ECONADAPT

The Economics of Adaptation

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An illustration of the application of the methods to cases, and recommendations on the implications for policy formulation, monitoring and revision over time

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Deliverable number	D4.3
Work Package Number	WP4
Submission date	September 30th, 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	An illustration of the application of the methods to cases, and recommendations on the implications for policy formulation, monitoring and revision over time
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Work Package Number	WP4
Deliverable number	D4.3
Filename:	ECONADAPT_Deliverable_D4.3.docx
Document history:	Final version 1
Type of Activity	RTD
Nature	R = Report
Dissemination / distribution level	PU = Public
Citation:	ECONADAPT Deliverable 4.3 Report. Khabarov N, Hunt A, Ermolieva T, Hochrainer S, Kaprová K, Melichar J, Mochizuki J, Sainz de Murieta E, Pardy J, Parrado R, Scussolini P, Szewczyk W, WellmanJ (2016).
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The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

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Executive Summary

This document provides a rather condensed reflection on the broad analysis carried out in the case studies work packages of the ECONADAPT project (WP5-WP9). The specific aim of this reflection is to present a retrospective overview of the methods that have been employed in the case studies to include and treat existing uncertainties pertinent to climate change adaptation assessments. The main focus of this review is the representation of relevant uncertainties as this is the basis and a prerequisite for a further application of appropriate methods. Special attention in this overview of the case studies is paid to the epistemic uncertainty as it presents a factor limiting the analysis in many cases. We also paid attention to the substantial improvements of the models or previously applied approaches, and where these had been made, we have provided respective highlights. We have also picked and highlighted some implications and recommendations informed by those case studies.

In summary, the findings from the case studies and recommendations supported by those can be summarized in the following bullet points:

1) Uncertainties in climate change and socio-economic projections **do play an important role** in the analysis of adaptations and cannot be ignored; however there are cases where there is an urgent need for change due to already observed climatic changes.

2) The specific type of uncertainty – epistemic – and its influence on the assessment results drives the need to **close knowledge gaps**. Therefore, an effort is required to create and gather new knowledge.

3) There is a strong **need for monitoring and data collection**, because data limitations play a critical role in adaptation assessments as demonstrated by the majority of the project's case studies. The data are needed to support research and creation of knowledge.

4) At the science – policy interface, there is a **need to communicate** the findings of analyses that include a wide representation of uncertainties and therefore provide more sophisticated information than assessments carried out before. There is a need in common language and common understanding of modelled/estimated processes.

5) There is a need to implement and carry out a **real-life testing of new approaches**. This is where the practice could prove and also correct and improve the methodology.

6) Continuation of the research that was pushed forward thanks to the ECONADAPT project and deepening of the understanding of uncertainties pertinent to the models and translated into assessments is apparently necessary. This can be achieved in an iterative way where the next step would be **revisiting the model's parametrizations and creating multidimensional clouds of plausible estimates** for a deeper exploration.

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1 Introduction

In the ECONADAPT Work Package 4 we have first explored uncertainties relevant to the assessment of adaptation projects in the context of climate change. Among the conclusions we came up at this stage was the inference that these uncertainties have to be considered within a **scope wider** than only uncertainty in climate projections. Due to the mid and long-term planning horizon of the adaptation projects, socio-economic uncertainties have to be included into the analysis. The illustration of existing uncertainties in projections and their translation to impacts along with other concepts are documented in the deliverable D4.1. This research was followed by the analysis of the methodologies available for handling this wide range of uncertainties where some of those uncertainties are expected to be reduced with time. These considerations have led to the need for keeping flexibilities for future if permitted by a particular adaptation problem. These **future flexibilities** shall be taken into account in a project assessment. The analysis of extreme events impacts and respective protective actions requires the application of **advanced risk measures**. The deliverable D4.2 is devoted to discussion and illustration of these aspects. The findings presented in this document are a continuation of the work previously carried out within the ECONADAPT WP4.

This report D4.3 expands beyond a single particular work package as it highlights the links established in the course of the project's work between WP4 and the case study work packages WP5-9. These links have materialized in the inclusion to the case studies climate projections uncertainties, projected socio-economic trends uncertainty, representation and unveiling of epistemic uncertainties (knowledge gaps) and application where possible of upgraded models and tools. In the next chapter we provide a condensed overview of these aspects in the ECONADAPT's case studies.

2 Methods for uncertainty modeling as adopted by ECONADAPT case-studies and respective implications/recommendations

2.1 Case study: Disaster Risk Management (WP5)

The aim of the WP5 case study is to provide further analytical bases for climate risk analysis, within an iterative risk management framework. In particular, this study focuses on the domain of public finance and fiscal planning, and illustrates how climate risk concerns could be 'mainstreamed' into decision-making processes. Through the pan-European assessment of the fiscal consequences of extreme weather events in the EU, this work (1) **quantifies extreme event risks** (in terms of potential capital stock losses) across an illustrative range of climate scenarios (with a time horizon of 2030 in the short-term and 2050 in the long-term); (2) **identifies the fiscal repercussions in terms of public debt trajectories** and, (3) **identifies options for better stochastic planning** to reduce and finance fiscal risks.

Below, based on the content of the WP5 deliverables and in close interaction with responsible project partners, we provide a condensed overview specifically on the application of methods selected and developed in the course of the ECONADAPT project and employed in the WP5 case study. From the methodological and modeling standpoint we highlight recommendations on the policy implications.

The WP5 case study builds on the CATSIM framework to model the fiscal and economic risk of extreme events. The CATSIM framework assists policymakers to quantify public sector risk of extreme events and develop pre- and post- disaster risk management strategies. Public and private sector losses due to flood events are estimated and compared to the financial resources available, such as reserve fund, budget diversion and international and domestic borrowing.

2.1.1 Uncertainty representation and modeling methods

Climate scenario - only the SRES A1B scenario is looked at and here the mean ensemble runs of 12 climate simulations derived from a combination of 4 GCMs and 7 RCMs are used [1], [2] - the **"full" climate model uncertainty could not been explicitly dealt with**.

Based on the results from the flood model (LISFLOOD, JRC) for the ECONADAPT D5.2 Austrian case the interdependency of risk (in terms of loss distribution) on the country level was implemented for the first time [3], which is a **major upgrade** of the current risk assessment approaches available so far (e.g. LISFLOOD) and the model is fully in line with the major findings of WP4 on interdependent risks.

Along with the recommendations presented in D4.2 on the necessity of communicating risk in terms of distributional characteristics which are much more informative than just average annual loss values (AAL) commonly used as state-of-the-art, D5.2 makes a **significant step forward** and presents for a range of EU countries in addition to AAL also the scale of projected damage estimates for rare events [4] (e.g. 100 year flood loss event) up to 2050 induced by climate and exposure changes (page 20 of D5.2). This is enables a risk based perspective on the financial vulnerabilities of disaster risk on the country scale. Consequently, risk based management strategies can now be looked at in much more detail.

The CATSIM model employed in the case study inherently includes stochastic modeling of fiscal consequences, originally without explicit treatment of extremes caused by climate change. In the course of the work supported by ECONADAPT, the model received a **major upgrade** in the form of inclusion of climate related risks and their integration into the macro-economic assessment framework of CATSIM (full documentation is presented in D5.2).

Another significant upgrade of the CATSIM assessment framework carried out in the course of the ECONADAPT project is the **explicit inclusion of socio-economic uncertainty** in the form of extending the framework with shared socio-economic pathways (SSPs) that are "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale ([5], p.387)," which allow for the standardization of assumptions and storylines used in integrated assessments.

2.1.2 Implications and recommendations

The estimates of the type "annual DRR investment of 100 million will reduce the probability of disaster fund depletion to 5% (2015-2030) and 3% (2031-2050)" (page 25 of D5.2) as obtained for Austria, provide a rough indication to policy makers on adaptation possibilities and outcomes. However, this type of probabilistic estimates might need to be communicated and refined in an iterative way, in a close dialogue between science, policy, and society.

Despite a series of methodological advances and model improvements presented in D5.2, there still remain challenges strongly demanding further research. Among these the implementation of wider CC uncertainty by accommodating a range of RCMs outputs, inclusion additional SSP scenarios for representation of the population dynamics (currently only SSP2 in EU/Austrian case study), inclusion of structural protection measures being part of national flood protection plans into the modeling. These improvements needed to substantially refine the model, now after experience acquired in ECONADAPT, have a solid basis for implementation and could be logically carried out in a continuation of the ECONADAPT project provided a respective funding.

2.2 Case study: Economic Project Appraisal – Bilbao (WP6)

The Bilbao case study is focused on an investment in adaptation measures to reduce the risk of flooding of the district of Zorrotzaurre in Bilbao. The adaptation measure consists in the opening of a channel that will convert the Zorrotzaurre area from a peninsula to an island, which will alter the hydrodynamics of the river lowering the water depth in the event of flood.

2.2.1 Uncertainty representation and modeling methods

Uncertainties in future emissions of greenhouse gases have been addressed by employing IPCC scenarios from a set of the Representative Concentration Pathways (RCPs). The **RCP4.5 and 8.5** employed for the case study represent middle and high GHG concentrations and, respectively, middle and high severity of climate change. Before, the Basque Water Agency has been using data from climate models that adopt the SRES climate change scenarios of the IPCC (IPCC, 2000). In this case study the aim was to show the implementation of the **more recent** RCP scenarios.

The climatic data employed in this case-study span the 1971-2000 and 2071-2100 time periods, representing respectively the baseline and projected for the end-of-the-century climate change, for both RCP4.5 and RCP8.5. These projections were provided by an ensemble of eleven EURO-CORDEX RCMs. The set of employed 11 runs sampled five Global Climate Models and four RCMs. In line with the WP4's recommendations, the **uncertainty in future emissions** and respective climate response **is taken into account**. However, this representation is limited as employed climate projections are for mean monthly values and do not explicitly consider changes in day-to-day or year-to-year variability or extreme events (such as heavy rainfall, drought or heatwaves). This limitation reflects the uncertainty due to the **knowledge gap** in the long term modeling of climate. A similar challenge is presented by the task of hydrologic modeling of peak discharges under climate change, where the model was calibrated with data of historic events, with the aim of producing a set of correction parameters for potential events. For future hydrologic projections, it has been assumed that the adjusted parameters of the hydrologic model do not change meaning that the physical processes of the watershed (such as change in vegetation or soils) have been considered to remain constant. This assumption creates an uncertainty due to the **knowledge gap** in the long term hydrological modeling. Both knowledge gaps in climate and hydrological modeling highlighted in D6.3 case study Bilbao fit the classification of uncertainty presented in D4.1.

The Bilbao case study includes into the analysis a wide range of flood damage types - three types of direct property damage and eight types of indirect damage. All these **estimates include uncertainty** represented in the study by ranges (low and high value) specifically for each of the three classes of floods severity (10-, 100-, and 500-year return periods). However, these estimates are based on historical data and it has not been possible to update the damage results to incorporate the **future effects of climate change** for the selected RCPs.

2.2.2 Implications and recommendations

The uncertainty is accumulating through the modeling chain from climate and socio-economic scenarios to hydrological and flood damage modeling with and without adaptation. This leads ultimately to a high uncertainty of estimates that are greatly dependent on assumptions filling the current knowledge gaps. In the Bilbao case study one of such gaps can be potentially attacked by carrying out a sound area-specific hydrological modeling under projected climate change including implied uncertainties assessment. That was unfortunately impossible due to an excessive effort required, but is important to reflect projected climate change impacts on river floods in addition to the projected sea-level rise. This consideration calls for future revision and improvement of inventory of tools serving the assessment of adaptation especially for such developed case studies as the ECONADAPT’s Bilbao/ Zorrotzaurre that is well equipped with **advanced modeling methods** such as real options and advanced quantile-based risk measurement approaches.

2.3 Case study: Vltava – Costs and Benefits of Adaptation (WP6)

2.3.1 Uncertainty representation and modeling methods

Climate: For the simulation of future hydrological regime in the Vltava river basin, daily time series of precipitation and temperature, until year 2100, have been acquired from **14 simulation sets** from the WCRP CORDEX database, run with greenhouse forcing boundary conditions based on the IPCC's Representative Concentration Pathway (RCP) scenarios **RCP4.5 and RCP8.5**. That way, the future emissions of greenhouse gases, a driving factor of climate change, and their uncertainty have been addressed by employing these RCPs that represent middle and high GHG concentrations and, respectively, projected middle and high severity of climate change. In line with the WP4's recommendations, the **uncertainty in future emissions** and **is taken into account**. The employed set of models/RCP combinations is considered by the Danish Meteorological Institute to approximate the variability in the potential evolution of climate. Even though this model selection does not cover the entire possible range of emission scenarios, it is, however, considered to include a large part of this variability. In line with the findings of D4.1, the **climate uncertainty is well represented** in the Vltava case study.

Hydrology: In the Vltava case study, the output of the hydrological modelling illustrates how the uncertainties in climate conditions modelled by respective RCM result in **large differences** among the predicted maximum runoffs which increase with the horizon of the prediction. The changes according to particular simulations are between -60% to +350% (maximum runoff, in factor units) of the mean values for the sets of models and respective RCP scenarios. These estimates were produced by an organization external to ECONADAPT - T. G. Masaryk Water Management Institute (TGM WRI) and this analysis (as highlighted in D6.3) was carried out under the assumption that the derived relationship between (extreme) precipitation and (extreme) runoff holds also under changed climate conditions. The degree to which this assumption holds is not known yet and therefore represents a current **knowledge gap** fitting well the uncertainty classification suggested in WP4's D4.1.

Assets at risk: In the Vltava case study the authors have also assessed the **uncertainty** associated with the accuracy and completeness of the **spatial data on assets at risk** – the number of buildings exposed to floods of different return periods. For the purposes of assessment of damage to infrastructure only the damages related to roads were included. The damage to agriculture is represented by crop losses in the fields.

Damage functions: There exists a **knowledge gap** - the uncertainty related to the shape of the **depth-damage function**. A sensitivity analysis of the damage estimates to the depth-damage function employed in the case study would help revealing the impact uncertainty in a more comprehensive way; however, it was **not inspected** within this case study due to a number of reasons (excessive effort needed being the decisive one). Nevertheless, the **uncertainty** in the employed linear damage function **is reflected** as the min, average, and max values of damage for a certain water depth.

The uncertainty of damages to roads is included **as a range** (min, average, and max per m2). Similarly, the uncertainty in damage to agriculture is expressed as **min and max losses** equal to cost of planting crops per hectare (for five categories of basic crops).

The authors have also highlighted the contribution of **uncertainties in crop damage function** to the aggregated damage estimate, stating that these "would have practically no effect on the results". The authors employ the concept of shared socio-economic pathways (SSPs) and emphasize that within the time horizon until year 2100, there is a large **uncertainty in technological, demographic, and socio-economic trends** (population growth, migration, density, economic growth), which all affect the amount, state and value of assets under risk. As authors highlight, “these general uncertainties are very complex and are not in most cases considered in the cost-benefit analyses of flood protection”.

Costs: The aim of the flood protection project in Prague (started in 1997) was to resist a 100-year flood, defined using the runoff of the last catastrophic flood in Prague in year 1890. In 2002, Prague experienced a catastrophic flood of even larger scale and subsequently, the flood protection project of Prague has been redesigned to manage the level of flood in year 2002, plus a freeboard of 30 cm. So, as the estimation of an **uncertain level** of a 100-year flood, two largest floods observed in 100 years were used and a **security reserve** of +30 cm to that maximum flood level was applied. Operating costs estimation is characterized currently by a **large uncertainty** as explicitly stated in D6.3. (According to the **sensitivity analysis** carried out in the case study, operating costs are less important than climate change projections and discount rate, which are the major contributors to the overall uncertainty in the ENPV estimation.) On top of investment and operating costs, there are also more certain “one-off” costs associated with the individual flood events (for those comparable to or larger than the 50-year return period). The floods in this case study are explicitly stratified into groups of different return frequency (frequent – smaller, rarer – larger). This representation of flood extent and respective damage is **in line with the findings of WP4** and goes beyond the state-of-the-art approach where often only an annual average loss is estimated.

This comprehensive analysis, despite existing possibilities to improve, **contains the most critical elements on uncertainty** representation emphasized in D4.2. The most critical factors found in the case study are discount rate and climate scenario assumption.

2.3.2 Implications and recommendations

Due to a wide **range of technical, conceptual, and data availability challenges** posed by the case study, the selected CBA methodology as augmented by an **extensive inclusion of uncertainty** in development of estimates of multiple crucial input factors, seems to be appropriate **and in line with the findings of WP4**.

The issue of evaluating investment-intensive protection measures as it relates to extreme weather events was and still remains challenging. Among factors that make it exceedingly complicated are trade-offs between risk aversion and cost minimization, quantification problems especially vivid in case of pricing the loss of life, necessity to plan for longer time horizons where uncertainty rapidly grows with the length of the planning horizon. In this context, the necessity to take into account climate change uncertainty and induced socio-economic uncertainties creates additional challenges shifting the problem’s complexity beyond tractability. However, as long-term decisions have to be made in many cases despite many unresolved/unquantified uncertainties, such pragmatic methods as cost and benefit analyses for a rich set of assumptions provide valuable input for an ultimate assessment. The decision making process is similar to a science-policy interaction where scientifically sound, preferably quantitative estimates provide a basis for decision making. An example from flood management practice can be taken from Austria, where quantitative cost and avoided damage estimates were combined with qualitative estimates of intangible values by a group of relevant experts [6]. These considerations call for a close interaction between public, science, and policymakers.

2.4 Case study: Policy Impact Assessment (WP7)

This case study is designed to assess different financial and structural CAP policies in terms of their individual and combined costs and benefits for producers, consumers and the environment, both within and outside the European Union, in light of the uncertainties posed by climate change. For the analysis the authors apply GLOBIOM model, which is a global recursive-dynamic, partial-equilibrium model running at the level of major countries and world regions. The model integrates the agricultural, bioenergy, and forestry sectors allowing for a policy analysis on global and regional issues concerning land use competition and land use transformations driven by climate change, increasing demands for food, feed, water, and biofuels.

2.4.1 Uncertainty representation and modeling methods

In the course of the ECONADAPT project, the authors of the case study have carried out a **major upgrade** of the agro-economic model GLOBIOM from deterministic to **stochastic version**. For the purposes of illustration of the implemented stochastic approach, the authors compare model results with its deterministic counterpart. The deterministic model uses a **scenario-by-scenario analysis** of potential climatic shocks to derive **scenario-dependent** policy advice regarding adaptation measures. The new stochastic version employs **uncertainty in yields** to simultaneously account for different policies and derive measures that are optimal (**robust**) with respect to all the scenarios. The performed model upgrade is **addressing methodological issues** related to deterministic scenario-oriented approaches as discussed in the WP4's deliverables D4.1/4.2.

Both the deterministic and the stochastic model run for a time horizon of 40 years (from 2010 to 2050) with time steps of 10 years. In the case study stochastic yields are represented by a finite **set of yield scenarios** from 1960 to 2012 informed by FAO reported statistics. This approach serves the purpose of illustration of methodology and is expandable to using yield scenarios from bio-physical crop models reflecting future climate change impacts. A wide range of climate scenarios (**RCP 2.6, 4.5, 6.0, 8.5**) and an **ensemble of GCMs** (HadGEM2-ES, IPSL-CM5A-LR, GFDL-ESM2M, MIROC-ESM-CHEM, and NorESM-1 M) informing respective yield estimates (provided by a bio-physical crop model EPIC) have been incorporated into the GLOBIOM model in the course of the ECONADAPT project [7]. The modeling framework based on the GLOBIOM model is therefore **addressing uncertainties in climate change** projections as discussed and recommended by WP4's in D4.1/4.2. The **socio-economic uncertainty** is reflected through implementation of the SSP scenarios (currently SSP2, yet expandable).

In the case study's CAP context, the authors model reversible "low regret" adaptation measures that are **short term** and address current climate variability, such as different direct payment measures, and autonomous adaptation of switching to less impacted and more profitable crops. The structural, **long term** measures relate to the construction of irrigation schemes or storage facilities. Thus, the authors **reflect on the findings of WP4** advocating for classification of adaptation measures as short and long term (operational and strategic decisions).

The need for **integrated assessments as highlighted in WP4**'s D4.2 is addressed by the GLOBIOM modeling framework as it covers the complexities of the economic **interaction between sectors**, countries and continents. The modelled policy measures influence production and demand in other regions through trade and therefore create feedbacks. This dimension is important to take into account for a policy appraisal as it might impact the effectiveness of concrete adaptation options.

Similar to other applications in ECONADAPT, this case study on CAP analysis, points out to several existing sources of **epistemic uncertainties** (knowledge gaps) as discussed in WP4's D4.1 e.g. uncertainties and missing values in spatially-detailed land cover and in particular grassland data, uncertainties in yield scenarios from bio-physical crop models, where local information on current management practices and cultivars are poorly known, environmental parameters like water use, fertilizer use, etc. These parameters are relevant for bio-physical modeling that is one level below the economic assessment in the applied framework and therefore has not been explored beyond the basic uncertainty accumulation analysis provided in WP4's D4.1.

2.4.2 Implications and recommendations

The results of the case study show that the **robust recommendations** of the **stochastic model**, compared with a deterministic model, can **save a considerable amount** of maladaptation and sunk costs. Using a deterministic model, an extreme shock may lead to a large uptake in cropland, which may imply large irreversible costs.

The modeling results, as pointed out by the case study authors, highlight a strong **synergy** between financial and structural measures. The introduction of both direct payments and storage facilities decrease water demand and save investments into irrigation expansion, implying a **substitution effect** between policy measures.

Two main recommendations stand out in analyzing the effects of optimal combination of CAP policies in light of climate change: (1) It is essential to assess policy measures using a **variety of possible outcomes** as a result of climate change in order to overcome irreversible costs of **maladaptation**. (2) Agricultural policies are interdependent and crop and location specific. The optimal combination of policies should not only maximize benefits to producers and consumers, but also optimize **environmental parameters** like water use, fertilizer use, land cover change, and greenhouse gas emissions.

2.5 Case study: Modelling Autonomous Adaptation with the CAGE-GEME3 Model (WP8)

2.5.1 Uncertainty representation and modeling methods

This work applies CAGE-GEME3 model for quantitative analysis of autonomous adaptation for a set of **four climate impact areas**: agriculture, sea level rise (SLR), energy and labor productivity. The effects related to autonomous adaptation are evaluated with this computable general equilibrium (CGE) model that captures both the first order effects of a shock (direct effect) and the second and higher order effects (indirect effects). This modeling approach is **in line** with the findings of WP4 on **integrated modeling** needs necessitated by impacts spreading throughout the systems. This particular application is focused on exploration of autonomous adaptation mechanisms in the model – the labor mobility across sectors and the degree of substitution of international trade.

The CGE analysis of climate impacts follows a static comparative approach, estimating the counterfactual of future climate change (simulated in the 2080s) occurring under the current socioeconomic conditions. Therefore, the climate shock-induced changes would occur in the economy as of today. In contrast, a 'dynamic' approach would account for changes that the economy and society will undergo until the end of the century, and apply the climate shocks to the version of economy as in 2100. Climate impacts might become larger as they would affect a bigger economy. Development of such representation of future economy, however, would **require numerous assumptions** about factors shaping the societal and economic development. The assumptions would be required to envisage impact of demography, technology (existing and new), degree of adaptation to climate change (both planned and autonomous), societal preferences and more. All these assumptions would **bear a (high) degree of uncertainty** and would further complicate the interpretation of the final results. The authors of the study intentionally apply a simplified model setting as they are interested in illustration of the role of labor mobility and international trade as important factors in autonomous adaptation. The authors admit the existing uncertainties and point to the high impact of assumptions on the estimates, which is a model-contextualized conclusion that is **in line** with the more general findings of WP4. The existing modeling framework allows for the inclusion of demographic, technological, and societal trends and respective uncertainties, **meeting recommendations** of WP4.

Three series of simulations are performed in order to analyze the degree and value of autonomous adaptation: benchmark case (current adaptive capacity of the markets), the semi-rigid case (lower flexibility of trade), the rigid scenario (restricting both trade and the degree of substitutability between capital and labor). This analysis is an important step helping to **include the uncertainty** associated with the markets' adaptive capacity into the model.

Four climate impact areas considered in the analysis – agricultural crops production, sea level rise, labor productivity and energy demand – cannot be directly estimated by the CAGE-GEME3 model and therefore the case-study authors **integrate** ClimateCost estimates, DIVA and POLES model outputs to feed the CGE-based assessment. The integration challenges and required effort to produce climate scenario-specific outputs for a range of external models explain why only one of the climate scenarios (A1B IPCC SRES) has been currently used in the study. This, however, is a rather technical difficulty and the **set of scenarios can be potentially expanded** to better reflect uncertainty in climate change projections.

2.5.2 Implications and recommendations

The proposed modelling framework allows the exploration of how climate impacts propagate throughout economy, affecting the overall economic activity (GDP) and consumer's welfare. In this respect, the preliminary results should be interpreted as a way to identify trends and mechanisms rather than a precise quantitative assessment. The case study authors clearly indicate the limited applicability of estimates obtained with the current version of the CAGE-GEME3 model. The existing overall uncertainty pertinent to the problem under consideration points to the need for future extension and refinement of the modelling carried out so far.

2.6 Case study: Planned Adaptation in Agriculture and to SLR (WP8)

2.6.1 Uncertainty representation and modeling methods

2.6.1.1 The implications of irrigation as a planned adaptation measure on an economy wide context

One of the important components of the economic assessment of irrigation is the water price and as the case-study authors emphasize, the information on market price of water used for irrigation is largely lacking. It is imposed that water contributes the 10% of the value of irrigable land in the USA. Values for the other regions are adjusted, using the ratio of irrigated yield to rainfed yield as a proxy of land rents ratio. Costs of irrigation services must be also considered. The authors emphasize that these costs vary quite a lot depending on many factors, e.g. irrigation system, water prices, operation and maintenance (O&M) costs, wages etc. Following crop budget data for the US, it is assumed that 60% of the irrigated land value is given by (irrigable) land and 40% by irrigation services. The knowledge gaps in water price and cost of irrigation as highlighted by the authors represent sources of uncertainty that can be hardly eliminated without a further data collection and research, so illustrating well the **epistemic uncertainty** as discussed in WP4's D4.1 (lack of information or knowledge for characterizing phenomena).

The population and economic growth rates reference for this study are those of the OECD version of Shared Socioeconomic Pathway SSP2. An inclusion of additional SSPs is technically possible and can provide the state-of-the-art representation of socioeconomic uncertainty **in line** with the recommendations of WP4. Climate change impacts on crops' yields derive from the Agricultural Model Intercomparison and Improvement Project (AgMIP) which provides several sets of climate change impacts using five crop models. Specifically, we used yield impacts in the four Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6, and RCP8.5), for four crops (maize, rice, soy and wheat) with and without irrigation. Both uncertainty in climate projections and model uncertainty are represented by employed datasets **in line** with the recommendations of WP4. Another source of **epistemic uncertainty** is that employed data do not include growth-enhancing effects from CO_2 fertilization, which are subject to large uncertainties, as the authors highlight. Finally, while for rice and wheat there is a perfect correspondence with the ICEs-IRR sectors, the authors have used maize data as representative of other cereal crops, soy data for vegetable and fruits and the data on rainfed land for soy as a proxy for pasture land. The need to use proxies rather than direct estimates is due to the lack of data on specific agricultural products – these assessments are not available for the set of climate projections. This knowledge gap highlighted by the authors is **representing uncertainty** that is hard to quantify, being a rather common feature in the climate impacts and adaptation context, as discussed in WP4 D4.1/4.2.

Simulation results are reported by the case-study authors for "with" and "without irrigation expansion for each RCP. The simulation period is 2008–2050. The authors summarize results for each region in the model with the average and a 95% **confidence interval** computed using results from the five AgMIP crop models. This study allows providing **ranges** for the economy-wide impacts of climate change on world agricultural output using selected climatic models (RCP2.6: MRI-CGCM3 and MIROC-ESM-CHEM; RCP8.5: MIROC-ESM-CHEM and CNRM-CM5). Deriving and presenting results in the form of the confidence intervals (to be interpreted with caution as fed by an ensemble of crop models) is a **step forward** in terms of the state of the art uncertainty representation and **in line** with the findings and recommendations of WP4.

2.6.1.2 Modelling planned adaptation for coastal zone protection in a general equilibrium framework

The case study authors employ future projections of SLR damages that are generated by the DIVA modelling framework. DIVA is a socio-economically driven geo-bio-physical model which projects the impacts and costs of sea-level rise, and subsequent adaptation for a range of scenarios. Outputs from two climate models (MIROC and NorESM) and the SSP2 socioeconomic scenario were used as drivers for the DIVA model for RCP2.6 and RCP8.5 scenarios. Even though three more climate projections provided by ISI-MIP project models are available for both RCPs, the included **climate uncertainty** representation serves well the purpose of the case study and is **in line** with the recommendations of WP4. The inclusion of additional climate projections is rather a technical step that can be carried out **within** the suggested modeling framework without its major modifications.

The DIVA assessment is of partial equilibrium in nature as it **cannot capture** explicitly the inter-sectoral/international economic impacts triggered by sea level rise, nor their rebounds on the sectors and countries initially impacted. This is however possible with CGE models that **ultimately quantify** the impacts on the value of production and ultimately on GDP accounting for all those interactions. Thus, application of CGE supports an integrated approach to inter-sectoral economic assessment and is **addressing the integration need** for climate change adaptation assessments as highlighted in WP4's deliverables D4.1/D4.2.

To account for uncertainty in land-based ice melt, the 5%, and 95% percentiles ice melting uncertainty offering a 'very likely' range for low and high SLR estimates. The socio-economic assumptions are those of the SSP2 scenario. Inclusion of additional SSPs is technically possible to provide a wider representation uncertainty in its socioeconomic component that is fully **in line** with the recommendations of WP4. Employing percentiles for **uncertainty representation in SLR** estimates is an important aspect in model application that is **in line** with the findings and recommendations of WP4.

The case-study authors explicitly mention the expected/average nature of the employed indicators included among other data for each scenario: **expected annual** damages to assets by sea floods, **expected annual** number of people flooded per year, annual cost of construction of new dikes, annual cost of maintaining existing dikes. Even though as generally stated by D4.2 mean annual damage (and alike mean-based indicators) has its obvious drawbacks as a representative of risk due to natural and human caused disasters, the application of these indicators in the case study is justified by an aggregated nature of CGE and simplified representation of economic sectors. The case-study is a vivid example where an inclusion of alternative **quantile-based risk indicators** as advocated in D4.2 would require a major **paradigm shift** in the modeling approach and hence lead to a necessity to close relevant knowledge and data gaps as discussed in WP4's D4.1.

The authors highlight assumptions relevant to the uncertainty that is not yet duly quantified as e.g. the assumptions on labor productivity losses are computed assuming that expected people flooded are not able to work for 2 working weeks per year that is rather arbitrary as the authors of the study admit. This uncertainty can be hardly eliminated without additional data collection and research, so illustrating well the **epistemic uncertainty** as discussed in WP4's D4.1.

2.6.2 Implications and recommendations

The presented results on ECONADAPT's two case studies on planned adaptation in agriculture and to sea level rise communicate among others two messages important for policy formulation as it regards climate change adaptation assessments' uncertainty. First, within the existing modeling frameworks there is a large set of knowledge gaps classified as epistemic uncertainty according to WP4's D4.1 – the lack of information or understanding for characterizing a phenomena. And these uncertainties have to be understood, assessed, and ultimately reduced in an iterative process. A probably most straightforward way in this direction is improving the **data collection and availability** for a set of indicators explicitly highlighted in the case studies. Second, even though it poses a challenge on a conceptually new level, a **paradigm shift** in the modeling approaches might be beneficial for a more comprehensive policy analysis as it regards risk. That type of shift can only be substantiated and supported by rich data availability covering both bio-physic and socio-economic aspects at a global scale with a sufficiently fine level of detail. However, given the current limitations on data collection, economic assessments performed using model ensembles and feeding bottom-up data/results to top-down models such as CGEs are still a useful resource to analyze, communicate and identify uncertainty gaps for current and future research.

2.7 Case study: Project Appraisal for Climate Mainstreaming in Rwanda's Tea and Coffee Sectors (WP9)

The case study evaluates an investment into physical and informational adaptation options for the tea and coffee sectors in Rwanda. The physical adaptation options are designed to address current climate variability and the adaptation deficit at the smallholder farmer level. They include soil and water conservation measures and farmer field schools. The informational adaptation options are designed to provide strategic information about climate risks, including climate risk mapping for Rwanda, which are important for the Government's plans to expand the production of export crops. More specifically, climate risk mapping will provide information about altitude bands that are suitable to grow tea/coffee in both current and future climate scenarios. Without climate risk mapping, new tea and coffee plantations may be developed at altitude bands that are optimal for today's climate but sub-optimal for the future climate. The authors explore the differences in outcomes for the smallholder plantations with both physical and information adaptation options in different climate scenarios.

2.7.1 Uncertainty representation and modeling methods

The authors have reviewed climate projections from **five alternative sources** that combine a large number of GCM runs for a set of RCPs/SRES scenarios (including **RCP 2.6, 4.5, 6.0, 8.5**, SRES A1B, A2, B1) and inform on the temperature and precipitation changes by the mid and the end of 21st century. The consideration of a wide range of climate projections was necessary to take into account the existing climate change uncertainty and is **fully in line** with the recommendations of WP4/D4.1.

The authors analyze the **uncertainty in climate projections** and point out that for temperature, all employed climate projections agree on the direction of change (the actual amount of change varies), however, the projections for rainfall are much **more uncertain**; not all the climate projections agree on the direction of change (positive or negative) and the magnitude of change varies significantly between different sources. In this case study both temperature and precipitation (future uncertain climatic variables) are relevant for the project appraisal. The analysis of uncertainties in the key climatic variables is **in line** with the methodologies suggested in WP4.

In this case study for the purposes of numerical estimates two climate scenarios are used (RCP2.6 and 8.5) that represent the **highest and lowest** annual mean temperature projections for Rwanda. To capture emissions' and model uncertainty, the **90th percentile** temperature from the highest emission scenario (RCP8.5) and **10th percentile** temperature from the lowest emission scenario (RCP2.6) are used in the analysis (20 GCMs are employed). By taking these extremes, this method excludes outliers, captures a **wide range of uncertainty** associated with current climate information and minimizes the number of scenarios that need to be analyzed. This approach is useful in a developing country policy context. By employing an ensemble of climate models and applying a **percentile-based selection** from those, the authors attain the goal of representing the climate uncertainty **as required by the findings of WP4** at a reasonable level of effort as appropriate for the case study.

The model employed in this case study captures climate effects through the climate suitability functions for both tea and coffee. The functions have been developed through a **literature review** and by **consulting experts**, and they translate changes in the projected future temperature and precipitation to effects on tea and coffee production. The output for each crop is defined in two ways: **yield** (quantity) and **quality** (price). The authors emphasize that both yield and quality are determined by a number of factors, including climate, soil type, nutrient and water availability, vegetative cover, cultivar, and management. Therefore, the calibration of these functions, as highlighted by the authors, is subject to numerous not yet quantified uncertainties, **unveiling several existing knowledge gaps**. The majority of evidence used in their development is from coffee plantations in South America or tea plantations in East Africa. Hence the **pertinent uncertainty** in the obtained estimates has yet to be explored in more local studies. The strong need for a reduction of **epistemic uncertainty** (knowledge gap) is supported by the fact that quantifying the relationship between rainfall and tea yield/quality is even more difficult than with temperature. There is even less quantitative evidence for the interaction between precipitation and quality for coffee.

The authors also point out that shocks from **extreme weather events**, such as floods and landslides, are difficult to model. This is due to the lack of information on hectares at risk (incidence), the frequency of these events (probability) and their severity (yield/quality impacts). Therefore, such events have been excluded from the analysis. The authors explicitly state that these impacts might influence the returns for the project. Similarly, the authors highlight that the other important factors – change in pest and disease incidence, frequency, and severity have not been modelled for the same reasons. The possibilities to fill these knowledge gaps and **reduce associated uncertainties** can be explored in local studies.

The case study addresses uncertainties associated with specific adaptation options, using **sensitivity analysis** to test their impact on the project's outcome. Where evidence of a particular option's impact is not conclusive, the authors test the direction and/or magnitude of change. For example, the effect shade trees will have on coffee yield is not certain, so the authors test a range of positive impacts. Similarly, the study uses switching values to test the point at which particular investments would no longer be worthwhile. This sensitivity analysis helps address uncertainty about the impact of particular investments on the tea and coffee sectors in Rwanda.

The analysis of **socio-economic scenarios** in a quantitative form was not carried out in this case study. This is because the case study intends to focus on quantifying the effect climate change uncertainty may have on the project's outcome. However, future social welfare and demographic trends will play a significant role in the rate of climate change adaptation, which adds another **layer of uncertainty** about the future vulnerability of the tea and coffee sectors to climate change. **In line** with the findings of WP4, the authors do address **socio-economic uncertainty**, and within the objective frame of the case study do carry out a qualitative analysis of socio-economic factors.

2.7.2 Implications and recommendations

The ECONADAPT's case study on Rwanda's Tea and Coffee Sectors vividly highlights two important aspects. First, as it regards estimates of bio-physical impacts of climate change, there is a set of knowledge gaps and respective **uncertainties unveiled** by the case study authors. Second, due to the nature of existing uncertainties (lack of data and/or scientific understanding), the **quantification of many of these uncertainties** is extremely difficult, therefore, the quantitative estimates have to be substituted with qualitative assessments that communicate the knowledge in a "soft" way. The case study demonstrates well a rather universal need for the sustainable **long-term data collection**/monitoring and accumulation of **local-specific knowledge**. These activities are expected to deliver both short- and long-term benefits especially within the context of climate adaptation appraisal.

2.8 Case study: Adapting to Climate Change in Zanzibar's Seaweed Farming Sector (WP9)

This case study is designed to examine the treatment of risk and uncertainty in economic appraisals of climate adaptation projects in the context of international development funded by European countries. The case study examines adaptation options for the seaweed farming industry in the Zanzibar islands.

2.8.1 Uncertainty representation and modeling methods

Future climate projections suggesting increases in sea surface temperatures (SST) are informed by **nine regional climate models** representing different combinations of inputs from global climate models. The lower distribution assumes **RCP4.5**, and the upper distribution assumes **RCP8.5**. The climate uncertainty in this case study is well represented **in line** with the findings of the WP4. The inclusion of a lower emission scenario RCP2.6 is technically possible, yet this would not impact the results of the study as the necessity to adapt is justified by an already observed increase in SST.

The selected RCP4.5 and RCP8.5 are well suited for **representation of future uncertainty** as to whether the seaweed farming would be feasible or not. As the authors point out, the long term uncertainty in the seaweed farming sector stems from ambiguous climate futures past 2040. Climate projections past this point suggest temperature increases of varying magnitudes, depending on the emissions pathway employed in modelling. The low emissions scenario (RCP 4.5) projects temperature increases that remain in the range of at least one species of seaweed grown in Zanzibar. However, a higher emissions scenario (RCP 8.5) expect temperatures to exceed the threshold for both spinosum and cottonii seaweed varieties by 2075. In the case of a high-emissions future, returns from investments in seaweed farming may fall to zero.

The socio-economic uncertainties play a vivid role in this case study. The socio-economic pressures will likely impact on the sector's ability to continue supporting vulnerable populations. **Declining productivity** from agricultural activities and a **high population growth rate** both exert pressure on coastal populations and in turn increase interest in seaweed farming. The long-term quantification of the uncertainties highlighted by the authors is extremely difficult due to the unsustainable nature of current seaweed farming practices. This is a practical example of **epistemic uncertainty** as discussed in WP4's D4.1 (lack of information or knowledge for characterizing phenomena).

Another contributor to the epistemic uncertainty as highlighted by the authors is the fact that international demand continues to be **uncertain** without a formal marketing system for seaweed, contributing to an unstable price regime for farmers. In this regard, the authors point to the specific uncertainties associated with the influence of international trade: because of the large market share controlled by Indonesia and the Philippines, any disruption in seaweed farming in either country can have a substantial effect on global demand for seaweed. Spikes in prices paid to Zanzibar farmers can be matched with damaging typhoons in competitor countries. This aspect illustrates well the need for **integrated assessments** as advocated in the WP4's work: with an increased occurrence of extreme events in the first and second producers of seaweed, frequency of high demand for seaweed in Zanzibar could also increase in the future. However, a reliable quantification of the frequency of future extreme events represents a current **knowledge gap** in climate modeling as discussed in WP4's D4.1. The study includes a high- and low-price scenario to capture uncertainty around demand and resulting prices for seaweed in the global market. For the low-price scenario, a weighted average of seaweed prices in Zanzibar over the past 10 years is calculated, with more recent prices weighted more than distant prices. The high-price scenario estimates a growth trend from historical prices and extends this trend over 10 years into the future. These price uncertainties do not change the findings of the analysis, demonstrating robustness in the results.

The authors reflect **uncertainty** in cost estimates for sturdy boats as a **range** from 1 million to 3 million TZS per boat, depending on material used and price negotiated with the manufacturer of the boat. Exact specifications of farming boats are not known—this is one area of the project analysis that would benefit from a local pilot study. The model maintains the assumption that 10 farmers would share a boat. However, this assumption, as clearly stated by the authors, is rather **uncertain** and therefore is a subject to clarification in the course of a local pilot study. If the sharing of a common asset is not adopted, the costs might substantially increase or entirely prevent local people from using this suggested option.

The authors explored the **uncertainty in the discount rate** applied for the NPV estimates. Even though the discount rate was found to have a big influence on the numeric estimates, this source of uncertainty might play a relatively small role in practice as, first, the access to credits is hampered by a subsistence nature of the seaweed farming, and, second, by not having options alternative to seaweed farming especially for women in coastal villages, the discount rate does not produce dramatic shifts in terms of preferred option within the considered set of adaptation options.

2.8.2 Implications and recommendations

The case-study is illustrating well a complex nature of an adaptation project, where a wide range of factors – where many are currently hardly quantifiable – have to be taken into account: health impacts (fatigue, saltwater rashes and stings from sea urchins), productivity of a seaweed farm, risk that male villagers will use boats for fishing (eliminating gender benefits from seaweed farming), governance issues. All these factors add to the complexity and **increase uncertainties** around the project assessment. Due to uncertainty around future climate change represented by different concentration pathways, policymakers cannot reliably project the viability of seaweed farming past mid-century. However, as the poor population is very vulnerable to a majority of disturbances both in short and long term perspectives, the **case study illustrates an urgent need to adapt** to the changes already seen. In this context, respective uncertainties after being analyzed and understood cannot be seen as a hurdle for action.

Concurrent investments in monitoring equipment for sea surface temperatures are recommended in support of a real options analysis which will improve the ability of decision makers to respond to changing climate conditions in the future. Though future climate scenarios exist as a current source of uncertainty, these investments in improving access to climate information will reduce this particular source of uncertainty in the future and allow the government and other decision makers to take better-informed actions.

3 Overall summary and conclusions

The work presented in case studies of ECONADAPT and summarized here in a condensed form with a special emphasis on representation of uncertainty, provides a valuable information on the state-of-the-art capacity in assessment of adaptation options. The work carried out in the case study work packages demonstrated also the progress beyond the state-of-the-art and led to several important implications. In summary, the findings from the case studies and recommendations supported by those can be summarized in the following bullet points:

1) Uncertainties in climate change and socio-economic projections **do play an important role** in the analysis of adaptations and cannot be ignored (e.g. projected shifts in tea and coffee altitude suitability bands as in Rwanda WP9, projected changes in crop yields and agricultural production as in WP7, projected sea level rise as in Bilbao WP6). There are, however, cases where there is an urgent need for change due to already observed climatic changes (e.g. seaweed farming in Zanzibar WP9).

2) The specific type of uncertainty – epistemic – and its influence on the assessment results drives the need to **close knowledge gaps**. Therefore, an effort is required to create and gather new knowledge. All the case-studies were able to unveil and demonstrate these gaps, e.g. inclusion into the modeling of structural protection measures that are part of national flood protection plans (WP5), long term hydrological modeling (WP6 Bilbao and Vltava), depth-damage functions (WP6 Vltava), spatially-detailed land cover (WP7), agricultural crops production (WP8 Autonomous adaptation), water price and cost of irrigation (WP8 Planned adaptation), climate induced changes in pest and disease modeling (WP9 Rwanda), quantification of the frequency of future extreme events (WP9 Zanzibar).

3) There is a strong **need for monitoring and data collection**, because data limitations frequently play a critical role in adaptation assessments as demonstrated by the project's case studies. The data are needed to support research and creation of knowledge. Even though in many cases a long enough time series data might be needed to better calibrate respective impact models (e.g. a cultivar parametrization potentially useful for crop yield assessments), in some cases a one-time consistent picture could help fill the gap (e.g. a spatially-detailed land cover in WP7).

4) At the science – policy interface, there is a **need to communicate** the findings of analyses that include a wide representation of uncertainties and therefore provide more sophisticated information than assessments carried out before, e.g. probabilistic formulation of disaster risk reduction investments benefits as a reduced possibility of disaster fund depletion in WP5, results of the real options approach in WP6 Bilbao, robust recommendations derived from an application of the stochastic GLOBIOM model in WP7. There is a need for common language and common understanding of modelled/estimated processes.

5) There is a need to implement and carry out a **real-life testing of new approaches**. This is where the practice could prove and also correct and improve the methodology.

6) Continuation of the research that was pushed forward thanks to the ECONADAPT project and deepening of the understanding of uncertainties pertinent to the models and translated into assessments is apparently necessary. This can be achieved in an iterative way where the next step would be **revisiting the model's parametrizations and creating multidimensional clouds of plausible estimates** for a deeper exploration.

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