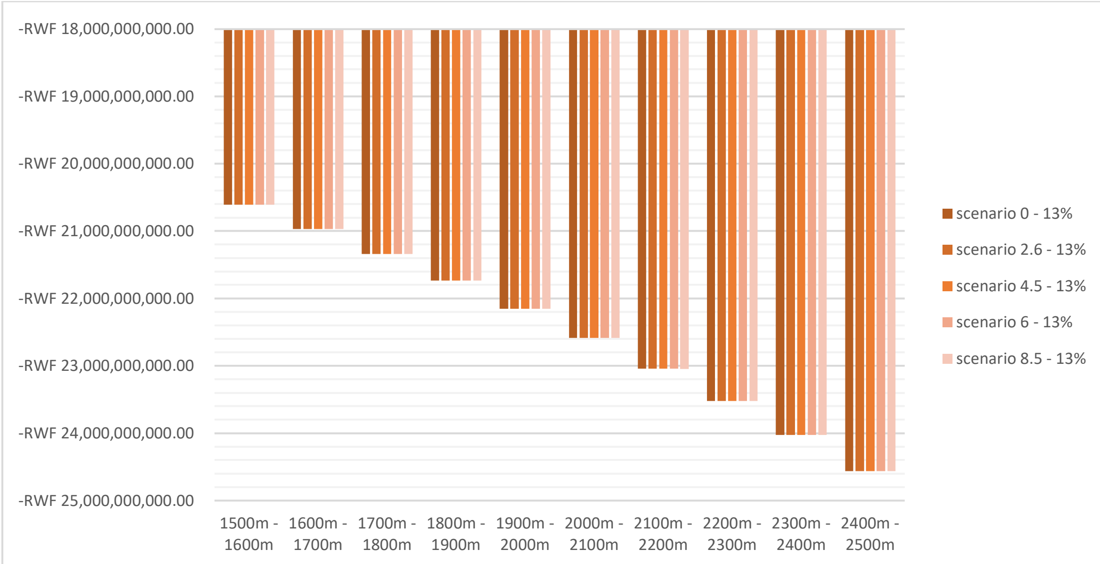
According to the CBA the last two altitude bands remain the ones suitable for the portfolio analysis. The 2,300-2,400mt elevation has the best ENPV, whereas the 2,400-2,500mt band has the lowest standard deviation among all. Furthermore, they are not perfectly correlated, leaving to the portfolio analysis the opportunity to mix the investment among them in the attempt to find more efficient allocations. The PA will be discussed later in the following pages.

Figure 4.13: ENPV of the different elevations (same probabilities to each scenario; 3.5%/3% SDR)



Now the second assumption for the SDR can be evaluated. The 13% SDR is a very extreme parameter and it significantly underestimate the positive long-term effects of the tea investment, especially in the climate change scenarios. The results are presented in the next figure.

Figure 4.14: NPVs of the various elevations in the diverse climate change scenarios (13% - SDR)

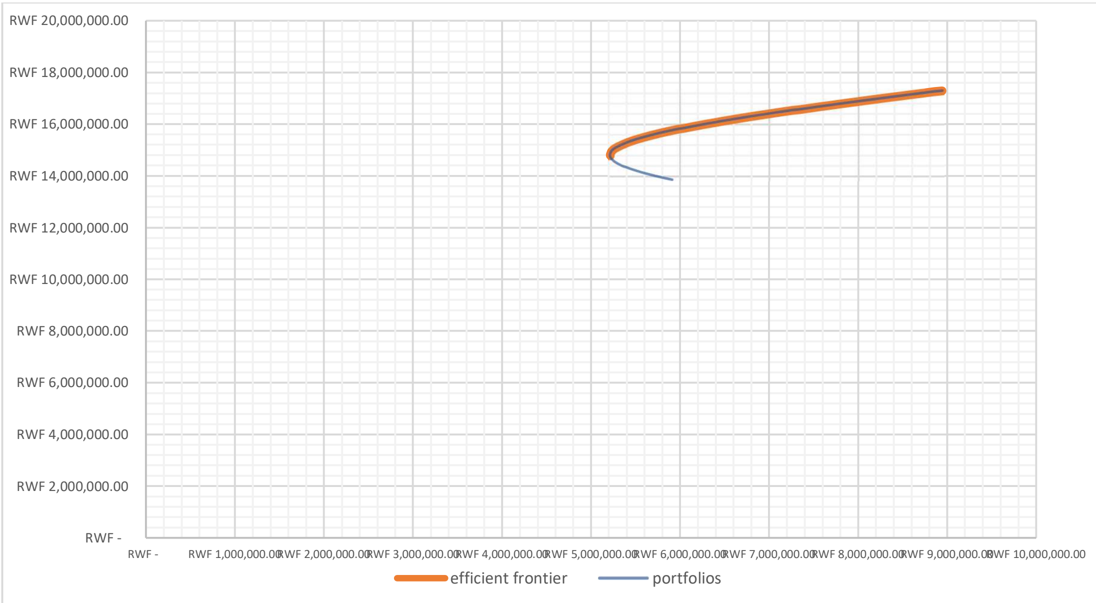


The first key result is that the NPVs of the elevations are now all negative, in every climate scenario. The discount rate is very high, and it significantly rises the relative importance of the initial investment, reducing the weight of the expected cash flows. Therefore, according to this SDR, the economic performance of the altitude bands is here driven basically just by the amount of the starting costs of the project. Consequently, due to the presence of increasing costs in the higher altitudes (+5% in every higher band), the lowest elevations are now the most efficient in economic terms.

Another interesting insight is connected to the climate scenarios. This new assumption about the SDR drastically reduces the weight of the future cash flows. Thus, the differences among the economic performances of the altitude bands in the scenario are here cancelled. The NPVs of the investments remain approximately the same in all the possible futures.

Due to the data collected in these analyses, the portfolio analysis is made just for the first SDR assumption. In the next figure the results of the portfolio analysis for the decreasing SDR 3.5%/3% are shown.

Figure 4.15: Portfolio Analysis of the tea plantation investments considering the two highest elevations and a decreasing discount rate – 3.5%/3%



Comparing the 0% SDR portfolios with the Declining SDR, the ENPV are lower and the standard deviation is generally higher compared to the ENPV. Again, the positive effect of the investment diversification is here shown. The left handle of the curve contains a series of investment solutions which are more economically efficient than investing all the 3,415 hectares at the highest elevation possible. There are 55 possible investment solutions which have a lower standard deviation of the highest altitude band. The portfolio N.72 is the investment with the lowest risk. It has the 72% of the whole investment settled at the highest elevation and the 28% at the 2,300-2,400mt band. The standard deviation of this portfolio is 800 Million RWF lower than the highest one.

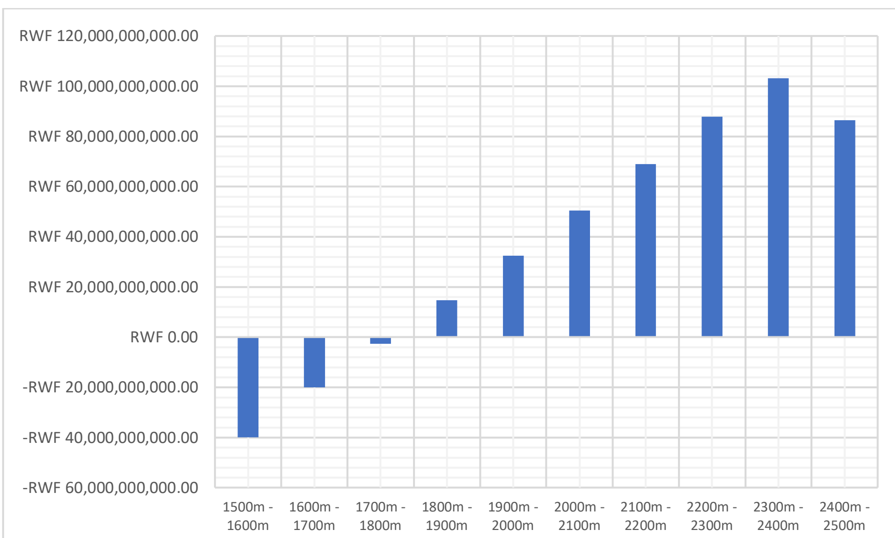
4.1.5.5 Sensitivity analysis – different weights to the climate change scenarios

Another important part of the sensitivity analysis should be the assessment of different distribution of probabilities for the various climate change scenarios. This work starts from the considerations about the deep uncertainty which characterizes the forecasts about the expected future climates. This is why this thesis initially assumes equal likely scenarios, assigning 20% of probabilities to each of them. However, this is a big assumption in a climate change framework, especially for the long-term investments, which have to deal with a very wide variety of climate conditions in the next decades. Although this research work has discussed the ability of the portfolio analysis in dealing with climate change uncertainty, the analysis relies on this strong assumption (even though this assumption is absolutely coherent with the indications coming from the literature review; Ando and Mallory, 2012). Consequently, this sensitivity analysis will basically test two alternative probability distributions for the climate change scenarios, in the attempt to evaluate the importance of these parameters on the outcomes of the analysis.

The distributions considered are: i) a "*light climate change future*", with the following probability distribution – 40% to the no climate change scenario; 40% to the RCP 2.6 scenario; 10% to the RCP 4.5 scenario; 5% to the RCP 6 scenario; 5% to the RCP 8.5 scenario; ii) a "*heavy climate change future*", with the following probability distribution – 5% to the no climate change scenario; 5% to the RCP 2.6 scenario; 10% to the RCP 4.5 scenario; 40% to the RCP 6 scenario; 40% to the RCP 8.5 scenario. Thanks to these distributions the analysis now evaluate the investment in three conditions: i) an optimistic world, where the greenhouse gas emissions are radically reduced, significantly limiting the climate change impacts; ii) a pessimistic view, where the mitigation efforts are scarce and inefficient, leading to unprecedented increases of the average temperature; iii) and a balanced future, where there is no prevalence of one scenario (the assumption considered in the main analysis). The percentages used for the "*light climate change future*" and for the "*heavy climate change future*" have been decided by the authors of this work. However, in the scientific literature, even though there are no indications about the weights, there are examples of sensitivity analyses which consider different possible futures and average temperatures. In Ando and Mallory (2012), they employ two sample probability distributions to demonstrate the sensitivity of optimal portfolio analysis to assumptions about outcome probabilities: one distribution, called "*no change likely*", is weighted heavily toward historic conditions, whereas the other, called "*uniform*", assumes each climate scenario is equally likely to occur.

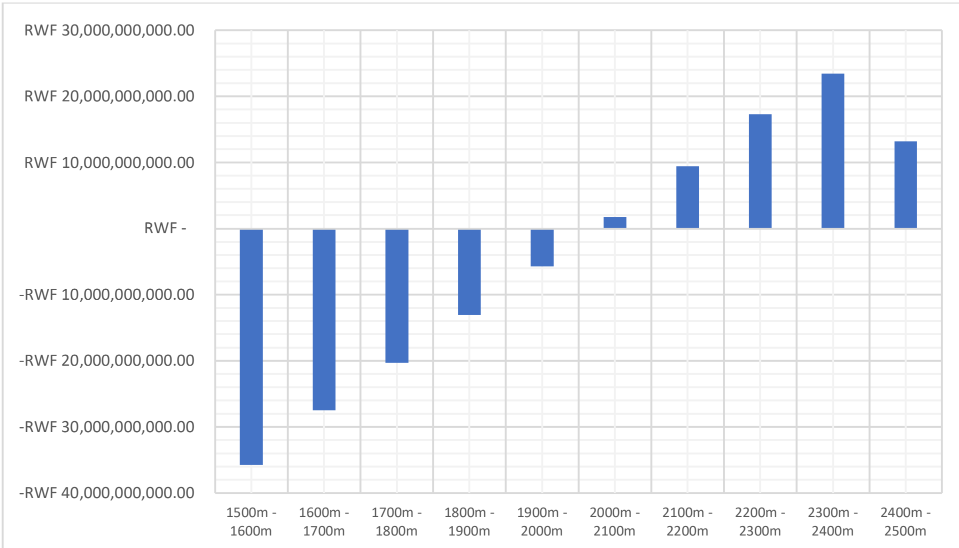
Following the same steps of the SDR sensitivity analysis, the analysis starts with the estimate of the ENPVs and the standard deviations of the various elevations, with the aim to evaluate the opportunity to go further with the portfolio analysis.

Figure 4.16: "Light climate change future" ENPVs and Standard Deviations of the various altitude bands (0% SDR)



	1500m - 1600m	1600m - 1700m	1700m - 1800m	1800m - 1900m	1900m - 2000m	2000m - 2100m	2100m - 2200m	2200m - 2300m	2300m - 2400m	2400m - 2500m
St. D (RWF)	21,991,064,778.49	20,649,302,842.79	19,896,930,988.55	19,777,546,998.62	19,852,431,492.98	20,063,317,607.47	20,494,883,650.16	20,996,347,156.72	17,996,483,666.50	17,518,780,866.51

Figure 4.17: "Light climate change future" ENPVs and Standard Deviations of the various altitude bands (3.5%/3% SDR)



	1500m - 1600m	1600m - 1700m	1700m - 1800m	1800m - 1900m	1900m - 2000m	2000m - 2100m	2100m - 2200m	2200m - 2300m	2300m - 2400m	2400m - 2500m
St.D. (RWF)	8,123,098, 008.23	7,394,887, 983.64	7,105,671, 041.52	7,080,873, 482.28	7,140,354, 991.71	7,251,569, 612.82	7,417,156, 497.38	7,597,420, 141.36	6,204,569, 937.58	6,548,368, 596.02

These two figures (Figure 4.16; Figure 4.17) show the economic performances of the elevations in the *light climate change future*, considering the Social Discount Rates used in the previous paragraph (constant 0%; declining 3.5%). This is an optimistic assumption which imagines a world where the emissions are rapidly stopped, leading to a significant reduction of the negative impacts of climate change. Thus, there are two main effects in the CBA of the altitude bands:

i) there is a general increase of the ENPVs of the investments in the various altitude bands (in both the 0% SDR and 3.5%/3% DSDR there is one more altitude with a positive ENPV compared to the assumption of equally plausible scenarios);

ii) the 2,300-2,400mt band increases its relative performances compared to the other elevations. In the DSDR example, this altitude is the best even for the value of the Standard Deviation.

Therefore, the recommendation coming from this analysis seems to be that the penultimate elevation is the best solution and that the whole investment should be assigned to this location. However, the statistical correlation among the last two bands is still not perfect, suggesting that the process of diversification could give some positive results anyway. Consequently, the portfolio analysis has been performed and the results are presented in the next two figures (Figure 4.18; Figure 4.19), the first one referred to the 0% SDR and the following one on the DSDR 3.5%/3%.

Figure 4.18: Efficient frontier in a "light climate change future" (0% SDR)

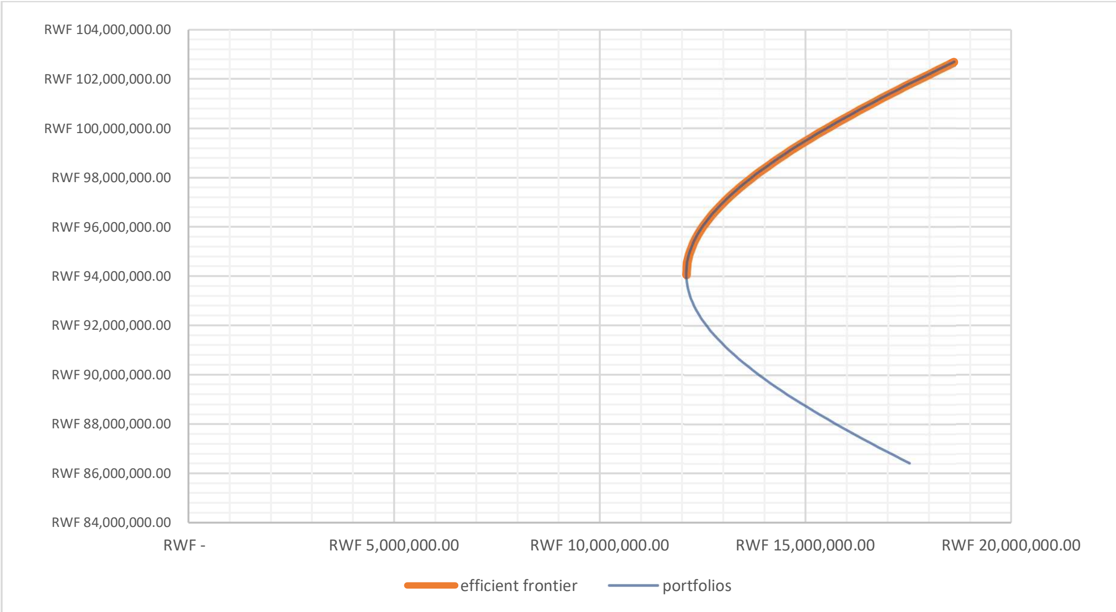
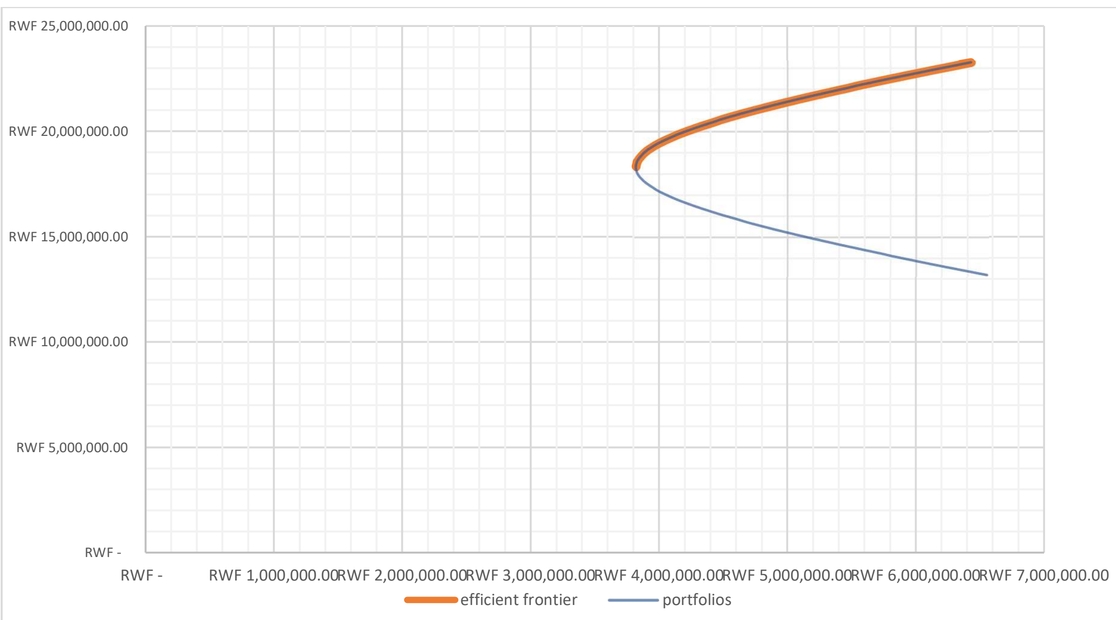


Figure 4.19: Efficient frontier in a "light climate change future" (3.5%/3% DSDR)



In both diagrams the lower ends of the curves represent the performance of the highest altitude, whereas the upper ends show the economic outcomes of the 2,300-2,400mt band, which have higher ENPVs and lower (or similar) Standard Deviation too (as we have observed in the CBA). However, the mix of the last two elevations is again useful and it produces new possible investment solutions which have a lower risk. These two bands are not perfectly correlated and the risk of the investment can be reduced through the creation of mixed portfolios of these two assets. The portfolios with the lower risk are: i) C.53 (53% at 2,400-2,500mt; 47% at 2,300-2,400mt) in the 0% SDR analysis;

ii) C.49 (49% at 2,400-2,500mt; 51% at 2,300-2,400mt) in the 3.5%/3% DSDR analysis. However, here, the results are less straightforward compared to the original analysis (i.e. 0% SDR and 20% probability to each scenario).

In the main analysis of this dissertation the reduction in the ENPV is more than compensated with the reduction of the risk. The ENPV of the penultimate elevation is 85.366 billion RWF, with a standard deviation of 25.704 billion RWF. This elevation has the best economic performance from the ENPV perspective; however, it has the highest standard deviation too. The standard deviation accounts for 29% of the value of the ENPV and, in the worst possible scenario, the ENPV would reach 59.662 billion RWF. On the contrary, the performance of the portfolio with the lower standard deviation (n.80) is completely different. The ENPV (84.353 billion RWF) is lower than the one of the penultimate band, but it has a lower standard deviation too (17.034 billion). Here the standard deviation accounts for the 20.2% of the ENPV and, in the worst case possible, the ENPV will not go under 67.319 billion RWF. This result is considerably better than the one of the penultimate altitude band (59.662) meaning that the penultimate elevation can give the highest economic returns but, at the same time, it is riskier that the investment in the portfolio, leading to considerable poor performances in the case of worst scenarios. Thus, should she bet on the penultimate elevation or should she prefer the portfolio and the more certain yields? the choice between the two opportunities relies on the risk attitude of the decision maker.

But, the results in the sensitivity analysis are different. The portfolios with the lower standard deviation are the number 53 and the number 49. The worst performances of these portfolios are 81.955 billion RWF and 14.311 billion RWF, whereas the worst economic results of the penultimate elevation are 84.072 billion RWF and 16.848 billion RWF. Thus, in this sensitivity analysis, even though the portfolios have a lower standard deviation, the performances of the penultimate elevations will be higher in any case. Consequently, although the C.53 and C.49 have a lower risk compared to the 2,300-2,400mt band, this altitude will probably be recommended to the decision-maker.

The "*heavy climate change future*" scenario leads instead to more unequivocal results. If the RCP 6 and 8.5 are heavy weighted, the analysis recommends to invest at the highest altitude. In the worst climate change scenarios, the highest elevation has the best ENPV and the lowest Standard Deviation. Moreover, the 2,300-2,400mt altitude is no longer a good alternative here. It is the second one both in the RCP 4.5, RCP 6 and RCP 8.5. Consequently, considering just the worst scenarios, the correlation among the two highest elevation is almost perfect and there will be no advantages in mixing these two investment solutions. The portfolio analysis returns a line which collects the highest elevation (with the best ENPV and standard deviation) with the penultimate one (the second one for ENPV and standard deviation) and every result is worse than investing 100% hectares on the highest band.

4.1.5 Potential extensions

The case study here discussed is inevitably a first, preliminary, example of the application of a portfolio analysis in the evaluation of agricultural investments in a climate change framework. The application of the Modern Portfolio Theory in this context is a demanding exercise, requiring a significant amount of biological and economic data, good computational skills and time. Moreover, this analysis is something new in the framework of the analysis of climate change adaptation policies and it can be considered highly innovative. Although the insights coming from this research work are interesting and relevant for the climate change adaptation practice, this analysis could be considered a promising starting point of more complex and comprehensive exercises. During the discussion of this case study various assumptions have been made, in the attempt to simplify the analysis. However, some of these simplifications might be faced in a next version of this research work, leading to a more realistic and affordable analysis.

The key points that can be included in a refined version of this exercise are here resumed:

i) a better description of the biological components needed for the growth of the plants should be introduced. A relation among the average temperature and the rate of growth of the tea plant and leaves have been identified. However, there are several other dimensions which can influence the tea yield, e.g. the characteristics of the soils, the humidity of soils and air, the gradient of the soils which can affect the exposition to the sunbeams. As we discussed in this dissertation, there are studies about the suitability of the Rwandan soils to the tea plants. The soils in the valley regions have good physical characteristics, great depth with excellent porosity, good permeability and high infiltration rates and it is easy to work; whereas, in the mountainous tea-growing regions, the study found that the dry and stony soils make it difficult for the tea bushes to access water and other nutrients. Therefore, in these areas a rising shortage of precipitations due to climate change could be a critical issue for the growth of tea plants. Consequently, the quality of the soil might be a limiting factor to the plantation of tea at the highest elevations, balancing the positive effect of the colder temperatures. This might be a decisive element in the choice of the most suitable areas, and it should be introduced in a hypothetical refined version of this study.

ii) a sensitivity analysis regarding the changes of the tea prices can be included. Tea leaves prices have been related to the average temperature, assuming that a lower temperature leads to a slower growth of the leaves and to an increase of the tea leaves quality. However, the tea price can be influenced even by the international market of tea. The global tea market is influenced by diverse changes which can be analysed more in depth. Climate change can be a critical factor for the global production of tea, and it can influence the quantity of tea available every year and its price.

iii) a refined analysis should develop a broader climate change analysis, identifying more details about the expected future scenarios. The current analysis has focused just on the modifications in the average temperature. Nevertheless, a wider number of components can be included, some of them particularly decisive for the tea yield performances: the changings in the distribution of the rainfalls, the length of the dry periods, the changes in the humidity of the soils and air. For example, researches demonstrate that drought and variable precipitation have negative effects on tea yield but also on quality (Ahmed et al. 2014).

iv) climate extremes have not been included in this analysis. Climate change will probably exacerbate the extreme events, leading to a higher number of both floods and droughts (IPCC, 2014). The increasing of the extreme events could be a dramatic issue for the agriculture sector both in the developed and developing countries. These phenomena (e.g. hailstorms, floods and severe droughts) are particularly important for the yields and sometimes they can compromise the whole production. A model which can randomly estimate the occurrence of extreme events could be developed, in the attempt to simulate the effects of the different climate scenarios on the extreme events distribution.

v) the tea investment can have a significant impact on the welfare of the farmers and their local communities. Climate change can produce severe impacts on the welfare of these people, especially the most vulnerable ones. Climate change can reduce the availability of water resources, the quality of some ecosystem services and it can increase the threats to the health of the most vulnerable people, due to the increasing of heat weaves and extreme events in general. Consequently, a robust and effective tea investment decision could be a very precious instrument in the attempt to help the local communities to rise their adaptive capacity against climate change. Where climate change brings new and massive challenges to the development of the local communities, a well-designed and robust investment decision might limit the negative effects of climate change. Therefore, a refined version of this work could include an economic and social analysis of the expected effects of the tea revenues on the local communities in the various climate scenarios.

vi) there is a variety of adaptation interventions, e.g. working on the capabilities of the local communities, introducing technical improvements, developing early warning systems. Obviously, the adaptation measures in agriculture are not limited to the selection of the best location for the investment. This analysis considers the decision regarding the ten altitude as a simplified way to experiment the portfolio analysis methodology in a climate change adaptation framework. However, the practice of the adaptation interventions in the agriculture sector suggests several other measures that can be integrated in the attempt to increase the adaptive capacity of the local farmers and the robustness of the agricultural yields. Therefore, in an updated version of this work, more adaptation measures can be introduced in the analysis, in the attempt to find a more comprehensive and effective adaptation strategy. The guiding principle for the selection of the other adaptation measure should be the correlation of their economic performances with the other measures in the various climate scenarios. Probably, there could be some no regret measures (i.e. measure which have good performances with or without climate change) that can be introduced in the portfolio analysis in the attempt to reduce the overall risk of the investment.

vii) Adger and other relevant researchers have identified various barriers to the implementation of concrete and effective adaptation measures. One of the most important barriers refers to the lack of comprehension about the values and the points of view of the local communities. Every community has its own preferences, values and knowledges. Thus, they might prefer an investment solution instead of another one. The distance between their preferences and the investment choice made, or suggested by a high-ranking decision-maker, influences the implementation of the measure, leading to good or bad results. A further step of this analysis could include an inquiry about the preferences of the local communities about the tea investment. An interview or workshops could be proposed, in the attempt to understand the main goals and values of the farmers in that specific part of Rwanda. The knowledge of their preferences might be integrated with the economic analysis, with the goal to develop some more appropriate policy recommendations.

viii) the possibility to put the whole 3,415 hectares at just one elevation has been another significant assumption of this research work. Although the South-West part of Rwanda is a mountainous area, the opportunity to dedicate this massive area to the tea plantations has to be verified. This might be complicated, especially at the highest elevations. A more detailed analysis of the site, the other economic activities already activated and the distribution of the population on that territories should be carefully designed, in the attempt to perform a more realistic analysis, with the aim to generate more coherent policy recommendations.

ix) this on-site analysis about the physical characteristics of the areas and about the position of the villages could be an interesting source of information for a refined study of the investment and management costs. In this work we assumed a 5% increase of the investment and management costs every higher altitude band. The increasing costs are the ones related to the human capital, whereas the costs for the materials and infrastructures has been kept stable. The assumption is that going at higher elevations requires more time and efforts, because further locations have to be reached. Even the costs of the transport for the management and for the harvest have been increased (e.g. more fuel). Although this assumption seems reasonable, it has been proposed according to a simple preliminary evaluation of the sites and of the locations of the farmers communities. Therefore, a more accurate analysis of the locations should be developed in a hypothetical new analysis, in the attempt to generate more accurate data about the costs of moving to the different sites.

x) The analysis developed for this case study doesn't consider the possible externalities produced by the project. The externalities connected to the job market and the economic growth have been partially considered in the economic analysis through the use of the conversion factors. However, there is a plurality of other possible externalities which could be integrated in the analysis. For example, Mupenzi et al (2011) highlighted the importance of soil preservation for the agriculture sector in Rwanda. They started from a consideration of the Environment Agency (2002) which evaluated the costs of damages to agricultural soils in England and Wales. They have estimated this cost as £ 264 million a year and the cost of treating water contaminated with agricultural pollutants is £ 203 million a year. Erosion and environmental contamination form degraded soil is occurring frequently in developing countries where it is a major problem. Soil degradation accelerated by erosion is a big problem in Rwanda where erosion is caused not only by the topography of the country, but also by deforestation. When plants (trees, shrubs, undergrowth) are cleared from a site, soil is exposed to sunlight and the eroding effects of wind and water. Soil aeration is then increased and the rate of weathering increases. In order to prevent soil erosion, in 1998, the Rwanda government tried to mobilize its people to plant trees in order to restore lost forest cover (Mupenzi et al, 2011).

xi) Another interesting development of this analysis could be the introduction of more decision points. Here the farmers decide to plant all the 3.4 thousands of hectares at time 0. However, in the reality, the decision might be postponed, waiting for more information about the performances of the investment and the scientific analyses of the climate. Even though the future climate cannot be exhaustively forecasted, especially in the long-run, refined information about the scientific principles that regulate the climate could be collected in the future, giving more accurate data about the expected climate. Therefore, this analysis could be structured in two or more decision points, maybe introducing an option value of waiting for better information about climate change.

Conclusions

After having presented the theoretical framework of the adaptation policies, the multidimensional issue of the climate change uncertainty and the Modern Portfolio Theory methodology, the dissertation has here discussed a case study. The main goal of this chapter has been the evaluation of a new decision support tool, the portfolio analysis, in the attempt to find good investment solutions for the adaptation to climate change.

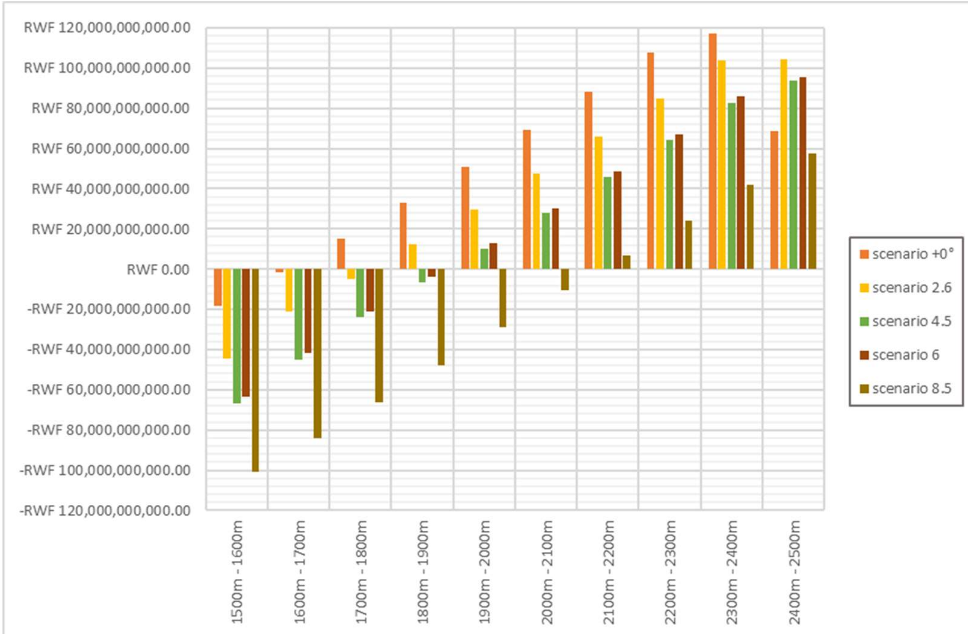
The methodology has been tested in the context of agricultural investments in Rwanda, a developing country which has rapidly grown during the last decade but is threaten by the possible severe impacts of climate change. The average temperature might progressively increase until approximately +0.6°C to +4°C in 2070; the pattern of the precipitations is highly uncertain with a tendency of more severe droughts; there will probably be an increase of the extreme events, as floods and inundations. Furthermore, the country is still socially and economically fragile and it predominantly relies on rain-fed agriculture, particularly exposed to the impacts of climate change.

Tea is a key asset for the economy of the country, especially due to its important role for the development of the exports. Rwanda tea trade grew by 110.2% between 2007 and 2016, placing the country among the ten most important nations for the export of black tea. However, tea is a long-term investment, particularly sensitive to climate change. The average temperature and the amount of precipitations are key elements for the production of tea plants, both for the quantity and quality of the yields. Therefore, climate change could be decisive for the development of this sector and the tea plantation investments should be carefully planned, considering the possible evolutions of the climate.

As a part of an eventual, more comprehensive, adaptation strategy for the agriculture sector, this thesis developed a portfolio analysis for the selection of the best locations where to plant the tea plantations, including in the analysis the expected climate change effects. The locations where to grow the tea plants are ten altitude bands, with an elevation of 100 meters each, ranging from 1,500mt above sea level, until 2,500mt. Every elevation has been characterised by an average temperature, taking the average temperature of Kigali in the last thirty years as a reference point (approximately at 1,500mt) and then decreasing by 0.65°C every higher band. Furthermore, economic data about the costs and benefits of the tea investment has been collected, starting from a survey made by the European project ECONADAPT.

Thanks to the information gathered, the cost-benefit analysis of investing the whole 3,400 hectares in every altitude band, in every climate scenario, has been developed. The following figure (Figure 4.20) shows the performances of the different altitude bands in the various climate scenarios.

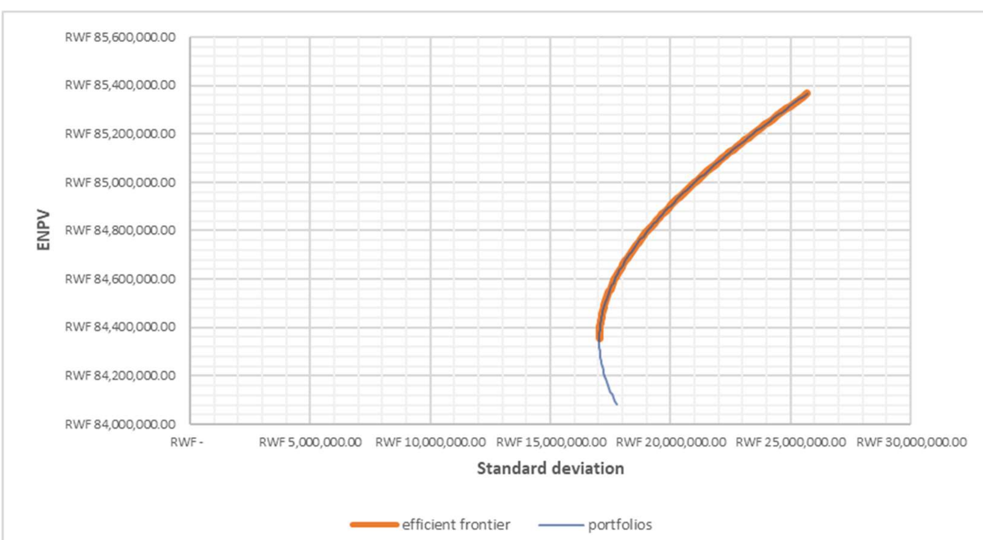
Figure 4.20: NPV of the altitude bands in the diverse climate scenarios (0% SDR)



The cost-benefit analysis of the single elevations (with a 0% SDR) shows that the penultimate elevation is the one with the best ENPV, whereas the last one has the lowest standard deviation, i.e. it is the less risky investment due to the low variability of its economic performance. The last two elevations are also non-perfectly correlated. Thus, these two elevations have been selected for the portfolio analysis and all the possible combinations of the investment among them have been tested, starting from 1% assigned to the penultimate band and 99% to the highest one, until the portfolio with the opposite share of hectares.

Then, the portfolios have been represented on a graph and the efficient frontier has been found.

Figure 4.21: The efficient frontier (0% SDR)



The graph clearly presents the gain in economic efficiency obtained with the portfolios. The upper extreme of the curve is the 2,300 – 2,400mt band, whereas the lowest extreme shows the outcome of the highest elevation. Starting from the lowest point there are several portfolios which have a lower standard deviation with a better ENPV, solutions that should be recommended instead of planting the whole 3.4 thousand hectares at the highest elevation. The portfolio N.80, i.e. 79% at the 2,400 – 2,500mt band and 21% at the lower one, is now the investment solution with the lowest risk. The standard deviation of the portfolio with the lowest risk (N.80) is approximately 8 Billion RWF lower than the standard deviation of the 2,300 - 2,400mt elevation (the one with the highest ENPV); this great reduction in the risk of the investment coincides with a very low difference in the ENPV between these two investment solutions, i.e. approximately 1 Billion RWF.

The decision-maker can choose the investment solution she prefers among the ones on the efficient frontier, according to her personal risk attitude; if she is risk seeker, she will choose the point of the efficient frontier with the best ENPV, even if it has the highest standard deviation; if she is risk neutral, she will probably choose again the point with the highest ENPV; whereas if she is risk adverse, she will choose the solution with the lower standard deviation.

The last step of this study has been the sensitivity analysis, in the attempt to verify the effects of the variations of two critical parameters used in the PA: the social discount rate (SDR) and the weights assigned to the various climate scenarios. A declining SDR and an extreme 13% constant SDR have been tested. The 13% SDR leads to a critical reduction in the benefits of the investment, overestimating the initial costs and ignoring the significant long-term effects of climate change on the tea yields. With the declining discount rate, the results of the CBA are similar to the 0% and the mix of the investment in the two higher bands leads to efficient solutions with a lower risk. There are 55 possible investment solutions which have a lower standard deviation of the highest altitude band. The portfolio N.72 is the investment with the lowest risk. It has the 72% of the whole investment settled at the highest elevation and the 28% at the 2,300-2,400mt band. This conclusion is analogous to the result of the 0% SDR analysis, where the portfolio with the lowest risk is the N.80, with a similar distribution of the shares of the investment over the two highest bands.

However, the sensitivity analysis on the climate scenarios generates rather different results. Even if the mix of the investment in the two highest bands is again effective in the reduction of risk, the investment in a single elevation is more effective in both the scenarios. In the light climate change scenario, the investment should be dedicated at the 2,300-2,400mt band, because even in the worst case the performances of this elevation would be higher than the ones of the less risky portfolio; whereas, in the heavy climate change scenario, the highest elevation becomes the recommended ones, due to the weight assigned to the RCP 6 and RCP 8.5 scenarios.

General conclusions

Climate change is a dramatic challenge of our age. Even though there are several scientific studies about the effects and the local impacts of the global warming, the evaluation of the costs of climate change and the benefits of the adaptation measures is complex and uncertain. Therefore, although there is a proliferation of adaptation policy recommendations, plans and intervention strategies, the effective implementation of adaptation measures is uneven. Despite this lack of concrete action, the adaptation policies are desperately needed, especially to assist the most vulnerable and marginalised peoples, who have the lowest adaptive capacity. They do not have the means to deal with climate change effects and they need the help of a public policy which gives them economic resources, new technologies, information and social capabilities. Furthermore, adaptation is needed also in the long-term investments, where climate change could heavily modify the efficacy of the projects. For example, the performances of a dam or the shape of a sewage network could be highly affected by the future average temperature and the pattern of the precipitations, probably leading to a waste of public resources in the case that climate change risk and uncertainty are not considered in the design of the infrastructure.

Although the importance of the climate change impacts for the welfare of the countries, especially the ones highly reliant on natural resources, the uncertainty about the costs of these effects and the benefits of adaptation can impair the decision-making processes. Even though a part of this uncertainty is going to be resolved by progresses in the scientific knowledge (led by the works of the IPCC), a significant share will remain unknown in the future. Due to this uncertainty, the traditional decision-making processes could lead now to ineffective solutions, with inefficient use of public resources.

In the previous chapters, new decision-making instruments and tools have been described, then developing a case study of a concrete application of the Modern Portfolio Theory (MPT) methodology to the assessment of an agricultural investment in Rwanda. Portfolio analysis is an instrument coming from finance that has been used also in the natural resource management framework. However, even though the potential of this tool in the evaluation of the public policies has been demonstrated, the practice of the portfolio analysis in the climate change adaptation environment is scarce. Moreover, there are no examples of the use of this instrument in the agricultural sector, which is a key asset for many countries, especially in the developing world, where agriculture is essential for the life of a large part of the society.

In Rwanda, a developing country which has rapidly grown during the last decade, the impacts of climate are going to be severe. The average temperature might progressively increase until approximately +0.6°C to +4°C in 2070; the pattern of the precipitations is highly uncertain with a tendency of more severe droughts; there will probably be an increase of the extreme events, such as floods. Furthermore, the country is poorly prepared for these expected impacts: firstly, the human development index (HDI) still places Rwanda among the low developed nations (0.524 – 158 among 189); secondly, the country is highly dependent on the agriculture sector and on the export of tea and coffee, which are predominantly rain-fed (just the 4.6% of the intensive croplands is irrigated) and the annual GDP of Rwanda significantly varies according to the pattern of the precipitations; thirdly, there will be other pressures on the society, due to the significant expected increase of the population in the next years, from 11 million today to 26 million in 2050 (combined with severe droughts in 2015 and 2016, the growth of the population brought an increase of the undernourished from 3.5 million to 4.3 million). Besides the predominant ethnic dimension, the demographic pressure and the scarcity of land suitable for agriculture were two additional motivations of the 1994 genocide. Climate change could exacerbate these conflicts and forward-looking adaptation measures are therefore essential.

Rwanda is highly reliant on the agriculture sector, which accounts for 35% of annual GDP and almost 90% of total employment. Tea is one of the most important crops. It was introduced in the 1950s and it is an essential asset of the Economic Development and Poverty Reduction Strategy II 2013-2018, the development program that should drive the nation to the status of middle developed country in 2020. Now, tea plantations produce 24 thousand tons of black tea and they cover approximately 24 thousand hectares, especially located in the mountainous areas of the East part of the country. Rwanda tea trade grew by 110.2% between 2007 and 2016, placing the country among the ten most important for the export of black tea. However, tea is particularly sensitive to climate change.

The average temperature and the amount of precipitations are key elements for the production of tea plants, both for the quantity and quality of the yields. The expected increase of the temperature is therefore going to be decisive for the suitability of some areas to the tea plants. Places now optimal for the cultivation of tea might become absolutely unadapt in the future, due to too high temperature. Even the possible increase of the extreme events could be decisive for the suitability of some parts of the country to the tea plantation. Even though there are various predictions about the expected increase of the average temperature, the studies about the possible patterns of the precipitation are more uneven. However, extreme events like droughts and floods are expected to increase. The study made for the NAPA of Rwanda shows that one of the key areas of the tea plantations, the South-East of the country, will be severely hit by the negative effects caused by heavy rains. These territories are particularly exposed to destructive erosion, considerable soil degradation, landslides and landslips. Furthermore, climate change might decrease the quality of the soils, foster the dissemination of new pests and diseases and it might increase the financial vulnerability of the tea farmers.

This is why, besides the main development plans (Vision 2020 and EDPRS II), the Government of Rwanda designed important climate change adaptation strategies. In 2006 the Rwanda administration developed its NAPA, where the main vulnerabilities of the country were analysed and six adaptation options and seven high priority projects were identified. The dissemination of the irrigation techniques, the protection of land against flood and erosion and the increase of the adaptive capacity of the population in the rural areas were three of the most important policies designed in the attempt to face the most urgent challenges posed by climate change. Then, in 2011, the National Strategy for Climate Change and Low Carbon Development were issued. This represents a more comprehensive climate change strategy for Rwanda, looking both at the mitigation and adaptation priorities and focusing on the distant future, 2050. Another milestone for the planning of adaptation policies in Rwanda was the NDC (2017) for the Paris Agreement. This document presented a detailed description of the adaptation measures needed in the most affected sectors of the administration. For the agriculture sector various important measures were selected: the dissemination of agroforestry techniques, the increase of the use of organic fertilizers, a better management of the waste water, even for irrigation purposes, a better analysis and classification of the soils and land available for agriculture, the dissemination of soil conservation practices, the distribution of sustainable methods for the management of pests and the spreading of irrigation techniques.

However, although these adaptation strategies are essential for the sustainable development of the Rwandan agricultural sector, a crucial policy should be the mainstreaming of the data and the forecasts about the expected climate into the design of long-term projects. Investing in new perennial crops just focusing on the past climate trends is no longer an optimal solution and climate change predictions have to be inevitably included in the design and management phases. The amount of economic resources available (or free land) is indeed scarce and the choice of the activity or the place to assign the investment should be therefore carefully planned.

In our case study, there is a fixed number of hectares of tea plantations that have to be settled (3,400 ha). Tea plants are basically a "hard" investment, requiring high investment costs and giving a good economic return after several years. The plant usually reaches 100% production after 7/8 years since its plantation. Therefore, the investment decision should be cautiously designed, looking at the expected evolutions of the climate. Thus, the aim of the decision-makers should be no longer the choice of the best place to settle the plants, but rather the identification of the lands that guarantee also robust performances in the diverse climate scenarios. The expected consequences connected to the different climate scenarios have to be thus included in the economic analysis, with the aim of considering the performances of the investment under a plurality of possible environmental conditions. However, the traditional decision support tools like the Cost-Benefit Analysis, the Cost-Effectiveness Analysis or the Multi-Criteria Assessment are not perfectly suitable for this task, because of the difficulties they have in dealing with the climate change uncertainty.

Therefore, the Modern Portfolio Theory methodology has been tested in the evaluation of a tea plantation investment in Rwanda. The research work has been guided by two essential questions: Does the inclusion of climate change scenarios modify the recommended investment decisions of a farmer in selecting the most suitable area for the plantation of new tea plants? Is the portfolio analysis effective in the identification of efficient solutions for the allocation of the plants, robust to the expected impacts of climate change?

In the attempt to perform the portfolio analysis some essential preliminary steps have been taken:

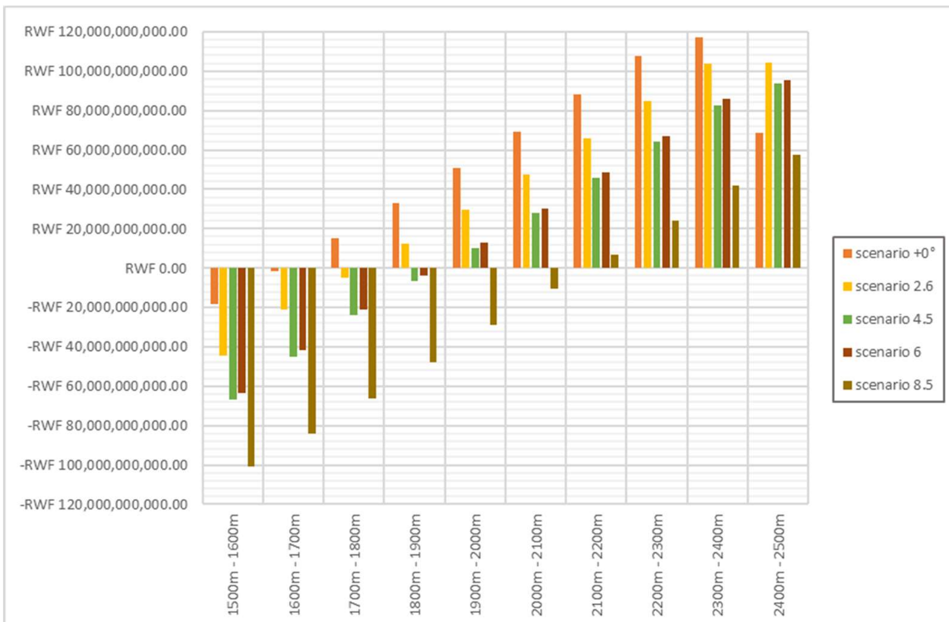
i) A recognition of the investment costs needed for the plantation of 1 hectare of tea plant;

ii) The identification of the relation between the average temperature and the quantity and quality of tea production;

iii) The analysis of the climate data and the selection of reliable and comprehensive future climate scenarios. In this specific case study, the climate data about Rwanda have been collected from the Climate Change Knowledge Portal 2.0 by the World Bank. The portal presents climate data downscaled for each country, using the Coupled Model Intercomparison Project, Phase 5 (CMIP 5) and assembling together 16 different models. Hereby, the data are recent, updated and they represent a wide variety of predictive models. The analysis considered four climate scenarios (RCP 2.6; RCP 4.5; RCP 6; RCP 8.5) and a no climate change scenario, where the average temperature remains stable in the future. According to the assumption of deep uncertainty about the future, the analysts decided to assign an equal distribution of probabilities to the scenarios (i.e. 20% each scenario).

iv) The last preliminary step has regarded the identification and description of the sites available for the expansion of the tea plantations. The places are 10 different altitude bands, with an elevation of 100 meters each, ranging from 1,500mt above sea level, until 2,500mt. Every elevation has been characterised by an average temperature, taking the average temperature of Kigali in the last thirty years as a reference point (approximately at 1,500mt) and then decreasing by 0.65°C every higher band. Using this information base, the Cost-Benefit Analysis of investing the whole 3,400 hectares in every altitude band, in every climate scenario, has been developed.

Figure GC 1: The economic performance of the elevations in the different climate scenarios



The coloured bars show the economic performances of the different altitude bands in the various possible climate scenarios. The first columns, the orange ones, presents the outcomes of the elevations in the no climate change scenario. It identifies the optimal choice of the decision-makers in a business as usual framework and represents the baseline to which the results of the other scenarios can be compared in terms expected economic impacts of climate change on the tea plantation investments (apart from the highest elevation, in the other bands the economic losses range from 13 billion RWF to 83 billion RWF). The 2,300 - 2,400mt would be the location where the farmer will settle the tea plants if he does not consider the effects of global warming. Considering instead the outcomes of the tea plants in the other scenarios, the highest elevation seems to be the most efficient in economic terms. However, the estimate of the ENPV (with 20% of likelihood assigned to each scenario) still recommends the penultimate elevation as the best investment solution, followed by 2,400 - 2,500mt and 2,200 - 2,300mt. Even though the economic performance is an important indicator for the investment decision, Markowitz (the forerunner of the Modern Portfolio Theory) stated that, in the context of high uncertainty about the future outcomes, the risk connected to this economic result is the other essential decision criteria for the investment choice. The risk is measured with the variance or standard deviation of the ENPV. Looking at this value the highest altitude band is the best solution. This elevation has an ENPV 2 billion RWF lower than the penultimate band, but it has a lower standard deviation too, of approximately 8 billion RWF. Therefore, with a sacrifice in the economic revenues, there is a much higher compensation in the reduction of risk.

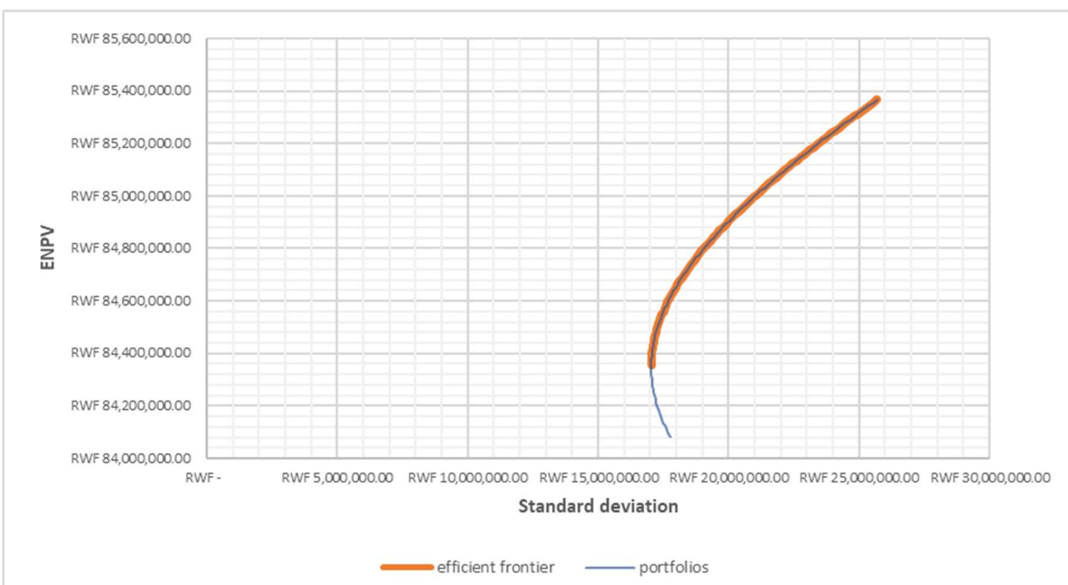
The analysis of the performances of the different elevations in the climate scenarios returns another crucial parameter for the correct development of a portfolio analysis: the statistical correlation coefficient among the economic revenues of the bands. One of the key prerequisites for the effectiveness of the portfolio analysis is that portfolios can reduce the risk of the investment if they mix assets with a low or negative correlation. Therefore, the correlation coefficients among the different bands have been estimated, looking at the pattern of their performances in the various scenarios. All altitude bands, except the last one, have a similar proportionate trend: their economic performances decrease following the worsening of the climate scenarios (from the no climate change scenario until the RCP 8.5). However, the highest elevation has a different pattern: it performs badly in the no climate change scenario, but in the RCP 2.5 the economic return increases, becoming the best investment solution. Therefore, the correlation among these performances and the ones of the other elevations is not perfect and it accounts for approximately 0.45. Hereby, the two highest altitude bands have been selected for the portfolio analysis. This is justified by two essential motivations:

i) They are the elevations with the highest economic performances and the lowest standard deviations;

ii) They are not perfectly correlated.

Thus, in the next step of the analysis the portfolios have been created, mixing different shares of hectares in the two highest elevations. Every combination of the tea investment has been tested, starting from 1% assigned to the penultimate band and 99% to the highest one, until the portfolio with the opposite share of hectares. The ENPV and the standard deviation has been estimated for every portfolio and the results have been presented on a graph. On this figure the efficient frontier has been designed, collecting all the points with the best ENPV for every possible standard deviation value.

Figure GC 2: The efficient frontier



The graph clearly presents the gain in economic efficiency obtained with the portfolios. The upper extreme of the curve is the 2,300 – 2,400mt band, whereas the lowest extreme shows the outcome of the highest elevation. Starting from the lowest point there are several portfolios which have a lower standard deviation with a better ENPV, solutions that should be recommended instead of planting the whole 3.4 thousand hectares in the highest elevation. The portfolio N.80, i.e. 79% at the 2,400 – 2,500mt band and 21% at the lower one, is now the investment solution with the lowest risk. The standard deviation of the portfolio with the lowest risk (N.80) is approximately 8 Billion RWF lower than the standard deviation of the 2,300 – 2,400mt elevation (the one with the highest ENPV); this great reduction in the risk of the investment coincides with a very low difference in the ENPV between these two investment solutions, i.e. approximately 1 Billion RWF. This might be a very important insight for the hypothetical decision-maker of our analysis.

However, the decision-maker has not the obligation to choose this specific combination but she can choose her favourite investment solution among the ones on the efficient frontier, according to her personal risk attitude. If she is risk seeker, she will choose the point of the efficient frontier with the best ENPV, even if it has the highest standard deviation; if she is risk neutral, she will probably choose again the point with the highest ENPV ("a person has risk neutral preferences when he or she is indifferent between certain amounts and lotteries with the same expected payoff" – Boardman et al, 2018); whereas if she is risk adverse, she will choose the solution with the lower standard deviation ("a person is risk adverse if he or she prefers a certain amount instead of the lottery" – Boardman et al, 2018).

The last step of this study has been the sensitivity analysis, in the attempt to verify the effects of the variations of two critical parameters used in the PA: the social discount rate (SDR) and the weights assigned to the various climate scenarios. The discount rate is a highly debated parameter of the economic analyses in the climate change framework. Climate change could create dramatic negative impacts on the future generations, reducing their welfare and compromising some essential natural resources. However, high discount rates assign a considerably stronger weight to the present values, reducing the relative importance of the costs and benefits occurring in the late future and diminishing the relevance of the future generations' welfare. There is a strong debate about this issue, especially in the climate change scientific community. As a result of these debates, lower and declining discount rates have been vastly used in the last years. France and UK use declining discount rate of 3.5% for the first 30 years, then decreasing to 3.0% from the 31st to the 75th and 2.5% from the 76th to the 100th year, whereas the African countries still use very high SDR, i.e. 12% or 13%.

The sensitivity analysis gave these two essential results:

i) With the highest SDR the economic returns are all negative and the elevations perform almost identically in the various scenarios; this happens because the strong DR significantly reduces the benefits occurring in the long-run and the tea plantation investment has positive benefits later in the future. Thus, the benefits of the adaptation measures and the impacts of climate change are here totally ignored.

ii) The declining SDR reduces the overall benefits of the project, however, the results are still positive and the mix of the investments in the portfolios again returns better investment solutions. Here the portfolio with the lowest standard deviation is the N.72, quite close to the one identified with the 0% SDR analysis (N.80).

The other sensitivity analysis regarded the test of different weights assigned to the climate change scenarios. The distributions considered were: i) a "light climate change future", with the following probability distribution – 40% to the no climate change scenario; 40% to the 2.6 scenario; 10% to the 4.5 scenario; 5% to the 6 scenario; 5% to the 8.5 scenario; ii) a "heavy climate change future", with the following probability distribution – 5% to the no climate change scenario; 5% to the 2.6 scenario; 10% to the 4.5 scenario; 40% to the 6 scenario; 40% to the 8.5 scenario. The first assumption has been tested with both SDR approaches (declining and 0%) and gave an efficient frontier where the portfolios with the lowest standard deviation were the N.53 and the N.49, but where the penultimate elevation is the best solution, even considering the rate between ENPV and standard deviation. The heavy assumption simply suggested to invest in the highest elevation possible, due to the severe climate changes expected.

Lastly, the conclusive step of the analysis has been the identification of the possible extensions of the work, looking at the most important assumptions which have been done during the PA in the attempt to simplify the analysis. These further steps range from a better understanding of the biological relations among tea and climate changes, a more precise description of the tea market, and a better characterization of the social and environmental effects of the tea investment.

Interesting scientific insights can emerge from this dissertation. They are concrete results that could be significant for the scientific debate around the climate change adaptation issues. These recommendations could also be helpful for the decision-makers who want to develop a project that embodies climate change risk. Apart from the above-mentioned results, there are other general considerations emerging from this research:

- **Climate change, a critical challenge to sustainable development**. Rwanda society is still based on agriculture. The 35% of GDP comes from agriculture, and 90% of the total employment is dedicated to this activity. In the past decade the GDP grew at an average rate of 7.8%, with a peak of 11.8% in 2008. However, irrigation is almost absent and the socio-economic development highly depends on the amount of precipitations. Hereby, the droughts of 2015 and 2016 slowed the economy pace which reached 3.3% and 2.4% growth rates. These slower paces and the increase of the population brought an escalation of the undernourished people too. Climate change is therefore a crucial problem for the sustainable development of the countries, especially in the case of poor, highly exposed nations, highly reliant on the natural resources. Due to the impossibility to avoid climate change now and in the next decades, conceiving a future without the planning of good adaptation policies is therefore risky and it could be even more dangerous for the future generations. In our analysis, the economic losses connected to climate change are significant. In the RCP 8.5 scenario, just the four highest bands have a positive NPV. Considering all the scenarios, the economic losses span from a minimum of 13 billion RWF (approximately 15 million $) to a maximum of 83 billion RWF (97 million $).
- **Climate change affects the performances of the investments**. In the attempt to reduce the exposure of people and socio/economic assets to climate change impacts, the forecasts about the climate change scenarios must be included in the economic analysis and in the design phase of every climate sensitive development project. This action should be a crucial part of every adaptation strategy. Especially in the case of long-term investments (both public and private) the effect of climate change could be decisive, eventually compromising the effectiveness of

the interventions. In this analysis, we have concretely estimated the performance of the tea investment in the different climate scenarios and we have seen that climate change could modify the recommended choice.

- **Facing uncertainty.** The uncertainty about the effects of climate change is still significant. Even though there have been thousands of scientific analyses, five IPCC reports and various climate models have been produced, the uncertainties about the future average temperature and the related weather dynamics still remain. The knowledge of the natural processes and the relations among the human greenhouse gas emissions and the expected increase of the temperature have been accurately discussed. However, the uncertainty regarding the identification of the impacts of climate change and the benefits of adaptation policies persists. Furthermore, a part of this uncertainty, e.g. the one connected to the emission patterns of the countries, will probably remain even in next decades. In the Rwanda case study, the uncertainty about the pattern of the precipitations is high, and the increase of the average temperature could range from +0.6°C to +4°C.

  However, even though the uncertainty is deep and it can significantly hamper the decision-making processes, there are strategies to take informed adaptation policies, robust to a high variety of possible climatic futures. Although the limitations explored in this research, in our case study the portfolio analysis truly helps in identifying good investment solutions, including in the analysis the possible uncertain effects of climate change. Obviously, some part of the analysis could be refined, but the indications coming from the analysis are coherent with the insights coming from the literature and they are a step forward compared to a simple Cost-Benefit Analysis. Therefore, climate change uncertainty is a demanding challenge, but there are solutions to face these obstacles and to take good decisions.
- **Mitigation urgency and adaptation limits.** The portfolio analysis made in this dissertation indirectly highlights the urgency of mitigation measures. Climate change damages the tea investments and pushes the farmers to more high and distant locations. The farmers will try to face the negative impacts of the temperature increase and they will probably abandon the lowest elevations. However, there are physical limits to the adaptation measures. A geographical analysis shows that the farmers cannot go to elevations higher than the ones considered in our study, because of the lack of suitable areas in that part of the country. In any case, in general, the more the farmer goes at higher altitude bands, the less space available for the tea plantation she/he finds. This is an evident adaptation limit (Adger et al, 2009; IPCC, 2014). Therefore, mitigation measures are absolutely necessary, with the goal to reduce the climate change effect, diminishing also the magnitude of the adaptation policies needed. However, as this dissertation analysed in the first chapter, mitigation policies are a global issue, relying on the political efforts of the industrialised and fast-growing emerging countries which have the larger potential for the reduction of greenhouse gas emissions; adaptation policies are instead a local challenge, especially concerning the local communities of the developing countries. This is why adaptation policies cannot be sufficient for the reduction of the climate change impacts in the most vulnerable nations, and a significant commitment of the major GHG emitters is thus required, through concrete and significant mitigation actions.
- **New decision criteria.** Climate change considerably increases the uncertainty about the future and the policies should be tested in a plurality of environmental conditions. Therefore, new decision criteria should be involved in the evaluation of the best interventions. The economic return of the investment is no longer sufficient and other decision criteria should be added. The variance of the economic performance alongside the various climate

scenarios could be another important indication about the efficacy of the policy. However, the literature review showed that different decision criteria and decision rules are available. Measures could be evaluated in terms of their robustness to the various possible expected effects of climate change or in terms of their flexibility in adapting to the occurrence of different scenarios. According to these new decision criteria there might be no longer a unique optimal measure, perfectly tailored on every climate future. The new decision criteria will probably suggest different strategies with their key strengths and weaknesses according to the different climate scenarios, and they will increase the measures available, identifying new possible allocations for the public resources.

- **New tools, new opportunities for the communication of climate risks.** This dissertation presented the need and the practice of new decision support tools that are able to facilitate the choices among different adaptation projects, identifying the risks connected to each strategy and the potential corrections that could increase the performance of the policy. The portfolio analysis has been here tested as a powerful instrument in dealing with uncertainty and climate change problems. This tool identified different investment solutions compared to the results of the conventional cost-benefit analysis, finding more efficient allocations of scarce resources with a better trade-off among economic return and risk. The efficient frontier is an effective and straightforward solution for the communication of the results to the decision-maker, easily highlighting the essential information needed for the decision. The efficient frontier could be useful in various contexts in the attempt to show the available options and the risk connected to these solutions. Both technical and non-technical actors could be informed through this representation of the economic results of the analysis, effectively communicating the climate change effects on the policy outcomes.

  Similarly, even the other decision support tools used in the climate change framework developed interesting instruments for the communication of the results of the technical assessment and of the climate change risks. For example, the Adaptation Pathways approach develops effective maps which present the available policy patterns, identifying in advance the climate conditions which compromise the efficacy of a specific measure, requiring the choice of new solutions. In the case study of the water management in The Netherlands, the adaptation pathway is represented as a map of a metro stations network, easily showing the available adaptations solutions and the connections between the policies. The choice of a policy implies the choice of a specific pathway, that it can be hit by specific climate change risks.

  Therefore, even though the climate change uncertainty could hamper the decision processes, there are tools and methodologies that can help the analysts in communicating the climate risks and the strengths and weaknesses of the political solutions available. This is an important point due to the need of disseminating climate change information and adaptation policies available in different settings, even in local communities that need straightforward messages, easy to understand.

- **Considering the welfare of the future generations: A precautionary approach.** The analysis showed how the benefits of the adaptation policies might occur late in the future, because of the progressive increase of the climate change impacts during the lifetime of the investments. In the Rwandan case study, the tea investments will be settled at the lower altitudes if just the short-term economic performances are considered. However, as much the life of the investment made is longer, the higher could be the impacts of climate change on that project.

In Rwanda, the increase of the average temperature will be slight in the first years but it will accelerate in the future, and it might reach a +4°C increase in 2070. Tea is a perennial crop and the economic assessment of this investment should even consider the long-term performances, and the positive or negative effects on the future generations. Moreover, the future generations will be the most affected by climate changes, with a socio-economic condition that might be worse compared to the one of the current populations. The uncertainty about the welfare of the future generations is affected by some debated issues, such as: i) the uneven political results achieved in the mitigation policies in the last years; a fact that rises some doubts about the effective implementation of the commitments contained in the Paris Agreement; ii) the lack of knowledge about some natural processes which can hide the possibility of surpassing some dangerous trigger points, leading to catastrophic events. These are two significant motivations that explain why the socio-economic condition of the future generations might be compromised by climate change and a precautionary approach could be recommended in the decision processes for long-term investments.

A key parameter for the inclusion of the welfare of the future generations in the economic analysis is the Social Discount Rate. The sensitivity analysis presents the effects of the choice of different SDRs on the investment solutions to be recommended. SDR assigns a weight to the time preferences to consumption of the communities involved in the project. With a high discount rate, we assume that decisions are taken with a strong preference for present consumption, thus reducing the weight of the future gains of the project. However, as previously stated, the impacts of climate change will probably grow in the future, compromising the benefits that an investment brought in the first years. Therefore, if we consider a very high discount rate (such as the one suggested by the developing countries investment banks, i.e. 12%/13%), the weight of the future economic performances of the project is reduced and the benefits of the adaptation measures (i.e. selecting higher elevations) are thus narrower. Thus, the application of a unique, high, discount rate could be a short-sighted decision, leading to choices that underestimate the welfare of the future generations. Following a precautionary approach, more than just a single SDR should be applied in the economic evaluation of the investment, using even low values that can be more effective for the inclusion of the long-term climate change impacts on the outcomes of the decision.

- **The complexity of the adaptation policies**. Even though the portfolio analysis is an important and effective tool in finding useful elements for better informed decisions, this tool still relies on monetary metrics (like the cost-benefit analysis) and on probabilities. This is why this instrument is not sufficient for the identification of the recommended measure for a specific community. Good policy processes should be designed, in the attempt to iteratively monitor and evaluate the performances of the measure, progressively updating the climate change scientific knowledge. Furthermore, a stakeholder engagement is essential. The literature review showed the importance of recognizing the values and the priorities of the local communities for the effectiveness of the adaptation measures. In our case study, planting tea at the highest elevation just focusing on the good economic performances might be again a short-sighted decision, because it does not consider the other needs of the farmers and their families. The locations where to plant tea might have a symbolic value or the farmers might have reasons to prefer closer agricultural fields instead of distant ones.

  Lastly, the adaptation decision should be included in a more comprehensive adaptation strategy, which should be accurately mainstreamed inside the general development goals of the administration. Adaptation is indeed often considered not as a stand-alone policy but as a new perspective that has to be included in the current policies of the administration. Furthermore, adaptation is more effective when an integration between the diverse parts of a public administration is performed, promoting a collaboration in the design of the policies. This integration should be horizontal, creating connections among the different sectors and technical competencies (agriculture, tourism, transports, energy, …), and vertical, improving the coherency between the action of the national, regional and local administrative levels.

However, even though the economic analysis of the adaptation measures is just a part of a wider adaptation process, the practice of the new decision support tools presented in this dissertation should be an important pillar for the design of these climate change policies. This research work has presented the efficacy of these instruments and processes in the inclusion of climate risk in the assessment of the most effective policy. The results suggest that the public governments should consider these new tools in their decision-making processes, updating their common methodologies for the identification of the most suitable measures.

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