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Model-based Approaches for Supporting Equitable Delta Adaptation Planning

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Model-based Approaches for Supporting Equitable Delta Adaptation Planning

Dissertation

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Summary

Problem statement and research approach

Climate change and anthropogenic pressures are threatening the livelihood of people in the world's deltas. To secure a sustainable future, alternative courses of actions should be well prepared in advance, and their efficacy should be evaluated against future uncertainties. The assessment of alternative adaptation plans often takes an aggregate perspective, where the projected outcomes are aggregated across all people and over the entire planning horizon. In reality, plans which are optimal at the aggregate level, may benefit some people while harming others. This is because climate change impacts and socio-economic pressures vary in space and time, and they affect people differently depending on one's adaptive capacity. Therefore, adaptation can exacerbate inequality.

Although the importance of considering equity is widely acknowledged, the existing practices in adaptation planning for deltas falls well short of what is needed to properly include equity considerations. It mainly uses aggregated indicators to evaluate alternative plans, such as reduction in expected annual damage and freshwater supply availability. How those indicators are distributed across people is rarely considered, thus fostering the risk of increasing inequality. For example, the dikes heightening policy in the Vietnam Mekong Delta (VMD), aimed at maximizing total rice production by protecting the paddy fields from flooding, eventually benefits only large-scale farmers while lowering the profitability of small-scale farmers.

To support adaptation planning in deltas, integrated impact assessment models are frequently used to quantitatively evaluate the performance of alternative adaptation plans under various scenarios of future changes. These models can also support equitable planning, as long as they allow for calculating outcomes for different groups of people. Yet, recent model-based studies incorporate equity only in an ad-hoc manner. Systematically including equity considerations in model-based analyses is not a trivial task. It requires modifications in the model structure, and new evaluative frameworks for analyzing model results. This brings us to the main research question of this dissertation:

What is an adequate approach to model-based policy analysis for supporting equitable delta adaptation planning?

This research question is answered by first doing a literature review on concepts related to distributive justice, climate ethics, and model-based planning for climate change. This review generated requirements that a model-based analysis should satisfy in order to account for equity. Next, a proof-of-concept modeling setup for fulfilling some of the requirements was proposed and tested using a hypothetical case study. The setup was then applied to a real-life case study, namely on adaptation planning for the upper VMD. Lastly, on this real-life case, two evaluative frameworks for assessing distributional outcomes were proposed and tested, namely explorative and normative analysis. These analyses support equitable adaptation planning by exploring who wins and who loses under certain circumstances, and by identifying the best performing policy based on certain distributive moral principles.

Results and policy implications

Based on the literature review, eleven requirements were identified for systematically including equity in model-based analyses. These requirements allow for assessing intragenerational (between people in the same generation) and intergenerational (between generations) justice. Some fundamental requirements, such as having disaggregated actor-based indicators and time-series indicators, have already largely been met in recent studies. Other requirements are, however, not yet adequately addressed: ensuring representation of different actors and their behavior in models, using multiple ethical principles, exploring changes in actors' behaviors and values, considering actor-differentiated policies, and assessing changes in policy space (i.e., available set of actions) over time. These requirements are necessary for ensuring fair representation of all stakeholders and freedom of choice of the future generations.

In my research, I propose the integration of a utility-based land-use change module into a biophysical impact assessment metamodel in order to improve the representation of different actors and their behavior. This setup allows for evaluating distributional impacts to people living in different locations, while also ensuring that people's autonomous behavior is taken into account. The hypothetical case study revealed that integrating land-use change dynamics is especially relevant when climate change impacts are severe, societal development is sensitive to climate events, and considered adaptation interventions are spatially targeted (e.g., zoning policies or dikes heightening only in certain locations). After successfully applying this model setup to a hypothetical case study, and the same setup is applied for a real-life case study on agriculture adaptation planning for the upper VMD.

Two evaluative analyses for assessing distributional outcomes are proposed for the VMD case study: explorative and normative. The goal of explorative analysis is to explore inequality patterns, i.e., who will be better-off or worse-off, and why? In the VMD case study, spatial inequality – in terms of district-level farm profitability – is calculated from more than 40,000 scenarios capturing uncertainties about climate change and socioeconomic developments, as well as different adaptation policies. Multiclass scenario discovery methods are then applied to distill insights from the large-scale computational experiment. The methods comprise two steps: clustering distinctive inequality patterns and identifying scenarios which best predict each cluster of inequality pattern. I thus found seven distinct spatial inequality patterns for the VMD case study, along with the scenario narratives behind them. By understanding the plausible distributional outcomes and their drivers, policy makers can better anticipate emerging inequalities by – among other things – preparing compensation measures for the worse-off.

Normative analysis aims at ranking alternative policies based on their distributional performance. This analysis makes use of alternative moral principles, drawn from theories of distributive justice. For example, the utilitarian principle postulates that any form of distribution is fair as long as it maximizes the total utility of all people. In contrast, the strict egalitarian principle opts for a distribution which minimizes the utility difference between the worst-off and the best-off. These different moral principles are operationalized into aggregation functions that summarize distributional outcomes from model-based analyses, so that a preference ranking of alternative policies can be generated. Applying the normative analysis to the VMD case study shows that the use of different moral principles leads to distinctive policy preference rankings. The policy with low dikes in Dong Thap performs best based on the utilitarian, prioritarian, sufficientarian, and envy-free principles, but it ranks second worst when seen from the Rawlsian difference principle. Furthermore, the preference rankings are also influenced by which scenarios unfold. In some scenarios, the use of two moral principles results in conflicting preference rankings, while in other scenarios the rankings are in agreement.

From this research, I derive two important recommendations for practice. First, distributional considerations should be considered explicitly in adaptation planning. For example, distributional considerations can be operationalized through (i) using both aggregated (e.g., total flood damage) and disaggregated (i.e., impacts experienced by different groups or stakeholders) indicators when defining adaptation objectives, (ii) exploring the future vulnerability of each stakeholder separately, and (iii) preparing for compensatory measures for stakeholders who benefit less or even become worse-off due to the implementation of certain measures. This also underscores the importance of combining explorative and normative analyses when using models for supporting adaptation planning. For the normative analysis, one should also consider ethical principles which are not currently preferred by stakeholders, in order to anticipate plausible value change in the future.

Second, as fulfilling all the eleven modeling requirements entails huge investments in model development, it is important to find an appropriate balance between model complexity, available resources (e.g., in terms of project budget), and project goals. When scoping the model, one should find a balance between breadth (what to incorporate) and depth (degree of detail). In this research, for instance, a metamodeling approach is applied by coupling and simplifying complex models from different domains, so that the different factors that influence distributional outcomes could be included in the analysis. Aiming for a fit for purpose model is useful for this. The model should be able to satisfy evaluative questions that assess its adequacy for answering the specific policy questions.

This research is a first step in systematically accounting for equity in adaptation planning for deltas. From the modeling side, many requirements, such as assessing policy changes over time, are not explicitly addressed. But each unsatisfied requirement can be a direction for future research. From a broader equitable planning perspective, it is important to account for distributional aspects in each stage of the planning process. Finally, assessing distributional outcomes is just one side of the coin. Procedural justice, a complementary account of justice which focuses on the fairness of decision-making processes, is perhaps as important as distributive justice.

Samenvatting

Probleemstelling en onderzoekmethode

Klimaatverandering en antropogene druk bedreigen de levensomstandigheden van de bevolking in de delta's wereldwijd. Om een duurzame toekomst veilig te stellen, moeten alternatieve maatregelen van tevoren goed worden voorbereid en moet hun effectiviteit worden geëvalueerd in relatie tot toekomstige onzekerheden. Bij de beoordeling van alternatieve adaptatieplannen wordt vaak uitgegaan van een geaggregeerd perspectief, waarbij de voorspelde uitkomsten worden samengevoegd over alle mensen en over de gehele planningshorizon. In werkelijkheid kunnen plannen die op geaggregeerd niveau optimaal zijn, sommige mensen ten goede komen en anderen schaden. Dit komt doordat de gevolgen van klimaatverandering en de sociaaleconomische druk variëren in plaats en tijd. Ook hebben de gevolgen effect op verschillende manieren per mens, afhankelijk van diens adaptief vermogen. Derhalve kan adaptatie ongelijkheid verergeren.

Hoewel algemeen wordt erkend dat het belangrijk is rekening te houden met gelijkheid, schiet de huidige praktijk van adaptatieplanning voor delta's ernstig tekort om overwegingen van gelijkheid naar behoren te integreren. Er wordt voornamelijk gebruik gemaakt van geaggregeerde indicatoren om alternatieve plannen te evalueren, zoals de vermindering van de verwachte jaarlijkse schade en de beschikbaarheid van zoetwater. Het wordt zelden in overweging genomen hoe deze indicatoren over de bevolking worden verdeeld. Hiermee wordt het risico van toenemende ongelijkheid versterkt. Als voorbeeld, het dijkenverhogingsbeleid in de Mekongdelta in Vietnam (VMD) dat gericht is op maximalisering van de totale rijstproductie door de rijstvelden te beschermen tegen overstromingen, is uiteindelijk alleen winstgevend voor grootschalige boeren terwijl het die van kleinschalige boeren verlaagt.

Ge-integreerde evaluatiemodellen worden vaak gebruikt om de effecten van alternatieve adaptatieplannen in verschillende scenario's van toekomstige veranderingen te evalueren. Deze modellen kunnen ook bijdragen aan een rechtvaardige planning, op voorwaarde dat zij de effecten voor verschillende groepen mensen kunnen berekenen. Toch wordt in recente modelmatige studies slechts op een ad hoc manier rekening gehouden met rechtvaardigheid. Het systematisch opnemen van overwegingen rondom rechtvaardigheid in modelmatige studies is geen triviale taak. Het vereist wijzigingen in de model structuur, en nieuwe raamwerken voor het evalueren en analyseren van model uitkomsten. Dit brengt ons tot de centrale onderzoeksvraag van dit proefschrift:

Wat is een adequate aanpak om modelgebaseerde beleidsanalyses uit te voeren voor het ondersteunen van rechtvaardige delta adaptatieplanning?

Deze onderzoeksvraag wordt beantwoord door eerst een literatuurstudie te doen naar concepten gerelateerd aan distributief rechtvaardigheid, klimaatethiek, en modelgebaseerde planning voor klimaatverandering. Deze literatuurstudie leverde voorwaarden op waaraan een modelgebaseerde analyse zou moeten voldoen om rekening te houden met rechtvaardigheid. Vervolgens werd een proof-of-concept modelopzet voor het vervullen van een aantal van de voorwaarden ontwikkeld en getest met behulp van een hypothetische case study. De opzet werd vervolgens toegepast op een real-life case study over adaptatieplanning voor de Vietnam Mekong Delta (VMD). Ten slotte werden twee raamwerken voor het evalueren en analyseren van de distributie van de uitkomsten geïntroduceerd namelijk een exploratieve en een normatieve analyse. Vervolgens werden deze getest op basis van de real-life case study. Deze analyses dragen bij aan een rechtvaardige adaptatieplanning door te onderzoeken wie wint en wie verliest onder bepaalde omstandigheden, en door te identificeren wat het best presterende beleid is op basis van bepaalde ethische principes.

Resultaten en beleidsimplicatie

Gebaseerd op het literatuuronderzoek zijn elf voorwaarden geïdentificeerd voor het systematisch opnemen van rechtvaardigheid in modelgebaseerde analyses. Deze voorwaarden maken het mogelijk om de intragenerationele (tussen mensen van dezelfde generatie) en intergenerationele (tussen generaties) rechtvaardigheid te evalueren. Sommige fundamentele voorwaarden, zoals het beschikken over uitgesplitste op actorgebaseerde indicatoren en tijdreeksindicatoren, zijn al grotendeels onderzocht in recente studies. Andere voorwaarden zijn echter nog niet voldoende voldaan: de vertegenwoordiging van verschillende actoren en hun gedrag in modellen, het gebruik van meerdere ethische principes, de integratie van veranderingen in het gedrag en de waarden van actoren, het in overweging nemen van door actor-gedifferentieerd beleid, en de evaluatie van veranderingen in de beleidsoplossing ruimte (d.w.z. beschikbare set aan acties) in de tijd. Deze voorwaarden zijn noodzakelijk voor het waarborgen van een eerlijke vertegenwoordiging van alle belanghebbenden en de keuzevrijheid van de toekomstige generaties.

In mijn onderzoek stel ik voor om de module over veranderende ruimtegebruik gebaseerd op nutsvoorzieningen te integreren met het integraal meta effect model. Hiermee zal het model verschillende actoren en hun gedrag beter kunnen representeren. Deze modelopzet maakt het mogelijk om de distributie-uitkomsten voor mensen die op verschillende locaties wonen te evalueren, terwijl er ook rekening wordt gehouden met het autonome gedrag van mensen. Uit de hypothetische case study is gebleken dat het integreren van de dynamiek van veranderende ruimtegebruik vooral relevant is wanneer de gevolgen van klimaatverandering ernstig zijn, de maatschappelijke ontwikkeling gevoelig is voor klimaatgebeurtenissen, en de adaptatie interventies ruimtelijk gericht zijn (bv. zoneringsbeleid of dijkverhoging alleen op bepaalde locaties). Na succesvolle toepassing van deze opzet op een hypothetische case study, wordt dezelfde opzet toegepast op een real-life case study over adaptatieplanning voor de landbouw in VMD.

Voor de VMD case study worden twee analyses uitgevoerd voor het evalueren en analyseren van de distributie van de uitkomsten: een exploratieve en een normatieve. Het doel van de exploratieve analyse is de ongelijkheidspatronen te onderzoeken, d.w.z. wie zal er beter of slechter aan toe zijn, en waarom? In de VMD case study wordt ruimtelijke ongelijkheid - uitgedrukt in de winstgevendheid van landbouwbedrijven op districtniveau - berekend op basis van meer dan 40.000 scenario's met onzekerheden over klimaatverandering, sociaaleconomische ontwikkelingen, en verschillende vormen van aanpassingsbeleid. Multiclass scenario discovery methoden worden vervolgens toegepast om inzichten te extraheren uit een grootschalig computationeel experiment. De methoden bestaan uit twee stappen: (1) het clusteren van kenmerkende ongelijkheidspatronen en (2) het identificeren van scenario's die elk cluster van ongelijkheidspatronen het best kunnen voorspellen. Hieruit resulteerde zeven verschillende ruimtelijke ongelijkheidspatronen en de achterliggende scenario's voor de VMD case study. Door inzicht te krijgen in de plausibele distributies van uitkomsten en hun drijvende krachten, kunnen beleidsmakers beter anticiperen op opkomende ongelijkheden door - onder andere - compensatiemaatregelen voor te bereiden voor de slechter bedeelden.

Normatieve analyse is gericht op het ordenen van alternatieve beleidsmaatregelen op basis van de distributie van uitkomsten. Deze analyse maakt gebruik van alternatieve morele principes, afkomstig van theorieën over distributief rechtvaardigheid. Bijvoorbeeld, het utilitaristische principe stelt dat elke vorm van distributie rechtvaardig is zolang het totale nut van alle mensen gemaximaliseerd wordt. Daarentegen, het egalitaire principe streeft naar een distributie die het verschil in nut tussen de slechtst en de best bedeelden minimaliseert. Deze verschillende morele principes worden geoperationaliseerd in aggregatiefuncties die de distributie van de uitkomsten van modelgebaseerde analyses samenvatten, zodat een voorkeursrangorde van alternatieve beleidsmaatregelen kan worden gegenereerd. De toepassing van de normatieve analyse op de VMD case study laat zien dat het gebruik van verschillende morele principes leidt tot uiteenlopende rangordes van beleidsvoorkeuren. Het beleid met lage dijken in Dong Thap scoort het best van alle beleidsopties op basis van de utilitaristische, prioritaristische, sufficientistische en afgunstvrije principes, maar het komt op de een na slechtste plaats wanneer wordt uitgegaan van het Rawlsiaanse principe. Bovendien wordt de rangschikking van de voorkeuren ook beïnvloed door de scenario's. In sommige scenario's resulteert het gebruik van twee morele principes in tegenstrijdige voorkeursrangschikkingen, terwijl in andere scenario's de rangschikkingen overeenkomen.

Uit dit onderzoek komen twee belangrijke aanbevelingen voor de praktijk naar voren. Ten eerste moet bij de planning van adaptatie expliciet rekening worden gehouden met distributie overwegingen. Bijvoorbeeld, distributie overwegingen kunnen worden geoperationaliseerd door (i) zowel geaggregeerde (bijv. totale overstromingsschade) als gedesaggregeerde (d.w.z. gevolgen ervaren door verschillende groepen of belanghebbenden) indicatoren te gebruiken bij het definiëren van adaptatiedoelstellingen, (ii) de toekomstige kwetsbaarheid van elke belanghebbende afzonderlijk te onderzoeken, en (iii) compenserende maatregelen voor te bereiden voor belanghebbenden die minder profiteren of zelfs slechter af zijn als gevolg van de implementatie van bepaalde maatregelen. Dit benadrukt ook het belang van een combinatie van exploratieve en normatieve analyses bij het gebruik van modellen ter ondersteuning van adaptatieplanning. Voor de normatieve analyse moet ook worden gekeken naar ethische principes die momenteel niet de voorkeur van belanghebbenden hebben, om zo te kunnen anticiperen op plausibele waardeveranderingen in de toekomst.

Ten tweede is het van belang een passend balans te vinden tussen de complexiteit van het model, de beschikbare middelen (b.v. in termen van projectbudget), en de projectdoelstellingen. Dit voornamelijk omdat het voldoen aan alle elf voorwaarden een enorme investeringen in model ontwikkeling veroorzaakt. Bij het opstellen van het model moet ook een balans worden gevonden tussen de omvang (bv. welke variabelen het model moet bevatten) en de diepgang (mate van detail). In dit onderzoek wordt, bijvoorbeeld, een metamodellerings benadering toegepast door complexe modellen uit verschillende domeinen te koppelen en te vereenvoudigen, zodat de verschillende factoren die de distributie van de uitkomsten beïnvloeden kunnen worden opgenomen in de analyse. Het streven naar een "fit for purpose"-model is hierbij behulpzaam. Het model moet kunnen voldoen aan evaluatie vragen die de mate van geschiktheid bepalen om specifieke beleidsvragen te kunnen beantwoorden.

Dit onderzoek is een eerste stap in het systematisch in acht nemen van rechtvaardigheid bij adaptatieplanning voor delta's. Vanuit de modellerings kant zijn er veel voorwaarden niet expliciet aan de orde gekomen, zoals de beoordeling van beleidsveranderingen in de loop van de tijd. Maar elke voorwaarde die niet aan de orde is gekomen kan een richting zijn voor toekomstig onderzoek. Het is, vanuit een breder perspectief van rechtvaardige planning, belangrijk om in elke fase van het planningsproces rekening te houden met distributie aspecten. Ten slotte is het evalueren van de distributie van de uitkomsten slechts één kant van de medaille. Procedurele rechtvaardigheid, een aanvullend aspect van rechtvaardigheid dat zich richt op de eerlijkheid van besluitvormingsprocessen, is wellicht even belangrijk als distributieve rechtvaardigheid.

1

Introduction

1.1. Background

The world's deltas are facing both climatic and anthropogenic pressures, jeopardizing people's livelihoods in the deltas. On the climatic side, changing precipitation, evapotranspiration, and accelerating sea level rise transform the geo- and biophysical characteristics of the deltas (Kuenzer and Renaud, 2012; Renaud et al., 2013; IPCC, 2021). Human activities aiming at improving people's livelihoods, such as land-use intensification and extensification, sand mining, and hydropower dam construction, eventually yield unintended consequences in the longer term, as they amplify the adverse transformation of the deltas (Anthony et al., 2015; Syvitski et al., 2009). How these pressures would evolve over time into the future is deeply uncertain. Still, decisions must be made and planned in advance, as failing to do so may result in adverse consequences of climate change and other developments (Füssel, 2007; Hallegatte, 2009) and preclude future adaptation options (Haasnoot et al., 2012). Therefore, the continuing intensification of these pressures calls for a comprehensive, long-term planning for the world's deltas.

A promising approach to long-term delta planning is adaptive pathways planning. This approach comprises four elements: taking an integrated view, identifying short-term actions that could contribute to long-term objectives, sequencing the available set of actions in advance that allows for adaptation over time, and implementing the actions based on how the future unfolds (Klijn et al., 2015; Marchand and Ludwig, 2014; Hermans et al., 2017). This approach thus monitors and anticipates future developments, avoids lock-in, and allows for seizing future opportunities. A popular method used in adaptive pathways planning is identifying 'adaptation pathways' (Haasnoot et al., 2013; Werners et al., 2021). In adaptation pathways, the efficacy of alternative policies is first evaluated, their adaptation tipping points and sell-by dates are established, and finally a set of possible sequences for implementing interventions is defined in the form of pathways.

Quantitative decision-support tools, mainly in the form of integrated impact assessment models, are often used to aid both long-term adaptation planning in general and delta planning in particular (Doukas and Nikas, 2020; Kwakkel et al., 2015; Watkiss et al., 2015). These tools are used to assess the outcomes of alternative adaptation policies in terms of costs and benefits. These tools are also used to evaluate the robustness of alternative policies (McPhail et al., 2018), i.e., to what extent the policy's outcomes are (adversely) affected by uncertainties. In developing adaptation pathways, computational tools are employed to calculate not only the performance of a policy but also its 'sell-by' date (Haasnoot et al., 2014; Kwakkel et al., 2015).

Adaptation planning in deltas often implicitly assumes the existence of a single planning authority who represents the union of objectives of all stakeholders (see e.g., Campos et al., 2016; Radhakrishnan et al., 2017; Van Beek et al., 2017; Zandvoort et al., 2017). As a consequence, decision-support tools used to aid adaptation planning often aggregate all costs and benefits of alternative adaptation policies across people and across time – a typical approach which is also followed in the broader climate adaptation planning domain (Beck and Krueger, 2016; Kolstad et al., 2014). Equity considerations play only little to no roles in such model-based planning. In reality, a policy that is optimal from a whole system perspective may not be beneficial to some actors at some point in time (Magnan et al., 2016; Garner et al., 2016). Hence, focusing only on aggregated benefits at the whole system-level might cause an equity issue of reinforcing and/or introducing new inequalities.

The issue of equity is concerned with the fairness of an outcome. Equity is one component within the Sustainable Development Goals (i.e., Goal no. 10), which postulates that future development should reduce inequality within countries and between nations. In recent years, equity considerations are being called for in planning for climate change (Klinsky et al., 2017). This is because climate change yields differential impacts to people with different socioeconomic backgrounds (Füssel, 2010a; Thomas et al., 2019), and similarly, mitigation and adaptation policies almost unavoidably have distributional consequences (Atteridge and Remling, 2018). To achieve equitable adaptation planning, the distributional impacts of alternative adaptation policies need to be considered, and this could be aided by the use of quantitative decision-support tools. This thesis is dedicated to advancing knowledge on how equity considerations could be accounted for in decision-support tools for delta adaptation planning.

1.1.1. Justice in planning for climate change

Accounting for equity in planning for climate change implies explicitly evaluating the fairness of both the planning process and the resulting plans. There are two dimensions of justice relevant in this context: procedural and distributive justice. Procedural justice is concerned with the fairness of the decision-making processes surrounding planning for climate change. Procedural justice is about the issues of recognition, participation, and transparency in the decision making process (Björnberg and Hansson, 2011; Klinsky and Dowlatabadi, 2009; Schlosberg, 2009). Distributive justice is concerned with the fairness of the distribution of policy outcomes of alternative policies (Konow, 2001; Muller, 2001). Quantitative decision-support tools can in principle be used to ensure that distributive justice is adequately considered in adaptation planning, by assessing the distributional outcomes of alternative policies. In practice, however, many quantitative models and evaluations of alternative policies consider only aggregated performance (Watkiss et al., 2015). This is because the inherent structure of most models is highly aggregated which implies that disentangling the impacts of a policy to individual groups of people becomes a non-trivial task (Kelly et al., 2013; Morgan et al., 1999). It is important to acknowledge that the use of quantitative decision-support tools can also have procedural justice implications, in addition to distributive justice.

Assuming there is a model capable of calculating the disaggregated impacts for different groups of people, two types of analysis are available to assess distributional outcomes of alternative policies. The first type is explorative analysis. The aim of this is to identify who benefits and who loses under various circumstances (i.e., under different combinations of alternative policies and uncertainties). Through identifying potential winners and losers, explorative analysis can help planners in ameliorating potential injustices that emerge under various uncertainty and policy scenarios. This could then decrease the possibility of maladaptation (Juhola et al., 2016; Magnan et al., 2016). The second type is normative analysis. Here, the goal is not to merely identify emerging distributional patterns, but also to establish which distributional pattern is the more just distributional outcomes. Ethical principles commonly found in the domain of climate ethics and distributive justice (see e.g., Konow, 2003; Van Hootegem et al., 2020) can be used to characterize morally ideal distributions. This allows one to calculate the preference ranking of alternative policies, and to identify the policy that performs best given a distributive moral principle.

Explorative analysis and normative analysis can be complementary in supporting equitable adaptation planning. While in explorative analysis the goal is to identify potentially benefitting or harmed groups of people under various uncertain futures and alternative policies, the goal of normative analysis is to create a preference ranking of alternative policies based on the selected distributive moral principles. How both types of analysis should be performed, and how they can complement each other to support equitable adaptation planning, are still unclear.

1.1.2. Justice considerations in adaptation planning for deltas

As the subject of this thesis is the inclusion of justice in model-based support for delta adaptation planning, it is important to have a sense of the extent to which justice has already been considered in delta adaptation planning. Fourteen delta adaptation planning studies recently reviewed (Werners et al., 2021) are examined in Table 1.1. The consideration of justice is evaluated by four characteristics of the case studies: the main objectives and/or goals, indicators used for identifying adaptation tipping points, indicators used to measure the overall performance of alternative adaptation pathways, and policy actions. For the first three characteristics, the explicit presence of group- and/or actor-specific indicators is evaluated. For policy actions, the presence of either group and/or actor-targeted policies as well as the presence of corrective and/or compensatory actions to potentially harmed groups are evaluated.

Table 1.1 shows that distributive justice is barely accounted for in past adaptation planning studies for deltas. None of the study goals comprise explicit justice considerations. Similarly, none of the tipping point indicators are related to distributional impacts to specific population subgroups. Only very few policy actions have explicit group differentiation, such as the compensatory financial support for small and medium enterprises in Bangladesh (Roy et al., 2021). When it comes to the assessment of alternative pathways, only one case study uses indicators that are specific for different population groups (i.e., metrics focusing on exposed population in Rosenzweig and Solecki (2014)). This brief review indicates that, although the importance of including justice and equity considerations in planning for climate change has long been raised in the broad mitigation and adaptation community (Klinsky et al., 2017; Paavola and Adger, 2006), its uptake in studies on delta adaptation planning is still limited.

It is worthwhile to highlight several recent studies on model-based support for delta adaptation planning that do include justice and equity considerations. Chapman and Darby (2016) evaluated the differential impacts of alternative cropping systems to small-scale and large-scale rice farmers in the Vietnam Mekong Delta (VMD). Ciullo et al. (2020) used ethical principles to construct several optimization problems for embankment raising on the Dutch-German Rhine. These studies, however, incorporate justice and/or equity only in an ad-hoc manner. What is lacking is a systematic approach on how quantitative models can be used to support fair and inclusive delta adaptation planning.

Table 1.1: Characteristics of fourteen past adaptation planning studies

Name of case study & reference	**Goal**	**Policy actions**	**Adaptation Tipping Point indicators**	**Pathways performance indicators**
1. Thames Estuary 2100 Project (Ranger et al., 2013)	Protection from tidal flood risk	• Improving existing defence infrastructure • Developing new barriers	• Decrease of target protection level of flood defence system	• Monetized variables (property at risk, risk to life, technical risk) • Non-monetized variables (water quality and quantity, recreation, biodiversity)
2. Long-term water security in the Dutch Delta (Haasnoot et al., 2013)	Flood-proof delta and sufficient freshwater supply	• Dikes heightening • Increasing pump capacity • Adapting infrastructure • Improving regional network management • Adapting land-use	• Flood safety • Water shortage	• Flood safety • Fresh water supply availability • Nature conservation • Sufficient water level for shipping activities
3. Coastal adaptation pathways for local community in Lake Entrance, Victoria, Australia (Barnett et al., 2014)	Safety from sea level rise	• Stringent controls over new built-up developments • Managed relocation	• Flooding duration and frequency	• No performance indicators, since there is only one pathway considered
4. Hurricane Sandy and adaptation pathways in New York (Rosenzweig and Solecki, 2014)	General climate change adaptation at a city level	• Mainstreaming climate risks in multiple urban service systems (e.g., public health, nature, waterfront) • Setting up long-term adaptation planning (e.g., assessing path dependency, periodical update of climate risk assessment)	• No specific indicator, adaptation is triggered by natural disasters	• Infrastructure and built-environment metrics • Metrics focusing on exposed population (e.g., % of residences in 100-year floodplain purchasing flood insurance)
5. Regional climate change adaptation plan for the Eyre Peninsula (Siebentritt et al., 2014)	General climate adaptation plan encompassing multiple sectors	• Agriculture: new crop varieties, soil modification, improve forecasting • Fisheries: improve stock assessment, improved marketing, change fleet location • Road infrastructure: increase design allowance, more frequent resealing • Coastal development: emergency flood, land heightening, dunes, sea walls	• Reduced rainfall • Sea level rise • Increased number of heatwaves • Increased frequency of drought • Increased frequency of storm events	• Environmental indicators (e.g. flood barrier reliability, extent of erosion and depositon) • Economic indicators (e.g. value of developed area)

6. Adaptation planning for London's urban water supply system (Kingsborough et al., 2016)	Reducing risks of water scarcity	• Tiered piercing • Education and awareness • Leakage reduction • Reservoirs construction • New desalination plant • Water re-use	• Population growth-induced increase in water demand	• Water supply risk metric • Present value of pathways cost
7. Urban storm water infrastructure planning in Singapore (Manocha and Babovic, 2017)	Flood protection	• Drainage constructions • Porous pavements • Green roofs	• Maximum precipitation that can still be withheld without causing flooding	• Investment and maintenance cost •Flood alleviation benefits • Sale of recycled water
8. Adapting to sea level rise in Los Angeles (Aerts et al., 2018a)	Flood protection	• Beach nourishment • Dune restoration • Flood-proofing buildings • Levees	• Sea level rise	• Flood safety • Recreation benefits • Environmental values • Adaptation costs
9. Adaptation pathways for flood-affected households in Bangladesh (Roy et al., 2021)	Flood protection	• Agricultural extension system • Leverage small and medium enterprises • Establish effective local networks • Climate-smart agricultural production system • Invest in hard infrastructure	• Flood depth	• The performance of alternative pathways is not explicitly discussed
10. Adapting to sea level rise in Ho Chi Minh city (Scussolini et al., 2017)	Flood protection	• Ring dike (for city center) • Ground elevation • Dryproofing buildings • Land-use change	• Sea level rise	• Expected annual damage • Annual potential casualties
11. Adaptation for pavement management in in coastal New Hampshire (Knott et al., 2019)	Maintaining and improving reliability of pavement in the future	• Recycling hot mix asphalt • Adding base • Repave	• Groundwater rise and temperature rise • Pavement reliability	• Pavement reliability • Present value of investment and operational costs
12. Adaptation pathways for tidal flood risk management in London (Hall et al., 2019)	Tidal flood protection	• Improve existing defence • Develop new barriers • Tidal flood storage • Barrier with locks	• Sea level rise • Barrier closing frequency • Rise of low tide level	• Expected annual flood damage • Cumulative cost • Economic regret (relative to best performing pathway)

13. Flood protection in Can Tho city, Vietnam Mekong Delta (Radhakrishnan et al., 2017)	Urban flood protection	• Dikes construction • Sluice gates • Bottom-up coping adaptation	• Spatial extent of flooding	• Spatial extent of flooding
14. Coastal Planning of Ilhavo and Vagos, Portugal (Campos et al., 2016)	Coastal flood protection	• Maintaining and reinforcing existing infrastructure • Sand nourishment • Sea walls and groynes	• Population exposed to flood • Breaking of the dune system	• Population exposed to flood • Breaking of the dune system • Technical complexity of the operations

1.2. Research questions and approach

With the ultimate aim of supporting inclusive delta adaptation planning, the above introduction leads to the main research question to be addressed in this thesis:

What is an adequate approach to model-based policy analysis for supporting equitable delta adaptation planning?

Addressing this main question requires answering five sub-research questions:

1. *How can justice and equity be incorporated in quantitative models used to support planning for climate change?*

Incorporating justice and equity in model-based support for planning for climate change requires calculating the distributional impacts of policies to the different population subgroups. How quantitative models can be used in such calculations, however, is currently not well understood. This research question is therefore aimed at defining requirements for quantitative modelling in order to enable incorporating justice and equity in planning for climate change. Furthermore, an assessment of the degree to which recent model-based studies for climate change planning meet those requirements is needed to identify research gaps in detail.

2. *What are the merits of endogenising land-use change dynamics in model-based support for delta planning?*

Incorporating justice and equity necessitates an explicit representation of different population subgroups. One straightforward and meaningful way to have such a disaggregated representation is by classifying population based on their location. Thus, land-use change becomes an important process to be accounted for in the model, as changes in land-use and livelihoods may influence the performance of alternative policies. Land-use change, however, is often treated as either static (i.e., remains unchanged for the entire planning horizon) or exogenously driven in model-based delta adaptation planning studies. This research question aims to understand the merits of considering endogenous land-use change by identifying the advantages, disadvantages, and conditions under which doing so yields policy-relevant insights.

3. *To what extent do distributional outcomes of adaptation planning depend on adaptation policies and climatic and socioeconomic uncertainties?*

Assessment of distributional impacts often focuses on either the impacts of climatic and socioeconomic uncertainties, or the impacts of adaptation policies. In reality, distributional outcomes are simultaneously influenced by both policies and uncertainties. In this research question, we aim to show how the interactions between adaptation policies and climatic and socioeconomic uncertainties yields non-linear impacts on the distribution of outcomes to different population subgroups.

4. *How to explore plausible patterns of distributional outcomes in adaptation planning under deep uncertainties?*
To anticipate unintended distributional consequences, it is important to understand the potentially emerging distributional outcomes. Given the deeply uncertain nature of adaptation planning, it is impractical to show thousands of distributional patterns resulting from thousands of scenarios to decision makers. Therefore, care needs to be given to how to cluster plausible distributional patterns and identify conditions that give rise to each representative distributional pattern.

5. *How can the use of multiple distributive moral principles in model-based support tools improve the considerations of equity in adaptation planning?*
This question is concerned with the normative analysis of distributional outcomes. In particular, we assess the distributional outcomes of alternative policies based on specific distributive moral principles, so that preference ranking of alternative policies can be generated. The merits of using different distributive moral principles on the policy preference ranking will be investigated in this research question. Furthermore, an assessment of how the rankings change under different scenarios will be conducted. The goal is to identify (i) distributive moral principles that yield more (or less) stable ranking across scenarios, (ii) policies that are more robust across all principles, and (iii) agreement of preference rankings from all pairs of moral principles.

1.3. Research approach and methods

The overarching research approach of this dissertation is developing and testing methods and metrics for including distributive justice considerations in model-based adaptation planning. In accordance with the sub-research questions (sub-RQs), the first step is to conduct a literature review on the topic (sub-RQ 1). The findings from the literature review, especially those related to modeling requirements, are first applied to a case study of the hypothetical Waas Delta (sub-RQ 2) and next to a more realistic case study of adaptation planning in the upper Vietnam Mekong Delta (VMD; sub-RQ 3). The VMD case study will be further used for sub-RQ 4 and 5. Last, exploratory modeling methods are central for investigating the last two sub-RQs, as these questions are concerned with evaluating outcomes under a multitude of circumstances (i.e., policies, uncertainties, and ethical principles).

1.3.1. Literature review

The first sub-RQ will be approached by doing a systematic literature review on two bodies of literature: (i) climate ethics and distributive justice, and (ii) model-based support tools for planning for climate change. A snowballing approach to literature review will be followed, where one starts with seminal literature on climate ethics and distributive justice followed by looking for more recent theoretical works on these topics. Results from literature review on climate ethics and distributive justice will be used to construct requirements that a model should meet in order to be able to enable the assessment of distributional impacts. Next, recent studies on model-based support for planning for climate change are reviewed. A literature gap analysis will then be conducted, where the extent to which these requirements are fulfilled in the recent studies is evaluated. Finally, remaining research gaps are highlighted for future studies.

1.3.2. The hypothetical Waas Delta and Integrated Assessment Metamodel

To understand the implications of incorporating some of the equity requirements constructed from sub-RQ 1, a case study of the hypothetical Waas river will be used (Haasnoot et al., 2012). This case study is a model-based delta planning study where the performance of alternative adaptation policies, mainly targeted at reducing flood risk, is evaluated as a part of developing adaptation pathways. The main motivation to use this case study is the readily available model to be further extended to comply with some of the equity requirements. Furthermore, this case study has previously been used for testing new computational methods for model-based long-term delta planning (Haasnoot et al., 2012; Kwakkel et al., 2015, 2016; Manocha and Babovic, 2017; McPhail et al., 2018).

The Waas case study uses a simulation model to test the efficacy of alternative policies. The model simulates flood events due to dike overtopping and/or breaching and their economic impacts based on the land-use types that they hit (Haasnoot et al., 2012). In addition, the model calculates the side effects of alternative policies to economic activities on the river (ship accessibility based on river depth) and to ecology (ecotope-/ecozone-based diversity index depending on flood extent and duration). The model follows a theory-informed metamodeling approach, where complex physical relationships between system variables are simplified either through what-if cause-effect relations or through statistical relations (Davis and Bigelow, 2003; Holzkämper et al., 2012; Razavi et al., 2012). This modelling approach has been deemed to be suitable for case studies which intention is not to predict, but to explore the efficacy of alternative adaptation policies under a wide range of uncertain futures (Haasnoot et al., 2014; Hamilton et al., 2015; Lempert et al., 2003).

The impact assessment metamodel (IAMM) from the original Waas case study will be extended with a behavioral land-use change module. This module will simulate land-use change responses of people within the study area to flood events. This module will follow a utility-based suitability framework (Hilferink and Rietveld, 1999; Koomen et al., 2015). In this framework, land-use decisions for each grid cell on the system are determined based on the land-use class that has the highest utility for that grid. The utility of a grid cell for each land-use type is calculated based on the local suitability of that cell, which is a combination of the neighborhood influence of the surrounding cells, physical properties (e.g., soil fertility, average rainfall), policy constraints (e.g., zoning restriction), and accessibility functions (e.g. distance to main roads).

The integration of the land-use change module to the IAMM will be done in a loosely-coupled and bidirectional manner (Antle et al., 2001; Harvey et al., 2019). An integrated model is categorised as loosely coupled when the coupling is done between two or more stand-alone (sub-)models (or modules) that can be run independently without the presence of the other (sub-)models. Conceptually, the state variables of one (sub-)model become the input vector for the other (sub-)models. Hence, the coupling involves states and time integration between the (sub-)models as schematized in Figure 1.1. The bidirectional nature implies that the state exchange happens in two directions. That is, each (sub-)model acts both as sender and receiver of state variables.

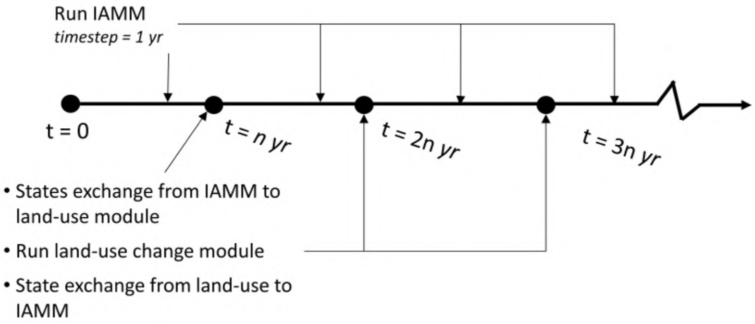

Figure 1.1: Conceptual scheme of state and time integration

1.3.3. Adaptation planning in the Vietnam Mekong Delta

The last three sub-research questions will be addressed using adaptation planning for rice farming in the upper VMD as a case study (see Figure 1.2). The VMD is the main rice producer in Vietnam as it supplies more than half of the country's rice commodity (GSO, 2019; Toan, 2014). Due to increasing salt intrusion downstream, rice production activities are mainly carried out in the upstream and middle part of the delta. The case study will therefore focus on Dong Thap and An Giang, two provinces in the upstream part of the delta. Approximately 75% of land in these two provinces are being used for rice farming activities (GAEN-View, 2013). Across several regional development scenarios in the future, these provinces are expected to still function as the main rice production machinery (Mekong Delta Plan Consortium, 2013).

Rice farmers used to harvest their crops twice a year (one after the monsoon season and one before the monsoon season), and they let their paddy fields inundated during the monsoon season. The construction of high dikes since the early 2000s has allowed farmers to harvest an additional crop in a year. However, it is recently found that this construction raises equity issues as it harms small scale farmers (Chapman and Darby,

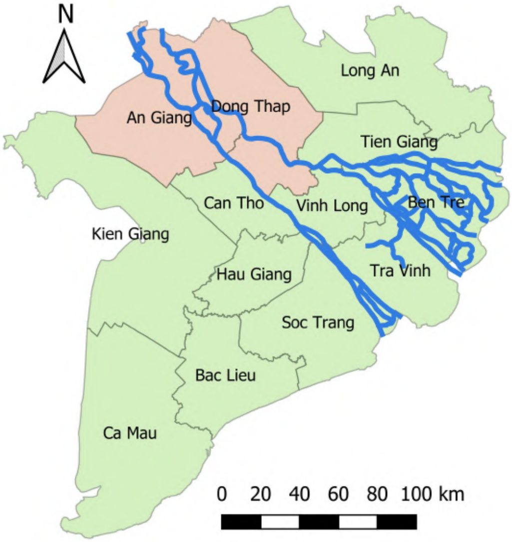

Figure 1.2: Provinces in the Vietnam Mekong Delta. The main branches of the Mekong river are plotted as blue lines. The case study in this thesis takes place in An Giang and Dong Thap (highlighted in red)

2016; Tran et al., 2018b). Furthermore, future climate change is expected to increase flood risk in the future while at the same time intensifies extreme drought (Dang et al., 2020; Tan Yen et al., 2019; Triet et al., 2020). Increasing flood risk is exacerbated by a high rate of land subsidence, among which is attributed to excessive groundwater extraction and drop in surface water table (Erban et al., 2014; Minderhoud et al., 2018). Future pressure on the agriculture sector is further amplified by hydropower dam construction upstream in Cambodia that reduces fertile sediment supply entering the VMD (Lauri et al., 2012; Manh et al., 2015).

There are three reasons why the VMD is suitable as a case study. First, recent studies have highlighted the existence of equity issues in agricultural adaptation planning in this area, making this area an interesting case study to look at (Chapman and Darby, 2016; Tran et al., 2018b; Triet et al., 2017, 2020). Second, these past studies are unfortunately lacking either the spatially explicit dynamics relevant for equity considerations or the multi-sectoral interactions that give rise to equity issues. This fact allows this thesis to make a significant contribution to the sparse literature on model-based adaptation planning in the area. Third, past studies on this topic consider only a narrow range of uncertain future (mainly focusing only on river discharge scenarios), despite the fact that ample research has emphasized the growing relevance of multiple drivers of future risks to agricultural livelihoods. Many past studies also only consider a relatively narrow set of policy alternatives (mainly focusing only on dikes construction). But even then, these studies already indicate the high sensitivity of the distributional outcomes to policy and uncertainty scenarios (Chapman and Darby, 2016; Triet et al., 2017, 2018, 2020). This fact motivates this research to look at the distributional outcomes of a wider set of policy options under a wider range of uncertain future.

1.3.4. Exploratory modeling

Exploratory modeling is a research methodology that uses computational experiments to analyze and understand complex systems under the influence of uncertainties (Moallemi et al., 2020; Bankes, 1993; Bankes et al., 2013). Through testing how an ensemble of plausible futures influences the outcomes of complex systems, exploratory modeling can help identify scenarios or conditions that are of interest for a specific planning problem. The method of scenario discovery is used for this purpose. Scenario discovery is a method to find policy-relevant scenarios (e.g., scenarios under which a policy fails to meet its goal) using various statistical data mining techniques (Bryant and Lempert, 2010; Groves and Lempert, 2007). Exploratory modeling methodology in general and scenario discovery in particular are especially relevant when the system under study is subject to deep uncertainties, i.e., conditions under which probability distribution of external variables is unknown, structural relationships between system variables are unknown, and goals between different stakeholders are conflicting (Walker et al., 2013b; Lempert et al., 2003; Marchau et al., 2019).

This research adopts the exploratory modeling methodology in order to understand how future distributional impacts are influenced not only by adaptation policies, but also by the unfolding uncertain scenarios. For sub-RQ 4, this research will further tailor the method of multiclass scenario discovery to allow for unraveling spatial inequality patterns among rice farmers in the upper VMD. Multiclass scenario discovery is an extension of the standard scenario discovery technique, where model outcomes are classified into more than just two categories (Gerst et al., 2013; Kwakkel and Jaxa-Rozen, 2016; Steinmann et al., 2020). In sub-RQ 5, the impact of normative uncertainties (in terms of socially-acceptable distributive moral principles) as well as climatic and socioeconomic uncertainties on the preference rankings of alternative policies will be evaluated.

1.4. Outline of the thesis

Each sub-research question outlined above is addressed in a separate chapter that is taken from journal papers written for that corresponding question (see Figure 1.3). Chapter 2 outlines the requirements that a model should have in order to be able to systematically incorporate distributive justice assessment in supporting inclusive planning for climate change. Chapter 3 presents the proof-of-concept case study on integrating land-use change dynamics in an integrated assessment metamodel used for supporting delta adaptation planning, which is an important element for improving the evaluation of distributive justice through the use of quantitative models. The next three chapters make use of the VMD case study. Chapter 4 shows how distributional outcomes in terms of farm profitability are jointly affected by policies and uncertainties. It uses a similar modeling paradigm as the proof-of-concept study in Chapter 3, where biophysical impact assessment modules are coupled with a land-use change module. Chapter 5 proposes and compares two multiclass scenario discovery approaches to explore plausible distributional patterns under deep uncertainty. Chapter 6 explores the impacts and the merits of using several distributive moral principles in assessing the preference ranking of alternative adaptation policies. Finally, all research questions are revisited in Chapter 7. Further, future academic reflection and recommendations for practice are outlined in Chapter 7.

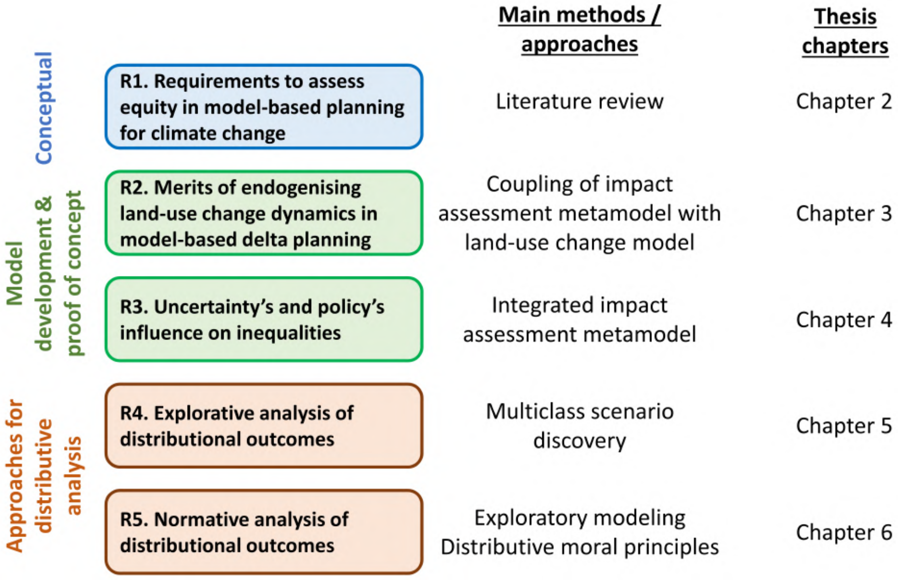

Figure 1.3: Overall setup of the dissertation

2

Enabling assessment of distributive justice through models for climate change planning: a review of recent advances and a research agenda

2.1. Introduction

Due to the complexity of climate planning and the presence of uncertainties, understanding the implications of alternative policies under different futures is becoming increasingly relevant to policy makers. Numerical models, mostly in the form of Integrated Assessment Models (IAMs), are among the most commonly used tools for this purpose (Patt et al., 2010; Sarofim and Reilly, 2011). Recent IPCC reports show that the evaluation of adaptation and mitigation policies through IAMs is often done from an aggregated perspective (Kolstad et al., 2014). Models aggregate costs and benefits of policies across an entire area, over all actors, and over the entire planning horizon. The reliance on this aggregated perspective is seen as one of the deficiencies of using IAMs (Stanton et al., 2009), because it obfuscates the distribution of burdens and benefits for different actors across different time and space. This gives rise to an inherent problem of justice; while a plan might be beneficial in the aggregate, its distribution of benefits and costs can give rise to injustices. These injustices, especially when not identified and accounted for in public policy, could give rise to contestations resulting in policy

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This chapter is based on: Jafino, B. A., Kwakkel, J. H., & Taebi, B. (2021). Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. Wiley Interdisciplinary Reviews: Climate Change, 12(4), e721. doi:10.1002/wcc.721.

deadlocks (Klinsky et al., 2017; Pesch et al., 2017).

There are several reasons why justice is crucial in planning for climate change. First, the physical processes of climate change vary in space and time and have different impacts on different people (Green, 2016). Second, people's vulnerability to these impacts, their capacity to adapt, and their historical contribution to climate change are often unequally distributed (Füssel, 2010a; Thomas et al., 2019). Third, options for mitigation and adaptation to climate change are likely to unevenly affect different groups, giving rise to unjust distributions of costs and benefits, and sometimes even exacerbating existing injustices (Atteridge and Remling, 2018). Fourth, power inequalities between the well-off and worse-off groups in society tend to favor allocation of more resources to the well-off at the expense of the worse-off; this could reinforce the previous three instances of injustice (Thomas and Warner, 2019). As a result, researchers have turned to theories of justice in order to address these concerns in climate change planning.

IAMs can be better equipped to address justice concerns in climate change planning, especially in assessing the distributional outcomes of alternative policies. There are already some examples of model-based studies that allow for ad-hoc justice evaluation in recent years (see e.g., Aerts et al., 2018b; Ciullo et al., 2020; Gold et al., 2019; Li et al., 2018; Van Ruijven et al., 2015). For example, in the agricultural sector, Thornton et al. (2010) simulate the distributional impacts of climate change on agricultural productivity in East Africa in order to identify winners and losers among countries. In the electricity sector, Rao (2013) evaluates the distributional impacts of low-carbon electric supply expansion in India, especially by comparing the trade-offs between overall welfare gains and income inequality among households from different income groups. These examples exemplify the partial efforts to incorporate justice in IAMs. Each study focuses on a specific aspect of justice, operationalizes it, and develops a model in light of this specific aspect. Consequently, the way justice is addressed in these studies is case specific and not directly transferable to other cases and contexts. A systematic understanding of how to facilitate the evaluation of justice in climate mitigation and adaptation policies through the use of IAMs, based on theories of justice, is currently missing.

In this paper, we contribute to the development of a systematic understanding of how IAMs can be used to facilitate the evaluation of justice in planning for climate change, especially by considering the potential injustices that aggregation gives rise to. Within the climate justice literature, it is common to make a distinction between distributive and procedural justice (Gardiner, 2010; Wood et al., 2018). Distributive justice is concerned with how outcomes are distributed across people and whether a distribution is morally acceptable (Konow, 2001; Vermunt and Törnblom, 1996). Procedural justice is concerned with fairness in and legitimacy of planning and decision-making processes (Okereke, 2010; Törnblom and Vermunt, 1999). Since we are focusing on how the results produced by IAMs can foster the evaluation of the distributional outcomes of mitigation and adaptation policies, in the remainder we will only consider distributive justice issues.

IAMs come in many guises, are used for many different purposes, and for a wide variety of decision making and planning problems at different levels of government. To help structure the wide variety of IAMs used in practice, various classifications have been proposed (Beck and Krueger, 2016; Füssel, 2010b; Kelly et al., 2013; Stanton et al., 2009). Based on the models' purposes, IAMs can be categorized into those focusing on mitigation, adaptation, and impacts assessment. Based on the way in which policies are assessed, IAMs are categorized into optimization and simulation models, although in recent years there is a growing interesting in simulation-optimization IAMs as well (Dittrich et al., 2016; Moallemi et al., 2020). While optimization-based IAMs are normally used in mitigation planning, simulation-based IAMs are more often used in adaptation planning. IAMs can also be categorized based on their geographical scope, ranging from the global to local level. Rather than focusing on a specific type of IAM (e.g., based on purpose, how policies are assessed, or the geographical scope), our discussion on model-supported justice assessment is generic enough to be applicable to a broad range of IAMs. In the remainder of this paper, we use the term IAM to refer to models used for supporting planning and decision-making for climate change adaptation and mitigation.

Our study comprises three steps. First, by systematically identifying ethical imperatives from conceptions of intra- and intergenerational distributive justice, we propose modeling requirements for enabling evaluation of distributive justice in alternative policies by using IAMs. Given that there are multiplicity of justice principles (e.g., equality, fairness, equity) that are relevant in different contexts (Van Hootegem et al., 2020); our intention is not to build preferences toward particular principles of justice, but rather facilitating, enabling and accommodating justice debates on the basis of model-based analyses. Therefore, the systematic requirements we present in this paper are a starting point, rather than an ultimate list, for improving the assessment of distributive justice in climate change planning through the use of model-based support tools. Second, we review recent attempts at meeting these requirements. Third, we propose a research agenda based on those requirements on which advances so far have been limited.

2.2. Justice in climate change

Theories of justice are rooted in ethics and political philosophy (Kolstad et al., 2014; Kymlicka, 2002). Justice in climate change was initially raised in the context of responsibilities for greenhouse gas (GHG) reductions. These responsibilities could be based on countries' past emissions (based on the principle of 'you-broke-it-you-fix-it'), their ability to bear mitigation cost (i.e., capacity determines responsibility) but also future forecasts of GHG emissions (Okereke, 2010; Posner and Weisbach, 2010; Singer, 2002). Recent debates have broadened the domain of climate justice to issues pertaining to equity measurement of adaptation success, distribution of funding and resources for adaptation, and trade-offs between mitigation and adaptation (Byskov et al., 2019; Gardiner, 2010; Grasso, 2007; Klinsky et al., 2017; Paavola and Adger, 2006; Pelling and Garschagen, 2019). Discussions about justice are usually divided into two main categories of procedural and distributive justice. Procedural justice is about the conditions under which a decision has been reached and it is concerned with fairness in planning and decision making processes (Törnblom and Vermunt, 1999). In a climate change context, procedural justice is often measured by the degree of recognition, participation, and transparency in the decision making process (Schlosberg, 2009). Distributive justice refers to the benefits and risks of activities and how those have been distributed (Caney, 2005; Konow, 2001). Indeed, procedural justice is important in climate change decision-making, both at the international level and within a country. Furthermore, procedural and distributive justice are somewhat connected. That is, power inequalities could result in an unfair allocation of resources and give rise to inequalities and exacerbate the existing inequalities (Thomas et al., 2019; Thomas and Warner, 2019). As we mentioned in the introduction, this is one of the reasons that justice needs to be explicitly addressed in climate planning. However, since the focus of the current paper is on how the results produced by IAMs can affect the distributions of burdens and benefits (and how to evaluate the ensuing justice issues), we will only consider distributive justice here. Procedural justice matters in our argument, in so far as it affects distributive issues, as they will be reflected in the IAMs.

The central goal of distributive justice is to ensure that risks and benefits are distributed in a just manner. There are three central questions in distributive justice, namely what is the shape, unit, and scope of distribution (Bell, 2004; Page, 2007). In other words, which patterns of distribution do we prefer (shape), what is it that is being distributed (unit) and to whom does this distribution relate (scope). Regarding the shape, different distributional principles could be followed (Konow, 2003). A utilitarian principle, for instance, would prescribe a distribution that could maximize the utility of all, while a Rawlsian model of distribution would aim to help the least well off (Taebi, 2019). The unit question, or the question as to what it is that we wish to distribute, could be answered in different ways too. Models often discuss the distribution of some kind of value, such as economic, values, biodiversity, social values or welfare. Indeed, a fair distribution of negative outcomes such as vulnerabilities are also important. Both the shape and the unit questions become more complex when we consider the question of scope or, to whom this distribution relates, both in the spatial (intra-generational) and temporal (intergenerational) sense. This becomes particularly intricate when we need to consider temporal distribution and the associated intergener-

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This paragraph is partially drawing on Taebi (2019) pp.69-70.

ational justice questions. What is it that we can pass on to future generations, to which future generations do we pass on these units, and what is the moral justification for that (Campos, 2018; Kermisch and Taebi, 2017; Page, 1999).

IAMs often focus on the aggregation of the outcome, either in a mathematical optimization form, or as utility aggregation of all actors across the entire time horizon (Beck and Krueger, 2016; Kolstad et al., 2014). This view in modeling, and more generally in the assessment of public policies, stems from consequentialist ethics. According to consequentialist theories, one should assess whether good consequences of an action outweigh the bad ones. Utilitarianism, a specific form of consequentialism, is most influential in public policy (Meinard and Tsoukiàs, 2019; Posner, 1979). Utilitarians aggregate positive and negative consequences in their calculus and they assess the rightness of an action in terms of whether it manages to maximize utility. The aim of the modelling exercise is then to look for alternative policies that maximize this aggregated utility. For two reasons, utilitarianism is highly influential in assessing public policy (Dennig, 2017; Thaler and Hartmann, 2016): it focuses on the aggregate outcome for everybody, and it is based on the premise of fundamental equality in that everybody counts for one and no more than one in the calculations. The utilitarian calculus is blind to people's standing, status, income, race, etc.; it presumes a similar utility function (i.e., value judgements about welfare changes associated with changes in income (or other indicators)) for all individuals. Ironically, it is the same fundamental equality principle that causes a blind spot for utilitarianism. That is, the distributions of burdens and benefits are not accounted for; all that matters for the evaluation is the aggregation of total outcomes.

Distributive justice matters to IAMs in the spatial and temporal sense. Temporally speaking, we need to consider what levels of burdens and benefits are being projected into the future (and which futures); this is called intergenerational justice. This involves, among others, determining the level of preference given to impacts occurring in the far future, relative to those occurring in the present time or the near future. In climate change planning, this is typically done through discounting methods (Caney, 2009; Fleurbaey et al., 2014). Most studies related to intergenerational justice in policy appraisal investigate what the appropriate discount rate are, taking into account the societal and ethical aspects of decisions (Broome, 1992; Davidson, 2015; Heilmann, 2017).

Spatially speaking, it is important to understand how burdens and benefits are being distributed among the currently living generation; this is referred to as intragenerational justice. It distinguishes the subjects of distribution based on their attributes, for instance in how each country contributes to international mitigation efforts (Grubb, 1995; Heyward, 2007). Intra-generational justice has been at the heart of the developments of the Kyoto Protocol and the underlying United Nations Framework Convention on Climate Change. Intra-generational justice partitions a population based on either their economic conditions (e.g., poor, middle, and rich income households (Krey, 2014; Sayers et al., 2018)), locations (e.g., between different cities in a region (Trindade et al., 2017)), social background (e.g., between men and women in the northern and southern hemisphere (Arora-Jonsson, 2011)), or means of economic livelihoods (e.g., between rice farmers, fruit farmers, and vegetable farmers in the Vietnam Mekong Delta (Smajgl et al., 2015)).

2.3. Requirements for incorporating justice in model-based climate planning

We develop requirements to enabling justice reasoning in model-based support for climate adaptation and mitigation planning. We systematically derive the requirements by identifying ethical imperatives from the three elements of distributive justice, referring to the unit, scope or shape of the distribution. In the context of model-based planning for climate change, a first critical step is to clearly delineate the people that might be affected by the alternative policies (i.e., the scope). Once they have been clearly identified, a subsequent step is to consider the values that they uphold that might be affected by the policies (i.e., the unit) and to determine an appropriate distribution of these values across the people (i.e., the shape). We therefore take the scope of the distribution as our point of departure. We specifically start from theories on intra-generational and intergenerational justice.

We use the XLRM framework (see Figure 2.1), a commonly used framework for structuring information in model-based decision support (Kwakkel, 2017; Lempert et al., 2003), to derive the requirements. The XLRM framework consists of four elements. The first element is the external factors ('X'). These are mainly uncertainties that affect the system but are outside the control of policy makers. The policy levers ('L') are interventions, in our case mitigation and adaptation policies, to be evaluated by the model. The relationships in the system ('R') refer to model structure and features. The performance metrics ('M') are outcome variables to be observed. We propose ethical imperatives, based on intra- and intergenerational justice, for elements within the XLRM framework. Based on the ethical imperatives, we derive eleven requirements to allow for justice evaluation as summarized in Table 2.1. Note that that these requirements operate on individual models. In practice, there might be flow of justice assumptions from one model to another; for instance, when some of the inputs to a given model are derived from the results of other models. In the subsequent subsections, we organize the discussion by first presenting requirements related to intra-generational justice (requirement 1.1-1.3, 2.1, 3.1, and 4.1) and then requirements related to intergenerational justice (requirement 1.4-1.5, 2.2, 3.2, and 4.2).

Table 2.1: Requirements to enable the evaluation of distributive justice in model-based support for climate planning

Domains of justice in IAMs	Dimensions of Justice	Ethical imperatives	Requirements	Extensiveness of application / discussion in literature
Performance metrics / indicators (M)	Intra-generational	Fair representation of actors (including acknowledgement of differentiated capacity, historical burdens and responsibility, values, and behavior) and fair assessment of distribution of outcomes	1.1 Actor-based disaggregated metrics	Many IAMs have considered this.
			1.2 Value-based disaggregated metrics	Some domain specific IAMs (such as flood risk management) still focus only on one value. Some IAMs (such as nexus-based study) have considered multiple values.
			1.3 Post-processing of actor- and value-based metrics to account for distributive principles	State-of-the-art approaches for this are found only in a very limited number of studies.
	Intergenerational		1.4 Time-series metrics	Most model-based climate planning have considered multi-temporal dimension, and thus time-series metrics.
			1.5 Post-processing of time-series metrics to account for distributive principles	Discounting method based on the Ramsey's equation is widely adopted. Attempts to use other discounting alternatives are very limited.
Relationships in the system / model structure (R)	Intra-generational		2.1 Disaggregated representation of actors and values	Many IAMs have attempted in having a more disaggregated representation of the system.
	Intergenerational		2.2 Multi-temporal dimension	Most model-based climate planning have considered multi-temporal dimension, some domain specific models are not multi-temporal.

Policy levers (L)	Intra-generational	Differentiated social vulnerability	3.1 Actor-differentiated policies	Still fairly limited. Policies are usually targeted to all actors.
	Intergenerational	Freedom of choice	3.2 Assessing changes in policy space over time	Still fairly limited. Policy space is assumed to be unchanged for the entire planning horizon. Lock-ins and path dependency are often neglected.
Exogenous uncertainties (X)	Intra-generational	Transparency of justice preferences	4.1 Using different distributive moral principles to account for normative uncertainties	Very limited. Utilitarian is often implicitly assumed. Few studies explicitly state this assumption and test the implications of adopting different principles.
	Intergenerational	Fair representation of actors	4.2 Exploring plausible uncertain changes in actors' behaviors and preferences/-values	Very limited. Actors behaviors and preferences are assumed to be static over time.

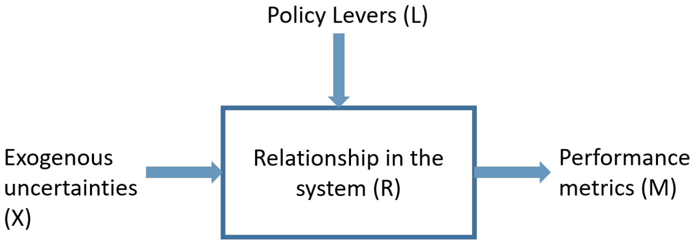
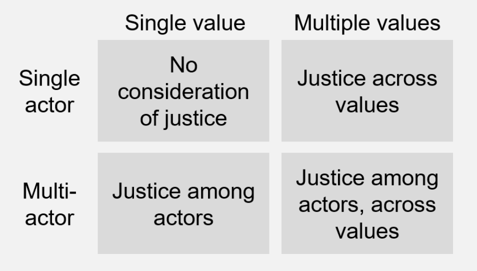


Figure 2.1: The XLRM framework for model-based policy analysis

2.3.1. Requirements from intra-generational justice

Accounting for intra-generational justice means acknowledging all actors who are affected by the climate planning problem as well as the existing injustice among them, and assessing the distribution of impacts between them on the basis of fairness. To realize these imperatives, one has to first understand the properties of the climate planning problem for which the model is being used. We propose two properties as relevant. The first property relates to a typology of actor representation as illustrated in Figure 2.2. The ethical imperative of fair representation of actors implies that the model structure of IAMs should allow for justice assessment among values, i.e., the unit of the distribution (requirement 1.2, e.g., balance between impacts to economic and environment) and assessment of the distribution of these values between actors, i.e., the scope of the distribution (requirement 1.1, e.g., economics performance across different districts). Some IAMs, however, combine diverse actors into a single representative agent and consider only a single value. Such model structures can be found in many IAM categories ranging from optimization-based IAMs for global mitigation (de Bruin et al., 2009; Nordhaus and Boyer, 2000) to simulation-based IAMs for local adaptation (Gohari et al., 2017; Hidayatno et al., 2017). In other studies, multiple actors are already explicitly represented and multiple values are also evaluated (Conway et al., 2015; Manne and Richels, 2005).



	Single value	Multiple values
Single actor	No consideration of justice	Justice across values
Multi-actor	Justice among actors	Justice among actors, across values

Figure 2.2: Typology of actor representation in model-based support for climate planning

The second property of climate planning problems relates to how policies are designed and evaluated. Broadly speaking, there are two approaches (Beck and Krueger, 2016; Herman et al., 2015): having a set of pre-specified alternative policies or using optimization to design policies. The way in which policies are generated affects how the distribution of outcomes is treated (requirement 1.3). If policies are pre-specified, which is the case for most simulation-based IAMs, the function of IAMs is to rank policies based on their performance. Accordingly, evaluation of justice can only be performed a posteriori, i.e., after the performance of the policies has been calculated. This requires post-processing of performance metrics, either by aggregating them into a single composite indicator (Chung and Lee, 2009; Luis et al., 2019), or by keeping them separate and evaluating trade-offs among them (Garner et al., 2016; Haasnoot et al., 2012). If policies are found through optimization, evaluation of justice can be included not only a posteriori, but also a priori in how the optimization problem is formulated (Ciullo et al., 2020; Gourevitch et al., 2020; Wild et al., 2019).

Explicitly specifying performance metrics for multiple actors and for diverse values implies two additional requirements (both encapsulated in requirement 2.1). First, in order to ensure a just representation of actors, one has to understand the heterogeneity of actors' background and behaviors, and accordingly represent this heterogeneity in the model. For instance, in models used to support adaptation planning for farmers, one has to specify the economic (e.g., small-, medium-, or large-scale) and social background (e.g., traditional and risk-averse, or modern and risk-taker) of the farmers, and identify the heterogeneity of the farmers' behaviors depending on their background. Accounting for heterogeneity is also useful for addressing corrective and compensatory justice (Ikeme, 2003; Page and Heyward, 2016), for instance by incorporating historical emission accountability or harm already done by climate impacts, although efforts to do so are only recently growing (Schinko et al., 2019). The second requirement is that the model has to be able to quantify the diverse values that the different actors cherish (e.g., economic, biodiversity, and social). This entails including multiple subsystems and hence the corresponding cross-sectoral interactions between them (Harrison et al., 2016; Verburg et al., 2016).

The design and evaluation procedure of alternative policies induces two further requirements. The first requirement is related to the subject of the policies (requirement 3.1). A policy can be designed to target either all actors simultaneously (García-Muros et al., 2017) or only some specific actors (Fell and Linn, 2013; Mérel and Wimberger, 2012). From a justice point of view, as is the case in the broader climate justice discussion (Grasso, 2010b), it is imperative to treat each actor differently based on his/her capability and vulnerability, and (historical) injustices among them. However, from a model-based policy analysis point of view, actor-specific policies and optimization for individual actors could lead to unintended consequences where a policy applied to one actor induces detrimental impacts to other actors (Ciullo et al., 2019; Fowlie and Muller, 2013).

The second requirement is related to the reflection on the distributive moral principles, i.e., the shape of the distribution, used to assess the distribution of the disaggregated metrics (requirement 4.1). When aggregating multiple performance metrics, or embedding them in an optimization problem, certain moral principles are (implicitly) used, such as utilitarian-based maximization of overall welfare (Eijgenraam et al., 2016; Sáez and Requena, 2007), egalitarian-based equalization of costs and benefits to all actors (Ciullo et al., 2020), or Rawls' difference principle of improvement for the least well-off (Dennig et al., 2015; Gold et al., 2019; Gourevitch et al., 2020). The implicit adoption of a moral principle conceals the social justice preferences of the modelers and thus reduces the transparency of the model. Furthermore, social justice preferences are specific in space, time, and contexts (Bell, 1993; Lau et al., 2021; Van Hootegem et al., 2020).

The diversity of moral principles can become a source of contestation among stakeholders (Hulme, 2009; Okereke, 2010). This is particularly evident in studies that use IAMs for supporting mitigation planning. Here, the choice of the guiding principles in allocating mitigation budgets and in calculating aggregate welfare strongly affects the distributional outcomes across nations (Adler et al., 2017; Höhne et al., 2014; Peters et al., 2015; Robiou du Pont et al., 2017). Shifting from people-based equity allocation to 'blended' sharing principles, for instance, implies a reduction of the required mitigation rate by around 60% for North American countries, while increasing it by almost 50% for African countries (Raupach et al., 2014). In this domain, the arbitrary use of certain distributive principles without proper ethical justification has been criticized (Kartha et al., 2018). The diverse preferences of moral principles are also a manifestation of ethical uncertainty, as different moral principles illuminate different ethical issues at stake (Taebi et al., 2020). Hence, it is useful to simultaneously explore multiple moral principles when comparing alternative policies.

2.3.2. Requirements from intergenerational justice

We identify five requirements grounded in intergenerational justice. The first two requirements are rooted in the imperatives of the fair representation of future generations and the fair assessment of the distribution of impacts on them, as well as fair accounting of past injustices to address corrective and compensatory justice. The two requirements are the disaggregation of performance metrics across time and the post-processing of such time-series metrics (requirement 1.4 and 1.5). Discounting methods are often used to aggregate time-series metrics by weighing impacts that occur in the future in comparison to impacts that occur now (Heal, 1997).

As for the third requirement, in order to output time-series metrics, the model needs to have a temporal dimension, so that impacts can be observed over time (requirement 2.2). Many climate mitigation IAMs on global and national scales are already multi-temporal in nature (Nordhaus and Boyer, 2000; Popp, 2004; Stehfest et al., 2014). Conversely, many simulation-based IAMs for local scale adaptation, such as those in the domains of flood risk management (Hsu et al., 2011; Triet et al., 2018) and agricultural management (Audsley et al., 2008; Münier et al., 2004), are often not multi-temporal. This does not necessarily mean that they cannot be used for calculating impacts across time. Such models can be run in a multi-temporal fashion. For instance, an inundation model can be run for multiple points in time in the future so that the model can still produce intertemporal outcomes.

The fourth requirement relates to policy lock-ins and lock-outs and how this reduces the set of possible policies available to future generations (requirement 3.2). This requirement stems from a moral duty to promote intergenerational freedom of choices, i.e., preserving the range of choices that future generations would still have to pursue a good life (Barry, 1997; Karnein, 2015). In climate change planning, the choice of implementing certain interventions at a particular point in time in combination with the unfolding exogenous changes may create lock-ins that prevent the execution of other interventions in the future (Haasnoot et al., 2020; Savini et al., 2015). Furthermore, some policies such as infrastructure development, are largely irreversible, although the degree to which irreversibility is acceptable is subject to ethical questions (Barry, 1997). Model-based support for climate planning often focuses solely on the outcomes calculated by the model while disregarding the potential lock-ins arising from those actions (Haasnoot et al., 2019). On an abstract level, it is worth noting that value judgements still need to be made in determining how much and what kind of freedom we should leave for future generations.

The fifth requirement arises from the fact that we do not know the values that future generations will uphold. Hence, in order to have a fair representation of future generations, we need to explore plausible value changes (requirements 4.2). As argued by Padilla (2002) and Taebi et al. (2020), accounting for intergenerational justice requires one to acknowledge that the values of the current generation cannot simply be assumed to also hold for future generations. Furthermore, the values that people uphold in turn influence how they behave under different circumstances (Ajzen, 1991). For example, if we look at the evolution of water management practices in the Dutch delta, we see that in the early 20th century flood safety was the sole objective. This started to change in late 1960s, when ecological damages resulting from dams closing made environmental concerns an additional objective of the water management (Correljé and Broekhans, 2015). In addition to uncertainties pertaining social aims of future generations, there also exists uncertainties in what distributive principles future generations will prefer – coined as evolutionary normative uncertainties (Taebi et al., 2020).

2.4. Recent practices in incorporating justice in model-based climate planning

In this section we review the degree to which the various requirements are being addressed in recent model-based climate planning studies. We conducted the review by looking at how recent IAMs from various scales, domains, purposes, and use-cases are meeting the requirements. We complemented this with requirements-specific keywords search, such as 'discounting' for the post-processing of time series metrics requirement (requirement 1.5), in order to find seminal publications. We then applied a snowball literature review approach starting from the seminal publications. Requirements related to performance metrics ('M' in Table 2.1) and model structure ('R' in Table 2.1) are increasingly being met.

2.4.1. Disaggregation of performance metrics and systems representation

Requirements 1.1, 1.2, and 2.1 relate to the disaggregation of actors and values. One of the earliest efforts to disaggregate the representative agent assumption is in IAMs used for cost-benefit analysis in mitigation planning. The RICE model modifies the DICE model by dividing the world into ten different regions (Nordhaus and Yang, 1996). This study was controversial as it revealed that high-income countries would be the main losers from cooperative policies. Later, it was found that this emerged because RICE was using the same diminishing marginal returns to income for all regions (Aronsson et al., 2010; Stanton, 2011). This makes shifting income from richer regions to poorer ones a preferable policy, as this increases total welfare. Furthermore, spatial disaggregation of actors in global IAMs also entail formulating regionally differentiated climate damage functions (Diaz and Moore, 2017; Nordhaus, 2014), the use of which is still subject to ethical criticisms (Pezzey, 2019; Pindyck, 2017). This illustrates the non-triviality of disaggregating the representation of actors within a model.

Twenty years after the RICE study, the importance of disaggregating performance metrics and actor representation is again emphasized by IAMs in various categories. In the local adaptation domain, Aerts et al. (2018b) distinguish agents in flood risk assessment based on their economic, social, geographic, and cultural background. Such distinctions are important for assessing distributional impacts as well as having a better representation of people's behavior to flood risk. To represent values heterogeneity, a regional adaptation simulation model developed by Harrison et al. (2016) explicitly considers cross-sectoral interactions between different domains in order to calculate 14 metrics of climate impacts on different values a society cherishes. The system dynamics modeling formalism has also been widely used for such multi-value analysis both for global mitigation and local adaptation purposes (Agusdinata, 2008; D'Alessandro et al., 2020; Walsh et al., 2017), especially due to the straightforwardness of constructing feedbacks among distinctive variables (Akhtar et al., 2013; Kelly et al., 2013). A systems-of-systems and coupled components modeling framework has also been proposed for accounting for multi-value multi-sector studies (Little et al., 2019). Red flags about such a framework, however, have been raised due to the potential technical and conceptual misalignments when one starts to couple models from different paradigms (Voinov and Shugart, 2013).

Rao et al. (2017) summarize the challenge of disaggregation of system representation and performance metrics, with a focus on IAMs used for supporting mitigation planning. They discuss state of the art practices for such disaggregation and future research directions to improve model outputs and model features. In line with the requirements proposed in this study, they suggest that in the future, outputs of models used for supporting climate change planning should consider multi-dimensional indicators and distributional impacts. To realize this, the model structure should reflect heterogeneity of household groups and sectoral impacts.

2.4.2. Post-processing for intra-generational justice

Disaggregating performance metrics results in a substantially higher number of metrics to be evaluated. There are two approaches for appraising high dimensional model outputs (requirement 1.3): calculating composite indicators or keeping the metrics separate. The first approach imposes an aggregation function on multiple performance metrics in order to transform them into a single overarching metric (Sikdar, 2009). Aggregation functions derived from welfare theory, so called social welfare functions (SWFs), are often used especially in IAMs for mitigation planning and burden sharing (Adler et al., 2017; Botzen and van den Bergh, 2014; Fankhauser et al., 1997). One of the most widely used SWFs is the utilitarian welfare function (Millner, 2013). This is an additive function where one performs linear aggregation across the utility of all individuals. Other SWFs, such as the Bernoulli-Nash (Cobb-Douglas) welfare function, have a multiplicative property instead.

It has been argued that both the utilitarian and Bernoulli-Nash SWFs neglect equity and fairness, as they aim to maximize the total welfare while ignoring its distribution (Tol, 2001; Tol et al., 2004). Equity weighting functions have been proposed to overcome this limitation (Anthoff et al., 2009; Hope, 2008). An example of an equity weighting SWF is the Negishi welfare function (Stanton, 2011), which attaches equity weights to individuals inversely proportional to their marginal utility of consumption. Adler et al. (2017) introduce the prioritarian SWF, where the original utility of individuals is transformed using a strictly increasing and concave function, thus giving more weight to the increase in utility of worse-off individuals. Different composite indicators can also be used simultaneously. For example, Huang et al. (2019) evaluate the implications of alternative carbon emissions trading systems in China by assessing the change in the aggregate household income, Gini coefficient, and the Oshima inequality index. While the use of equity weighting SWFs is prominent in global and regional optimization-based IAMs, their uptake in simulation-based IAMs is still limited (see e.g., Kind et al. (2017) for an example of the use of equity weighting functions in model-based adaptation planning). The use of composite indicators is more prevalent in simulation-based IAMs (e.g., Balica et al., 2012; Koks et al., 2015).

The second approach to deal with disaggregated metrics is by keeping them separate. This is because when using aggregation approaches, one risks having a subset of performance metrics dictating the overall performance of a policy, without knowing a priori which one will be the dictatorial metric (Franssen, 2005). Hence, some authors appeal to keeping the metrics disaggregated (Kasprzyk et al., 2016; Machado and Ratick, 2018; Watkiss, 2011). This approach is often found in simulation-based IAMs. For instance, Ahmed et al. (2017) assess the performance of alternative adaptation pathways for the western Ganges floodplain based on both their effectiveness in reducing flood risk, their impacts on economic development, and their sociopolitical feasibility. The advancement in many-objective optimization has contributed to the uptake of the disaggregated metrics approach in simulation-optimization IAMs. As an example, Trindade et al. (2017) combine both actor and value-based metrics in designing drought adaptation strategies for North Carolina. They consider the trade-offs between three different values: the reliability of water reservoir, the use of restricted water stock, and the total drought management cost, across four different water utilities (i.e., actors).

2.4.3. Post-processing for intergenerational justice

Using time-series metrics is an obvious way to represent impacts over time. However, instead of treating them as the dynamics of impacts over time, time-series metrics are often aggregated into a net present value. This is because such an aggregation results in a complete ranking of alternative policies, making comparison between policies easier. Ramsey's social discount rate is the most popular methods for doing this (Baum and Easterling, 2010; Stanton et al., 2009). Ramsey's social discount rate contains assumptions on how to weight impacts experienced by future generations. These assumptions are susceptible to empirical and normative uncertainties (Arrow et al., 2012; Storm, 2017). The empirical uncertainties mostly relate to the assumption of the welfare growth rate of future generations. The normative uncertainties concern ethical disagreements on how future generations should be valued in present day decision-making.

The normative and empirical uncertainties associated with Ramsey's social discount rate are often disregarded both in global IAMs for supporting mitigation planning, and in local and national IAMs for adaptation planning (Ackerman et al., 2009; De Cian et al., 2018). There are a few exceptions. Arrow et al. (2014) suggest using a declining discount rate for long-term governmental projects. Heal and Millner (2013) aggregate heterogeneous discount rates from actors with different pure rate of time preferences and explore several conditions that have to be met for the approach to be morally justifiable and analytically consistent. As illustrated by these examples, innovations in discounting are mostly found in methodological-focused studies using optimization-based IAMs for setting global mitigation target. Their uptake in simulation-based IAMs for adaptation planning is still fairly low.

2.4.4. Design of policies

Only recently, actor-differentiated policies are being considered in IAMs (requirement 3.1). This is mostly found in simulation-based IAMs for local adaptation that use either spatially explicit coupled components or agent-based modeling formalisms. For example, Andrée et al. (2017) evaluate alternative subsidy schemes to support the cultivation of biofuel crops in the Netherlands. Rather than applying a homogenous subsidy scheme to all farmers, they propose heterogeneous subsidy schemes based on the farmers' biophysical and economic production factors. Jafino et al. (2019) evaluate the efficacy of actor-differentiated soft policies, such as zoning policies, in addition to both aggregate and actor-differentiated hard infrastructure policies in a hypothetical delta planning. Actor-differentiated policies are only recently being adopted in IAMs operating at a larger scale, as exemplified by Stiglitz (2019) who applies a heterogeneous sector-specific carbon pricing mechanism for climate mitigation.

A recent innovation regarding policy specification is the explicit consideration of path dependency (requirement 3.2). Path dependency means that the initial action shapes the set of actions available in the future. The adaptation pathways approach attempts to include a path dependency analysis, and is often being used in combination with model-based decision support tools (Haasnoot et al., 2013). The final product of this approach is an adaptation pathways map; a metro-map like overview of alternative sequences of adaptation actions that could be taken in the future conditional on how exogenous conditions unfold. Path dependency and lock-in effects could be intrinsically considered when constructing adaptation pathways, or – as inspired by the significance of measuring flexibility in strategic planning (Rosenhead, 1980; Rosenhead et al., 1972) – explicitly quantified through the concept of "transfer costs" (Haasnoot et al., 2019). The adaptation pathways approach has been predominantly used in national and local scale IAMs in water and energy domains (de Ruig et al., 2019; Michas et al., 2020; Radhakrishnan et al., 2017).

2.5. Future research agenda

Here, we discuss three promising research directions based on requirements that have received only limited attention so far. A first research direction concerns post-processing for intra-generational justice. Requirement 1.3 on actor specific and value-based metrics, and the related requirement 4.1 on using multiple moral principles side by side, are both concerned with enabling the making of an informed choice amongst different alternative policies and social justice preferences. Neither requirement has received much attention. A second research direction is the processing of time series metrics, which is fundamental for intergenerational justice (requirement 1.5). While alternative discounting methods are being discussed at a theoretical level for global mitigation IAMs, their uptake in other types of IAMs is still limited. A third research direction is the explicit consideration of uncertainties in future actors' behaviors and preferences (requirement 4.2), as most studies still assume static behavior and preferences.

2.5.1. Using moral principles to process actor- and value-based metrics

The goal of post-processing disaggregated metrics (requirement 1.3) is to evaluate policies based on certain distributive principles. The main question is how one can make an informed choice among alternative policies based on their efficacy as estimated by IAMs, whereas the efficacy is evaluated based on how the policies satisfy the diverse values the society cherish and how the distribution of the impacts looks like. This question is also at the heart of social choice theory (Suzumura, 2001): how can one combine preferences and interests of diverse individuals? Therefore, methods and techniques from social choice theory, some of which exemplified in Table 2.2, are useful. From Table 2.2 it is evident that applications of aggregation-based SWFs are mainly found in optimization-based IAMs for mitigation planning while applications of disaggregation approaches are mainly found in simulation-based IAMs for adaptation planning.

There are two challenges in adopting techniques and methods from the social choice & welfare theory. The first challenge is correctly applying multiple distributive moral principles and interpreting their relevance and policy implications (requirement 4.1). The utility-maximizing principle is the most widely used in climate planning. Other ethical principles, such as prioritarian and Rawlsian maximin, have been applied in only a few studies. There are also ethical principles that have been argued to be relevant for climate planning, but to our knowledge have never been applied in model-based climate planning studies, such as the sufficientarian SWF. It is also important to note that any welfare function makes value judgements about welfare changes associated with changes in income (or other indicators). The task of an analyst working with a computational model is not to make such value judgements, but to shed light on the ethical underpinnings behind the aggregation approaches as well as their corresponding consequences (Kartha et al., 2018).

Table 2.2: Methods and techniques from the Social Choice and Welfare theory that are applicable for processing disaggregated metrics

Approaches	Sub-approaches	Methods and techniques	Sources for theoretical development	Examples of applications in climate change planning
Aggregation	SWFs that have been applied	Utilitarian WF	(Adler, 2019; Botzen and van den Bergh, 2014; Sen, 2018)	(Kind et al., 2017; Nordhaus, 2011; Tol et al., 2004)
		Negishi weighting	(Negishi, 1972)	(Stanton, 2011; Yang and Nordhaus, 2006)
		Prioritarian WF	(Boadway and Bruce, 1984; Parfit, 2012)	(Adler et al., 2017; Adler and Treich, 2015; Gourevitch et al., 2020)
		Bernoulli-Nash WF	(Boadway and Bruce, 1984; Nguyen and Rothe, 2014)	(Fankhauser et al., 1997; Tol et al., 2004)
		Rawlsian maximin WF	(Rawls, 1974)	(Botzen and van den Bergh, 2014; Tol et al., 2004)
		Egalitarian WF	(Kolm, 1977; Pazner and Schmeidler, 1978)	(Dietz and Asheim, 2012; Kind et al., 2017)
	SWFs that have not been applied and are potentially useful	Weighted utilitarian WF	(Baron, 1994)	-
		Relative egalitarian WF	(Sprumont, 2013)	-
		Sufficientarian WF	(Shields, 2012)	-
		The greatest unhappiness of the least number	(Bossert and Suzumura, 2017)	-
		Leximin	(Barbarà and Jackson, 1988)	-
		Relative utilitarian WF	(Dhillon and Mertens, 1999)	-
	Inequality indicators that have been applied	Gini coefficient	(Gini, 1936)	(Taconet et al., 2020; Van Ruijven et al., 2015)
		Oshima inequality index	(Oshima, 1970)	(Huang et al., 2019)
		Poverty indices	(Sen, 1997)	(Rao, 2013)

	Inequality indicators that have not been applied and are potentially useful	Generalized entropy	(Cowell and Flachaire, 2015)	-
		Mean deviation	(Cowell and Flachaire, 2015)	-
		Distributional dominance comparison	(Cowell and Flachaire, 2015)	-
		Envy measures	(Bosmans and Öztürk, 2018; Konow, 2003)	-
Dis-aggregation	Disaggregation approaches that have been applied	Pareto optimality	(Cohon and Marks, 1975)	(Kasprzyk et al., 2013, 2016)
	Disaggregation approaches that have not been applied and are potentially useful	Judgement aggregation theory	(List, 2012)	-

The second challenge is selecting or developing an appropriate operationalization of the chosen moral principle for model-based support for climate planning. Any social welfare function has certain requirements and assumptions that limit the scope of its application. For example, the greatest unhappiness for the least number principle assumes ‘ordinally measurable and interpersonally non-comparable utilities’ (Bossert and Suzumura, 2017). One has to make sure that the model outcomes and the nature of the problem do not violate the limitations posed by the social welfare function. Making these limitations and assumptions explicit and ensuring that the setup of the model-based support tools complies with the limitations of the moral principle are essential to ensure the validity of the chosen social welfare function.

2.5.2. Using alternative methods for dealing with time-series metrics

There are two options related to the processing of temporally disaggregated metrics. The first one is using alternative discounting methods. Multiple alternatives to Ramsey’s social discount rate have been proposed recently at a theoretical level: sustainable discounted utilitarianism, rank discounted utilitarianism, the Calvo criterion, and the Chichilnisky criterion (Asheim, 2017). Sustainable discounted utilitarianism discounts the utilities of future generations if and only if they are better off than the present generation (Asheim and Mitra, 2010). In rank discounted utilitarianism, utilities of different generations are discounted not based on the order of time of their occurrence. Rather, the utilities are first reordered based on their magnitude, and then the discount rate is applied based on this rank-ordered list (Zuber and Asheim, 2012). The Calvo criterion is built upon the maximin SWF (Calvo, 1978). It aggregates time-series metrics based on the minimum of the altruistic welfare calculated from the standard social discount rate. The Chichilnisky criterion applies a convex function to the net present utility generated by standard discounting and the limit of transformed well-being.

The second option, proposed by Heilmann (2017), is abandoning discounting altogether, and going for alternative frameworks that are less vulnerable to normative uncertainties. To this end, one can draw from the disaggregation approaches as used for intra-generational justice. Specifically, one can perform an inter-temporal trade-off analysis by calculating net present values for the different generations independently. This results in having multiple net present values belonging to different generations instead of a single overarching net present value as is the case in discounting methods. By following this approach, intergenerational trade-offs can be explicitly assessed. The methodological issue to this lies in determining the time horizon of a single generation due to the transgenerational community phenomenon (Campos, 2018; Gosseries, 2008); people live not within a particular generation, but within overlapping generations that encompass others who are born earlier or later.

2.5.3. Incorporating uncertainties in human behaviors and values preferences

A key requirement from an intergenerational perspective is guaranteeing a just representation of future generations by understanding the changes in their background, behaviors and values over time, which are uncertain by nature (requirement 4.2). This leads to two research challenges. The first one relates to the two properties of actor heterogeneity as presented in Figure 2.3: internalizing changes in actor group membership and actor behaviors. The relative membership proportion of each actor group refers to the distributional mix of the groups in the model (e.g., 60% poor, 30% middle-class, 10% rich agents), while the behavior is the actions and/or decision-making processes of each actor group in the model. The relative proportion and the behavior of each group can be either static or dynamic over time. When static properties are assumed, the proportion and behavior of each actor group remain unchanged for the entire simulation horizon (e.g., the distribution of poor, middle-income, and rich agents in the model remains constant at 60, 30, and 10% respectively). Conversely, dynamic properties imply that the properties may change over time. The dynamics can be represented as either exogenous (represented as uncertain forcings to the model) or endogenous (change due to internal processes within the model). This can be achieved, for instance, by drawing from theories of behavioral economics and cognitive psychology (Mathias et al., 2020; Schill et al., 2019).

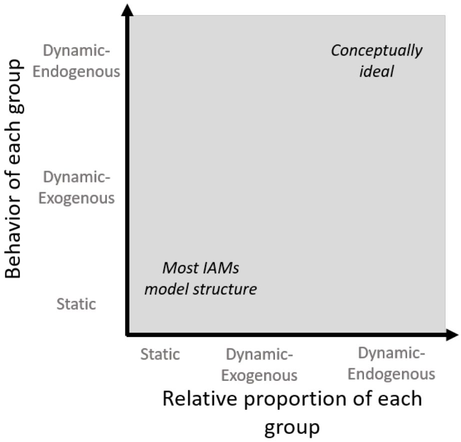


Figure 2.3: Representation of actor heterogeneity in IAMs

Many optimization-based IAMs are located in the bottom left region of Figure 2.3 where, for instance, adaptation behavior is considered to be constant over time (Füssel, 2010b; Schneider and Lane, 2005). Simulation-based IAMs, especially those with explicit individual actors representation such as microsimulation and agent-based models, have to some extent dynamic-exogenous representation of group proportion (e.g., Hallegatte and Rozenberg, 2017). Moving to the top right corner of the diagram poses an ethical trade-off. Modelers have to know, or at least assume how future generations would change their behavior under different circumstances (Sondoss et al., 2020). Such a presumptuous approach might increase the epistemic uncertainties in the model (Vezér et al., 2018). The approach might underestimate the uncertainties of human behavioral systems and hence limit the potential representation of future generations.

The second research challenge is incorporating uncertainties in the future generations' values. Selection of values to be considered is inevitable in model-based support for climate planning. The selection is often grounded in the observed behavior of actors. However, as is the case with other uncertainties, there is no guarantee that the historical observation will still hold true in the future, due to the prevalence of contextual factors and shocks (Bednar et al., 2015). Value change theories provide alternative modes – such as emergence of new values, changes in relevant values, and changes in the relative importance of different values – that could be a starting point to operationalize uncertainties in future values (Demski et al., 2015; van de Poel, 2018). It is important to re-emphasize that exploration of plausible value changes is not only about what societal aims future generations will value. What distributive moral principles they will prefer and apply are also subject to uncertainties. This highlights the importance of using multiple moral principles in model-based planning for climate change.

2.5.4. Priority issues for different types of models

While pursuing the three research items above would improve our abilities for assessing distributive justice, the urgency, relevance, and difficulty of each research item differ across the different types of IAMs. The mainstreaming of alternative moral principles in simulation-based IAMs, especially those used for adaptation planning, is fairly straightforward. It is a low-hanging fruit that can yield high societal impacts as more local- and national-level adaptation planning processes are supported by such models (Palutikof et al., 2019). Similarly, the use of multiple social discount rates in IAMs for supporting mitigation planning can be a short-term priority, owing to the recent theoretical developments of alternative social discounting frameworks (Asheim, 2017). Disaggregation approaches, both in dealing with actor-based and time-series metrics, are easier to implement in simulation-based IAMs. For optimization-based IAMs, adopting disaggregation approaches requires reformulating the internal model structure into a multi-objective optimization framework. This is even more challenging for IAMs that use multiple, recursive, and/or intertemporal optimization routines in their current structure (see Keppo et al. (2021) for examples of such models). Finally, incorporating uncertainties in human behaviors and value preferences is a hard problem especially for global optimization-based IAMs. This research item is more manageable in simulation-based IAMs for supporting smaller-scale (e.g., local or national) adaptation planning, as in-depth conceptual exploration of plausible value changes can be included in e.g., a participatory model building process.

2.6. Conclusions

Despite the mounting evidence of the importance of including justice in climate planning, and despite advances in the complexity of model structure, the degree to which justice deliberation can be facilitated by model-based support tools is still fairly limited. Grounded in theories of justice, this paper contributes to the literature by systematically constructing requirements for IAMs in order to allow for justice evaluation. The requirements are derived from ethical imperatives rooted in two conceptions of distributive justice, namely intra-generational (between people in the same generation) and intergenerational (between different generations) justice. Eleven requirements are proposed and structured based on the XLRM framework. This systematic operationalization of climate justice into requirements for model-based climate planning, along with a review of the degree to which these requirements are receiving attention in the literature, helps us in understanding where we stand with respect to methodically considering justice in model-based climate planning and how we can move forward.

Requirements associated with model structure ('R' in the XLRM framework) and performance metrics ('M') have largely been satisfied. These requirements are mainly concerned with the disaggregation of system representation by accounting for different actors and different values that the actors cherish. By explicitly modeling different actors and values, modelers and planners can observe the distributive impacts of policies on each actor and value. An assessment of intra-generational justice can then be made based on a given moral principle. In addition, by using IAMs in a multi-temporal fashion, modelers and planners can observe the expected impacts to future generations.

Three directions for future research have been proposed. The first one is the (post-)processing of actor- and value-based disaggregated metrics through the use of methods and techniques from the social choice and welfare theory. It is important to recognize that behind the seemingly neutral term of 'post-processing', there exists various ethical principles that reflect what society considers to be fair distributional outcomes. The second direction is the processing of temporally disaggregated metrics. This study has presented alternative discounting methods that are currently underexplored, as well as other alternatives for dealing with time-series metrics aside from using discounting methods. The third one is incorporating uncertainties in human values and behavioral systems with a higher granularity. This can be done by making value and behavioral changes an internal process in the model, although it comes at the expense of increasing normative uncertainties. These three challenges are rooted in the need to deal with the plurality of social justice preferences and values both now and in the future.

The requirements put forward in this paper are relevant to two different bodies of literature. In the climate justice literature, hitherto, the role of IAMs has not previously been discussed as a separate domain of climate justice requiring its own sphere of discussion (Byskov et al., 2019; Gardiner, 2010). Building on Beck and Krueger (2016), we argue that many justice considerations are actually intrinsic to IAMs and therefore require specific attention. With respect to the IAM literature, many of our findings support past suggestions on how to improve the quality of IAMs (Rao et al., 2017; Schneider, 1997; Stanton et al., 2009). Past works within this body of literature, however, focused only on how the design of the model structure and the specification of model outcomes could be improved to account for heterogeneity, and how implicit assumptions embodied within a model could be made explicit. While this, to some extent, enables evaluating distributive justice, here, we expand on this by highlighting the necessity of caring for how model outcomes should be evaluated, how policies should be designed, and what external uncertainties should be addressed.

Lastly, it is important to acknowledge that serious ethical concerns can be raised regarding whether numbers calculated by models can ever be used to meaningfully anticipate future injustices. In developing more detailed models, one needs to gather more data or make more heroic assumptions, which subjects the model to more uncertainty (Saltelli et al., 2020). In mitigation-based IAMs, for example, there are ethical controversies regarding the applicability of climate damage functions (Pezzey, 2019). This is further complicated by the presence of deep uncertainties pertaining future climate change and how climate-sensitive systems respond to it. Given the many assumptions, up to how many digits are the numbers produced by the model significant (Benessia et al., 2016)? Another reason is the plausible adverse impacts of quantification, for instance the blind trust on numbers. If decision-making authority is fully outsourced to number-based analysis, information on who wins and who loses could be gamed and abused (Aodha and Edmonds, 2017; Saltelli, 2020), and thus produces further injustices. In addition, it is worthwhile to be critical about whether adding transparency about justice to the modeling exercise is worth the added complexity, as it may exclude some stakeholders from any decision support using the more complicated analysis. Improving the institutions within which models are used has been proposed as an alternative solution for ethics of quantification (Saltelli, 2020). Similarly, in the context of planning for just adaptation and mitigation, climate justice should not be viewed only through numbers calculated by a set of tools. A more comprehensive account of justice in model-based climate planning could involve the incorporation of ethical imperatives from other views of justice – such as procedural justice in participatory modeling.

3

What are the merits of endogenising land-use change dynamics into a model-based climate adaptation planning?

3.1. Introduction

Decision makers in climate adaptation planning face uncertainties about the future context within which adaptation measures need to be implemented (Dessai and van der Sluijs, 2007). Nevertheless, decisions still have to be made, or at least planned in advance, as failing to do so may result in adverse impacts (Füssel, 2007) and may limit options (Haasnoot et al., 2012). Embracing this challenge means changing the adaptation planning approach from developing static plans that assume a well-characterised future to designing dynamic plans that perform good enough under deep uncertainties (Maier et al., 2016; Walker et al., 2013a). The central idea behind dynamic planning is that the plan should allow for flexible adjustment over time in response to new information that decision makers will obtain in the future. One way to develop dynamic plans is to evaluate alternative sequences of decisions (adaptation pathways) in order to identify short-term actions and long-term options for adaptation. This way of dynamic planning is exemplified by the Dynamic Adaptive Policy Pathways approach (Haasnoot et al., 2013). To support decision makers in developing dynamic plans, Haasnoot et al.

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(2014) suggest the use of fast integrated assessment models to design adaptation pathways.

Integrated assessment models (IAMs) combine the knowledge of a broad range of disciplines in order to provide added values for policy support and decision-making processes (Van Delden et al., 2011). The transdisciplinary nature of IAMs has increased their popularity as a decision support tool for climate adaptation planning (Chambwera et al., 2014; Patt et al., 2010). IAMs have been used for decision support at various scales, ranging from city scale (Chang et al., 2008; Hall et al., 2010), province scale (Carmona et al., 2013; Qureshi et al., 2013), national scale (Gao and Bryan, 2017; Oxley et al., 2013), regional scale (Cofala et al., 2010), and global scale (Rotmans et al., 1990; Schwanitz, 2013).

The shift to designing dynamic plans requires a modeling approach that considers a large ensemble of plausible futures (Lempert et al., 2003). This necessitates a model that has a limited simulation runtime. There is no one clear-cut time threshold to indicate whether a model is sufficiently fast. Rather, it depends on one's computational capacity and the time availability for the analysis. The model should be fast enough to run a large number of scenarios (in the order of thousands to hundreds of thousands of simulation runs).

Such models can be developed by simplifying detailed models while retaining the ability to sufficiently mimic the system. To realise this, Haasnoot et al. (2014) suggest the use of theory informed metamodeling, resulting in fast integrated assessment meta models (IAMMs). The aim of IAMMs is to approximate the behaviour of a more detailed model within a reasonably shorter runtime. IAMMs can be constructed purely based on statistical inferences between the variables in the complex model, or based on the combination of the statistics and the representation of the processes within the system (Davis and Bigelow, 2003). Given the same set of inputs, the IAMM is expected to yield outputs that are similar to the complex model (Hamilton et al., 2015).

Uncertainties in climate adaptation planning may arise from natural, social economics, and technological systems (Haasnoot et al., 2011; Moss et al., 2010; Refsgaard et al., 2007). Recent studies suggest that in the context of climate adaptation planning, the impacts of socioeconomic uncertainties may be more profound than climate change uncertainties (Harrison et al., 2016). For instance, Audsley et al. (2015) show that population growth and commodity imports dynamics have a bigger impact on agriculture intensification and deforestation, compared to uncertainties about precipitation and temperature. Holman et al. (2016) demonstrate that a higher variability in the urban, coastal, land-use, water, and biodiversity impact indicators can be attributed to socioeconomic scenarios rather than to uncertain temperature dynamics. Fant et al. (2016) investigate the magnitude of population exposed to water stress while isolating climatic and socioeconomic uncertainties independently, and find that the socioeconomic drivers yield higher variance in outcomes. In fact, a part of climate change adaptation is the autonomous choices by the people to change their social and economics livelihood, such as by migrating to areas that are less exposed to climate impacts (Hauer, 2017). Such autonomous adaptation is not comprehensively addresed in climate adaptation studies, or is treated as an uncertainty that is exogenous to the analysis. This practice may undermine human adaptations to climate change and may result in a flawed analysis which overestimates negative impacts (Cass, 2018).

In spatially explicit IAMs, socioeconomic uncertainties are often manifested in the form of several alternative future land-use maps (Swetnam et al., 2011). The land-use maps, however, are often treated as a static exogenous input to the IAMs (Wada et al., 2017). They are created by other independent means and then used as input to the IAM (Brown et al., 2005; Taylor et al., 2012). In reality, land-use dynamics and climate change are part of an inseparable socio-environmental system. There are bidirectional interactions between them (Filatova et al., 2013). Land-use decisions are influenced by the behaviour of the natural system (Lambin and Meyfroidt, 2010; Wagner and Waske, 2016), while the performance of the natural system is affected by land-use decisions (Abd El-Kawy et al., 2011; Stonestrom et al., 2009). Furthermore, as noted in Chapter 2, endogenising land-use change decisions is one alternative way to improve the representation of actor behavior and heterogeneity in IAMs. It improves the fair representation of actors, which is one of the ethical imperatives for enabling the evaluation of distributive justice through model-based planning (Jafino et al., 2021b). To this end, a recent study by Wagner et al. (2016) has demonstrated a new approach by dynamically adding new land-use maps to a hydrologic model at multiple points of time in the simulation. The standard static land-use maps approach has proven to underestimate the hydrological impacts if future land-use changes follow a non-linear path (Wagner et al., 2017). In spite of the innovativeness, the interaction between the dimensions in this work is still unidirectional: from the land-use to the environment.

This paper aims to identify the merits of making the land-use change dynamics an internal process in a spatially explicit integrated assessment model used for supporting climate adaptation planning, by answering two questions: what are the implications of endogenising land-use change dynamics in simulation models used for supporting adaptation planning? Under what circumstances do these implications materialise? For answering these questions, we utilise a flood risk IAMM of the stylised Waas case study (Haasnoot et al., 2012). We make the land-use change endogenous by extending the environmental-based IAMM with an independent land-use change model. We apply pairwise comparisons between simulation runs where land-use dynamics are endogenised and are kept exogenous, and observe how the policy performance indicators are affected. We also explore the potential of having policies that target the land-use dimension in addition to the original physical-based policies. We extend the performance indicators being observed by having disaggregated, actor-based policy performance indicators (e.g., welfare/utility of actor groups, flood risk for each dike rings) in addition to the aggregated policy performance indicators (e.g., total welfare, total rice production, total flood risk) that are prominent in model-based climate adaptation studies.

The remainder of the paper is structured as follows. In Section 3.2, we outline the building blocks of the model that comprise the environmental impact assessment model, the land-use change model, and the coupling mechanism between these two models. In Section 3.3, we introduce the case study and the experiments design. In Section 3.4, we report the results of the experiments, and in Section 3.5, we discuss the key findings from the experiments. Last but not least, the conclusions are presented in Section 3.6.

3.2. Loosely-coupled integrated assessment and land-use change model

3.2.1. The Environmental Impact Assessment Model

The natural system in this study is encapsulated in an environmental impact assessment model. The main aim of this model is to translate climatic pressures into socioeconomic impacts. The model is built upon the integrated assessment meta model (IAMM) paradigm. The IAMM follows the theory-motivated metamodel approach (Davis and Bigelow, 2003). In this approach, the IAMM is constructed partly from statistical inferences from more complex models, and partly from the physical processes of the system. The Drivers-Pressures-State-Impacts-Responses (DPSIR) concept (Niemeijer and de Groot, 2008) underlies the cause-effect relations. The approach is applied in the context of flood risk management in the presence of climate change (Haasnoot et al., 2012).

As an example of the DPSIR framework, uncertainties about future climate change and socioeconomic development (drivers) are translated into maximum annual river discharge and future land-use claims (pressures), which in turn affect the probability of flood events occurrence and the land-use pattern (state). If flood events occur, the damage (impact) is incurred based on the physical properties and the land-use function of the flooded area. Decision makers then respond to these risks by implementing policies (responses) that may reduce the probability (affecting the state) or the consequences (affecting the impacts) of the flood risks. In this paper, an iterative process of the DPSIR concept is followed: responses are predetermined and implemented in advance so that their efficacy can be evaluated ex-ante. The implementation of the DPSIR concept into the IAMM is schematised in the blue box in Figure 3.1a.

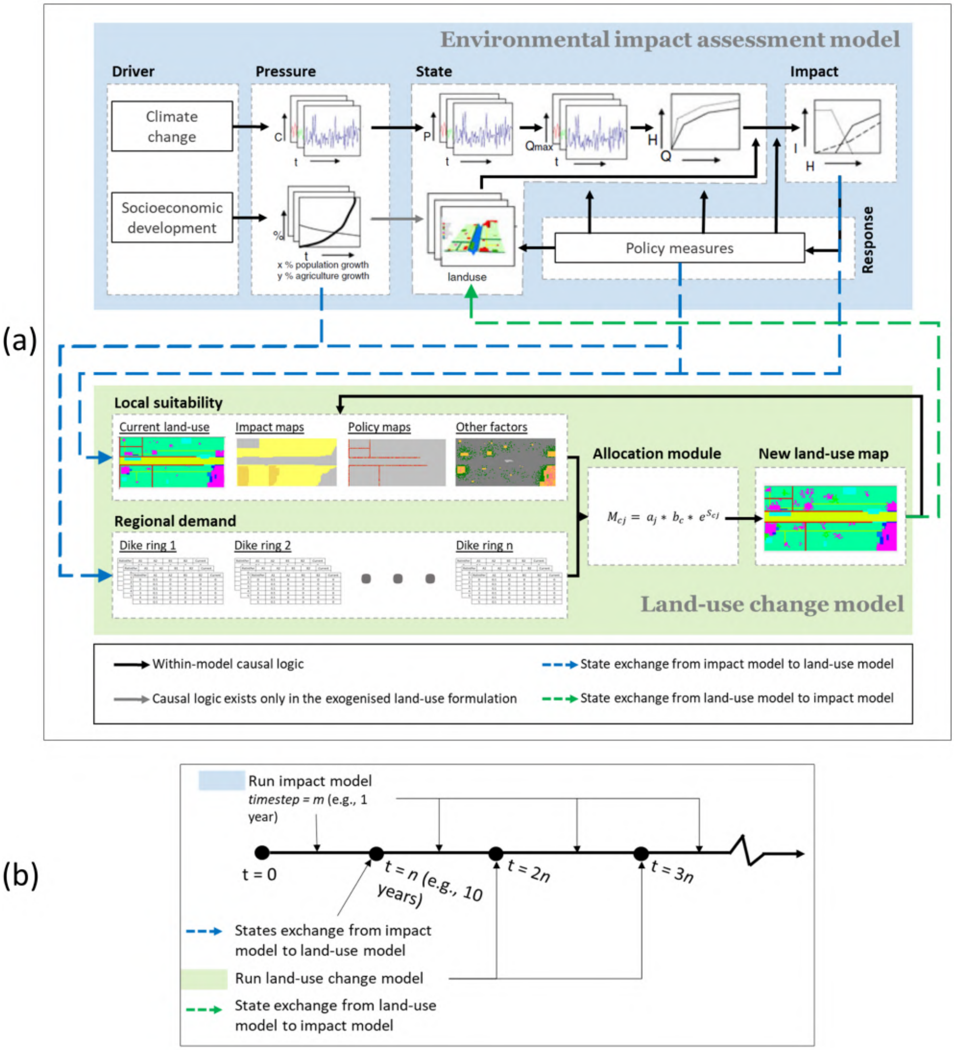

Figure 3.1: Conceptualisation of the integrated assessment model; (a) cause-effect relationships within- and between- the models, blue box: the IAMM adapted from Haasnoot et al. (2012), green box: the land-use change model; (b) the states and time integration scheme for models coupling, the colored boxes and arrows refer to modules and relationships in (a)

3.2.2. The land-use change model

Land-use modeling approaches can be classified into two categories: the inductive, data-driven approach, and the deductive, theory-induced approach (Overmars et al., 2007b). The two approaches differ in how local suitability, i.e. the attractiveness of a given parcel on a grid to each land-use class, is defined. Given a set of spatially explicit variables, the inductive approach employs statistical techniques to identify the variables that are significant in explaining land-use changes (see e.g., Lesschen et al., 2005; Serneels and Lambin, 2001). Conversely, the deductive approach starts from understanding the underlying decision making processes for each land-use class, then combines this information with the spatially explicit variables (see e.g., Diogo et al., 2015; Van Delden et al., 2010).

The inductive approach is more widely used in economics-based land-use modeling due to its better performance in reproducing historical land-use pattern (Overmars et al., 2007a). This approach, however, has a conceptual drawback. Due to the nature of statistical techniques, this approach fails to capture the importance of variables that historically have been constant. For instance, if the data shows no significant changes in precipitation patterns, then the importance of this variable would be underestimated by the inductive approach, while in reality this variable may play a significant role in the agriculture sector's decision making. This makes the inductive approach less suitable for model-based support for climate adaptation, in which the main objective is to explore the policies performance under uncertain changing conditions (Dessai et al., 2009). Therefore, in this paper we adopt the deductive approach.

The local suitability of the land-use classes is defined based on a utility framework (Koomen et al., 2015). Here, the local suitability of a parcel for a certain land-use class is calculated based on the combined economic and social utility of that parcel. This approach establishes a behavioural logic to the model and facilitates a forthright interpretation of the decision making processes.

Besides the local suitability module, the land-use change model in this study has two other modules: the regional demand module and the allocation module (Koomen et al., 2011). The regional demand module contains information on the projections of the total future demand for each land-use class, distributed over the specified regions. The projections and the current existing area of a land-use class become the future land claim of that land-use class, which in turn will be allocated to the individual parcels by the allocation module. The allocation module uses a doubly-constrained logit model that combines the land claims and the spatially explicit local suitability information (Hilferink and Rietveld, 1999). The relations among the local suitability, regional demand, and allocation modules are exhibited within the green box in Figure 3.1a.

3.2.3. Loose and bidirectional coupling of the model

We integrate the environmental impact assessment model and the land-use change model in a loosely-coupled and bidirectional manner (Antle et al., 2001). In this approach, the coupling is done between two or more standalone submodels that can still be run independently despite the presence of the other models. The state variables of one submodel become the input vector for the other submodels. The bidirectional nature implies that state exchange happens in two directions.

The loose and bidirectional coupling of the two models involves states and time integrations as schematized in Figure 3.1b. First, the environmental impact assessment model is run for m time step. Every n time step, where n ≥ m, several states from the environmental impact assessment model are fed into the local suitability and the regional demand modules within the land-use change model (the blue dashed lines in Figure 3.1a). The allocation module is then executed and the resulting new land-use map is fed back to the environmental impact assessment model. The impact assessment model then continues running and the same states exchange procedure is carried out every n time steps.

Three types of state information are transferred between the models: the impact maps, the socioeconomic pressures, and the land-use maps. The impact maps become one of the determinants of the local suitability. The socioeconomic pressures are translated into future land area claims of each land-use class in the regional demand module, distributed across the regions in the system. This is the key difference between the endogenised and the exogenised land-use dynamics model formulation. In the exogenised one, new land-use maps are created top-down in advance without taking into account the climatic impacts. In the endogenised case, new land-use maps emerge from bottom-up decisions that consider experienced climatic impacts.

There are two additional types of policies that could be implemented when land-use change dynamics are endogenised: the region-level and the grid-level zoning policies. The former influences the regional demand module while the latter adds additional policy maps to the local suitability module (see the green box in Figure 3.1a). An example of the first type could be the restriction of further industry development in disaster prone regions. Applying this policy means subtracting the industrial land claim in certain regions to zero and adding it to the other regions in the regional demand module. An example of the second type could be the protection of nature area from urban development. This policy could be applied by adding an additional policy map that represents the closeness of each parcel to the nature area. The closer a parcel to any existing nature area, the less suitable it is for future residential area.

3.3. Application: The extended Waas case

3.3.1. Background

We use the hypothetical 'Waas' case, a climate adaptation flood risk case study that schematises the Waal, a river reach in the Netherlands part of the Rhine Delta (Haasnoot et al., 2012). The Waas case simplifies the land-use representation of the Waal river, for instance by having fewer dike rings. However, the modelled physical processes are highly representative. The flooding mechanisms are derived from other validated models previously used for studies on the Waal river. This theoretical case study has been frequently used as a lab experiment to test the consequences of new approaches for model-based adaptation planning (e.g., Buurman and Babovic, 2016; Kwakkel et al., 2015; Manocha and Babovic, 2018; McPhail et al., 2018).

Figure 3.2 shows the spatial representation of the model. There are five dike rings protected by embankments alongside the river. Agricultural is the dominant land-use function. A large city exists on the higher elevated ground in the southeast part of the delta. The model encompasses an area of approximately 300km2 , divided into parcels 200m x 200m in size.

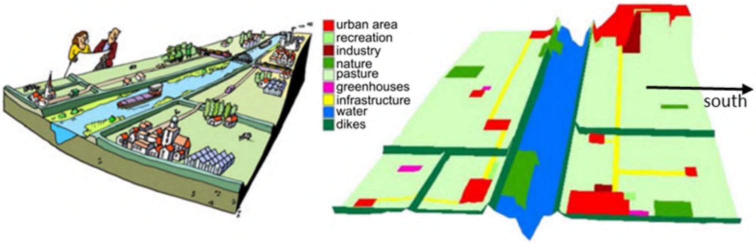

Figure 3.2: Spatial visualisation of the Waas River delta (Haasnoot et al., 2012)

The Waas model comprises cause-effect relations, depicted in the blue box in Figure 3.1a. The climate realisations (C) define the precipitation rate (P), in turn translated into the maximum annual discharge of the river (Qmax). The discharge is translated into maximum water levels (H) using discharge rating curves. The water levels are compared with the dike heights. The difference between the water levels and the dike height determines the probability of dike failures due to overtopping, breaching, and/or piping. Dike failures cause inundation of the floodplain. The water depth on the floodplain is calculated based on the intersection of the water level on the river and the elevation of the area. As we only consider large-scale annual flood events, smaller pluvial flood events caused by rainfall and surface runoff are not accounted in the model. Damages from flood events (I) are calculated based on the water depth and land-use damage relations functions. The model is developed by using the PCRaster library, a Python-based environment to simulate process-based spatiotemporal models

(Karssenberg et al., 2010; Schmitz et al., 2013; Wesselung et al., 1996).

Focusing on flood risks, we evaluate the following outcomes that were used in the original Waas case study: the total flood damage (M Euro), the area of residential sector flooded (km^2), and the agricultural flood damage (M euro). Flood damage on each cell is calculated based on the water level, the elevation, and the dominant land-use class on that cell. The shape of the damage curves is derived from the Standard Dutch Damage and Casualty Model (Kok, 2005). The model is run with an annual time step for a planning horizon of 100 years. Therefore, the values of each indicator are aggregated over all dike rings and accumulated across this planning horizon in order to assess the performance of the policies.

The same set of physical flood risk policies that was applied in the original Waas case paper is employed here (Table 3.1). The policies focus either on flood risk reduction or on flood damage reduction. The former aims at reducing the risk of flooding (i.e., both probability and consequences) while the latter aims at reducing only the damage incurred (i.e., consequences) from inundation.

Table 3.1: Overview of original policies

No	Name	Description	Category
1	No policy	Do nothing	-
2	DH500	Dike height rise to cope with a 1:500 discharge, based on measurements	Flood risk reduction
3	DH1000	Dike height rise to cope with a 1:1000 discharge, based on measurements	Flood risk reduction
4	DH1.5	Dike rise: adapting to 1.5 times the second highest discharge ever measured	Flood risk reduction
5	RfR small	Room for the river - Small scale: with extra side channels, the river is given more space after a threshold discharge is exceeded	Flood risk reduction
6	RfR medium	Room for the river - Medium scale: with extra side channels, the river is given more space after a threshold discharge is exceeded	Flood risk reduction
7	RfR large	Room for the river - Large scale: with extra side channels, the river is given more space after a threshold discharge is exceeded	Flood risk reduction
8	CopU	Upstream cooperation: discharges are reduced to 14.000 m3/s	Flood risk reduction
9	FloatH	Floating houses: resulting in damage functions with 10 times less damage for the residential land-use class	Flood damage reduction
10	FaC	Fort cities: extra embankments around the residential area	Flood damage reduction
11	Mound	All residential area are raised by 4 m, resulting in houses on an area of elevated ground	Flood damage reduction

Both climate and socioeconomic uncertainties are considered. Three categories of climate scenarios, formulated by the Royal Dutch Meteorological Institute (KNMI), are incorporated: no climate change, G scenario (moderate climate change, temperature rise of 1°C in 2100), and Wp scenario (severe climate change, temperature rise of

2^{o}C in 2100). These climate scenarios are grounded on the combination of downscaled General Climate Model and Regional Climate Model simulations used in IPCC reports, meteorological observations, and expert judgement (Van den Hurk et al., 2007). For each category, ten climate realisations are constructed by using the KNMI Rainfall Generator (Buishand and Brandsma, 1996) in combination with the delta change approach (Lenderink et al., 2007), resulting in a total of 30 climate realisations. Each climate realisation is a 100-year time series of precipitation. In general, a more severe climate change scenario leads to higher precipitation rates, and thus higher maximum river discharges.

The socioeconomic uncertainties take form of future land-use maps based on the work of Kwakkel et al. (2015). In this study, we use three socioeconomic scenarios: (i) no land-use claim change, (ii) deurbanisation, and (iii) urbanisation. In the deurbanisation scenario, future land-use maps are generated where the total number of residential area is reduced by 15% within the entire planning horizon. In the urbanisation scenario, the number of residential area is increased by more than 30% by the end of the simulation run. The increase and the decrease of the residential area are uniformly distributed throughout the simulation run.

3.3.2. Extension for the land-use change dynamics

We use the LandUse Scanner software (Hilferink and Rietveld, 1999) for the utility-based land-use change model. Coupling the land-use change model entails five additional steps: adjusting land-use maps resolution between the land-use change model and the Waas IAMM, differentiating between endogenous and the exogenous land-use classes, defining the local suitability function for each land-use class, formulating regional demand, and exchanging the states between the two models in a timely manner.

The parcels in the Waas IAMM have a different resolution compared to the parcels in the land-use change model. In the impact assessment model, a parcel is represented by a single land-use class, while in the land-use change model, a parcel consists of multiple layers of land-use classes. The the land-use class with the largest area in a certain parcel becomes the dominant land-use class of that parcel. Taking the example in Figure 3.3, as land-use class B has the largest area, it represents that parcel in the impact assessment model.

The land-use change model makes a distinction between endogenous and exogenous land-use classes (Koomen et al., 2011). Exogenous land-use classes do not undergo the local suitability calculation, and their spatial distribution is exogenously defined. Permanent land-use functions such as dikes, infrastructure, and water body/river belong to this category. Endogenous land-use classes undergo the local suitability cal-

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The KNMI climate change scenarios we used here were the same scenarios used in the original Waas case study paper (Haasnoot et al., 2012). Thus, it does not represent the latest climate change projections in IPCC AR5 nor AR6.

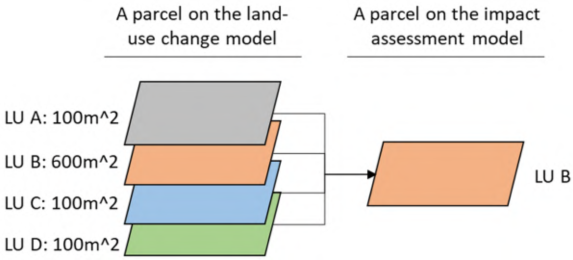

Figure 3.3: Schematisation of a parcel's resolution transformation

culation, and thus the allocation procedure, as their presence is not permanent and the spatial distribution of their utility changes over time. Residential, industry, agriculture, recreation, and greenhouse land-use classes belong to this category.

A similar formulation of utility-based local suitability is applied to all endogenous land-use classes. The utility of a land-use class is a function of: (i) the presence of that land-use class in the parcel, (ii) the distance decay factor to the nearest same land-use class (as suggested by Diogo et al. (2015)), and (iii) the severity of the flood events from the impact assessment model. The severity is defined as a function of the flood water depth and the 'flood sensitivity threshold' of the society. If the water depth on a given parcel exceeds this threshold, the land-use actors on that parcel will re-evaluate the local suitability of that parcel. Otherwise, they will maintain their current land-use decision. The base model formulation in this study assumes a flood sensitivity threshold of zero. This makes flooding events with any severity trigger the land-use actors to adjust their decisions. The logic of the utility calculation can be found in Appendix A.

The exogenous land-use maps developed in Kwakkel et al. (2015) are used as a basis for determining the regional demand in the land-use change model. Within each dike ring, the number of parcels of each land-use class in the new exogenous land-use map is subtracted from the number of parcels in the current land-use map. The difference between the two becomes the future area claim for the land-use class, to be inputted in the regional demand module of the land-use change model.

The exchange of state information between the models takes place every ten years (n = 10 in Figure 3.1b), which is similar to the time window of five to nine years as proposed by Wagner et al. (2017). The information of the occurrence of flood events in the impact assessment model within this time period is stored and is averaged by the end of the tenth year. The spatially explicit average flood water depth becomes one of the drivers that determines the local suitability (see the dashed blue line to the green box in Figure 3.1a). The land-use change model then creates a new land-use map. This new land-use map goes back into the impact assessment model and affects the impacts of the subsequent flood events.

3.3.3. Experiments design

Table 3.2 shows the five experiments carried out in order to answer different questions. The first four experiments are intended to compare the results of endogenising land-use dynamics with the exogenised land-use dynamics. The last one explores the potential of adding new land-use based policy performance indicators and a zoning policy in model-based support for climate adaptation.

Table 3.2: Overview of original policies

No	**Main questions**	**Uncertain variables**	**Policies**	**Endogenised land-use?**	**Number of simulation runs**
1	How does future climate change development influence the impact of endogenising land-use dynamics?	Climate change	11 original policies	Both – yes and no	330
2	How does future socioeconomic development influence the impact of endogenising land-use dynamics?	Socioeconomic (land-use claim)	11 original policies	Both – yes and no	330
3	How does the society's sensitivity to flood events influence the impact of endogenising land-use dynamics?	Climate change + flood sensitivity threshold	No policies	Both – yes and no	780
4	How does endogenising land-use dynamics affect the policy performance of each policy?	Climate change + Socioeconomic	11 original policies	Both – yes and no	990
5	What are the implications of adding land-use based policies and indicators on top of the standard ones?	Climate change + Socioeconomic	11 original and zoning policies	Yes	1980

In the first two experiments, the influence of the land-use claim (socioeconomic) scenarios and the climate change scenarios is independently assessed. A full factorial design is used to sample the parameters in these experiments. There is a total of 330 unique simulation runs in each experiment (3 climate change scenario categories x 10 precipitation realisations in each category x 11 original policies (see Table 3.1) in the first experiment, 1 climate change scenario category x 10 precipitation realisations x 3 land-use claim scenarios x 11 original policies in the second experiment).

The third experiment aims at investigating how the sensitivity of the society's land-use decisions to flood events affects the implications of endogenising land-use dynamics. To consider this factor, we introduce a new uncertain variable termed 'flood sensitivity threshold'. The value of this variable is set to zero in the other experiments, while the value will be an integer number between zero and twenty five in this experiment. The threshold value translates linearly to flood depth; a threshold value of one implies flood depth of 0.5 meter. Since flood events are climate-induced, only climate change uncertainties are considered. The full factorial design is used to sample the uncertainties.

The fourth experiment aims at evaluating how the performance of each policy is affected by the endogenised land-use dynamics. This experiment applies a full factorial design, resulting in ninety unique parameters settings (3 climate change scenario categories x 10 precipitation realisations in each category x 3 land-use claim scenarios). The performance of all policies listed in Table 3.1 is evaluated for each of the ninety parameters settings, resulting in a total of 990 simulation runs (90 parameters settings x 11 policies).

In the fifth experiment, an additional zoning policy is tested. The zoning policy applied here is a simple region-level zoning policy that aims at preventing future residential area development in flood-prone dike rings. This policy entails the displacement of residential land-use claim in dike ring 4 and 5 (regions at the south of the river) to dike ring 1, 2, and 3 (regions at the north of the river) in the regional demand module. This policy is applied concurrently with the eleven original policies, resulting in a total of 22 policies combinations. Using a full factorial design approach, this experiment setting results in 1980 simulation runs. Furthermore, an additional land-use based indicator, the weighted mean suitability (Bubeck and Koomen, 2008), is introduced. This indicator averages the local suitability of each land-use class from all parcels on the grid.

3.4. Experiment results

3.4.1. Experiment 1 – Influences of climate change uncertainties on endogenising land-use dynamics

Figure 3.4 shows the results of the first experiment. The figure condenses the outcomes of all policies. A more severe climate scenario in general has higher precipitation rate, thus higher flood events frequency. Consequently, the outcomes always get worsened when the climate scenario is more severe. When land-use dynamics are endogenised, this effect exacerbates in the cumulative total damage and cumulative area of residential sector flooded indicators, as shown in Figure 3.4a and Figure 3.4b. Conversely, Figure 3.4c shows that endogenising land-use dynamics causes a slight reduction in the damage to the agriculture sector. These facts show that, in this particular case study, the emerging land-use change dynamics benefit the agriculture sector at the expense of the residential sector. One plausible explanation behind this is the urban expansion agglomeration phenomenon that causes the residential land-use class taking over previously agricultural parcels which are inundated. This occurs, for instance, in the southwest part of the case study area where there is an existing large urban area (see Figure 3.2).

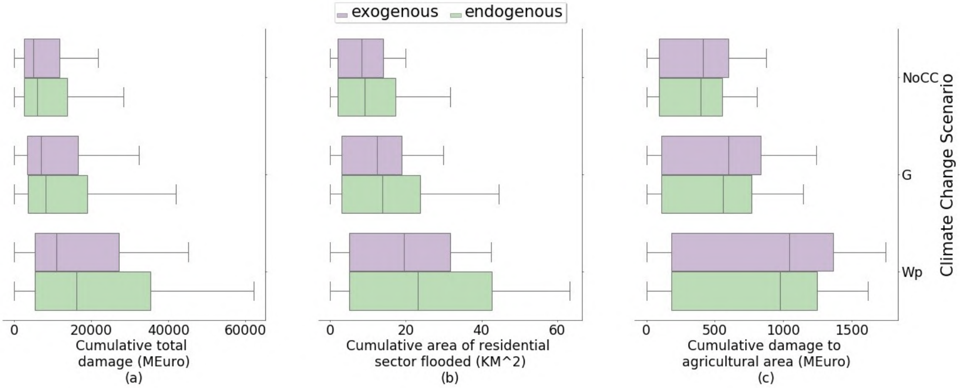

Figure 3.4: Implications of endogenising land-use dynamics under different climate change scenarios on (a) cumulative total damage, (b) cumulative area of residential sector flooded, and (c) cumulative damage to agricultural area. Lower rows correspond to more severe climate change scenarios

3.4.2. Experiment 2 – Influences of socioeconomic uncertainties on endogenising land-use dynamics

Figure 3.5 displays the results of the different socioeconomic scenarios. In the no land-use claim change and the deurbanisation scenarios, endogenising land-use dynamics increases the cumulative total damage and the area of residential sector flooded. Counterintuitively, the values of these indicators slightly decrease in the urbanisation scenario, although we would expect that there would be more residential areas in this scenario. This finding can be attributed to the difference between the exogenous runs' and the endogenous runs' spatial distribution of future residential area. In the exogenous runs, the future land-use is not allocated based on the internal dynamics of the system. Hence, the newer urban sprawl does not consider the spatial distribution of past flood events. The agriculture sector reacts oppositely. Here, by visually inspecting the graph we can see that the damage in the urbanisation scenario is reduced substantially when land-use dynamics are endogenised, while the deurbanisation scenario causes a slight increase to the damage.

3.4.3. Experiment 3 – Influences of the society's sensitivity to flood events on endogenising land-use dynamics

Figure 3.6 shows the comparison of the cumulative total damage from the endogenous runs and the exogenous runs for different flood sensitivity thresholds. Therefore, a ratio higher than one in Figure 3.6 implies that the total cumulative damage from the endogenised land-use dynamics is higher compared to the exogenous land-use dynamics. The x-axis shows the flood sensitivity threshold. The lower the value of this threshold,

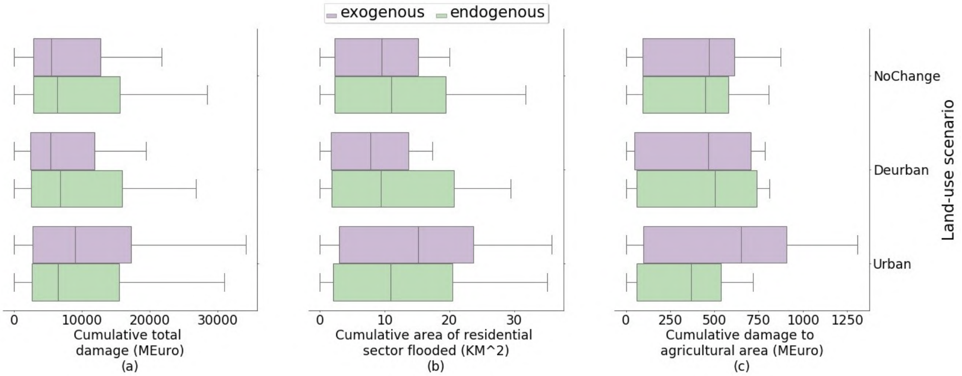

Figure 3.5: Implications of endogenising land-use dynamics under different socioeconomic (land-use) scenarios on (a) cumulative total damage, (b) cumulative area of residential sector flooded, and (c) cumulative damage to agricultural area

the more sensitive land-use change decisions are to flood events. Figure 3.6 shows that the median of the damage ratio tends to be higher when the flood sensitivity threshold is low. This can be attributed to the higher occurrence of land-use changes that exacerbates the increase in total damage as described in experiment 1 and 2. After a certain point when the threshold gets higher, the damage ratio converges to one, and the range of the boxplots starts to diminish. This happens because the flood events do not trigger the society to change its land-use pattern if the severity of the events does not exceed the high flood threshold value.

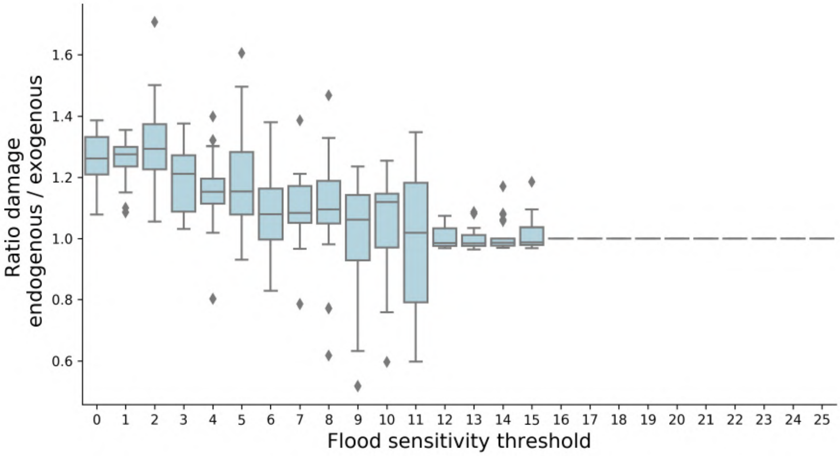

Figure 3.6: Ratio of cumulative damage between the endogenous runs and the exogenous runs for different flood sensitivity threshold values

3.4.4. Experiment 4 – Implications of endogenising land-use dynamics to each policy

Figure 3.7 compares the performance of the policies between the endogenous and the exogenous runs. There are some findings observed from this figure. First, the third indicator (the damage to agriculture sector) in most cases shows an opposite effect in comparison to the two other indicators. The only difference is for the fort cities (FaC) policy, where the values of all the indicators decrease when land-use change is endogenised. Second, the figure gives insights into which policies are sensitive to endogenised land-use dynamics. We observe that the dikes heightening (DH500, DH1000, DH1.5) and the room for the river (RfRSmall, RfRMed, RfRLarge) policies are less sensitive. For flood damage reduction measures, such as floating houses (FloatH) and fort cities (FaC), the implication of endogenising land-use dynamics is more noticeable. Third, although the magnitude of the indicators changes, the ranking of the policies does not change if we rank them based on the median value of the indicators (the approach followed in the original work in Haasnoot et al. (2012)).

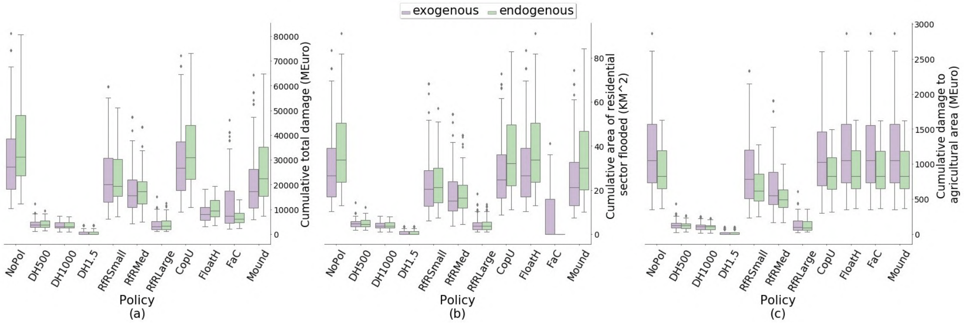

Figure 3.7: Implications of endogenising land-use dynamics to the performance of each policy, in terms of (a) cumulative total damage, (b) cumulative area of residential sector flooded, and (c) cumulative damage to agricultural area

3.4.5. Experiment 5 – Analysis of the additional zoning policy and the land-use based indicator

Figure 3.8 compares the performance of the original Policies when the additional zoning policy is applied. The zoning policy on the one hand almost does not yield any impact on the total cumulative damage from the flood risk reduction policies (Figure 3.8a). On the other hand, it increases the total cumulative damage of the floating house and fort cities policies. The reason behind this is that moving the protected houses to another area that is safer from floods has a drawback of leaving behind the other land-use classes vulnerable in the flood prone area. In the long run, more flood events hit the other unprotected land-use classes in the flood prone area, in turn incurring higher total damage. Figure 3.8b shows that the zoning policy proves to be effective in reducing the cumulative area of residential sector flooded, which is a conceivable result as the houses are moved to regions that are safer from flood events. Unsurprisingly, Figure 3.8c shows that the zoning policy has almost no effect to the agriculture sector.

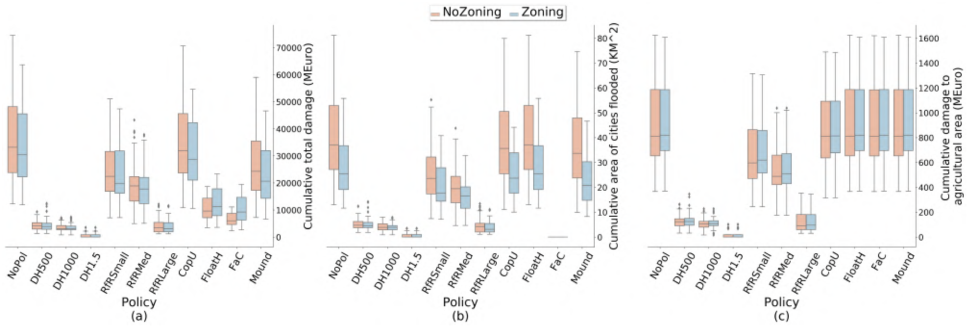

Figure 3.8: Implications of including a zoning policy in addition to the original policies, in terms of (a) cumulative total damage, (b) cumulative area of residential sector flooded, and (c) cumulative damage to agricultural area

Figure 3.9 contrasts the weighted mean suitability of each land-use class when the zoning policy is in place. The weighted mean suitability of each land-use class is an example of a disaggregated, actor-specific policy performance indicators that can be calculated in models used for adaptation planning. Each line in the figure represents the median of the weighted mean suitability values from a policy. We normalise the value in order to ease the comparison, as the concept of the local suitability itself has to be treated in a relative manner (Hilferink and Rietveld, 1999; Koomen et al., 2015). One clear pattern that we can observe here is that the zoning policy substantially increases the suitability of the residential area.

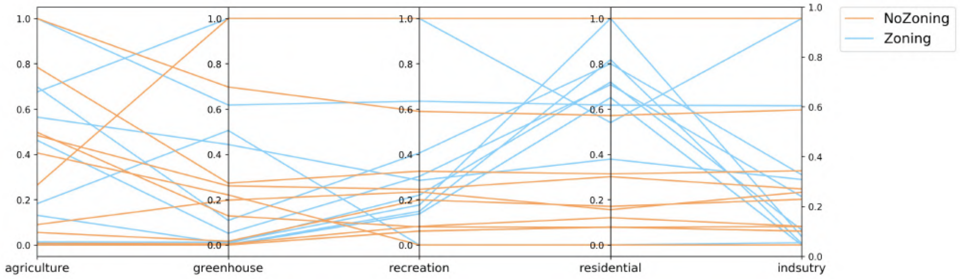

Figure 3.9: Parallel plot of the weighted mean suitability of the land-use classes. Each blue and orange line represents the median result of a single original policies (see Table 3.1

3.5. Discussion

3.5.1. What are the implications of endogenising land-use dynamics in model-based support for climate adaptation?

We find three implications of endogenising land-use dynamics: it affects the performance of the policies, enables the evaluation of land-use based zoning policies, and broadens the types of outcomes that can be evaluated.

First, we can see the implications to the performance of the policies by observing the changes in the ranking of preferred policies and the changes in the absolute values of the policy performance indicators. We observe that the ranking does not change if we rank them based on the median value of the indicators. It might change slightly if we also take into account the statistical dispersion of the indicators. For instance, from Figure 3.7b we see that endogenising land-use dynamics diminishes the variance of the fort cities policy (FaC), making this policy the most preferable one. This fact leads to the observation of the changes in the absolute values of the indicators, where the values may change when land-use dynamics are endogenised. This finding supports previous studies that show that the failure to capture this bottom-up responses in a climate adaptation study may lead to implausible conclusions (Cass, 2018; Di Baldassarre et al., 2016; Wada et al., 2017). This becomes important when the aim of the climate adaptation study is not only to rank policies, but also to assess their cost-benefit ratio. In that case, failing to better characterises the policy's performance may lead to a different conclusion on the attractiveness of the investments.

Second, by endogenising land-use change we can consider land-use zoning policies. In contrast to physical flood risk policies, zoning policies incur lower costs. This makes the combination of zoning policies and physical policies interesting. Such combinations are rarely evaluated in model-based climate adaptation studies (Newman et al., 2017), while they are relevant in practice. In this paper, we introduce an additional zoning policy where we restrict further residential land-use development in the flood prone area.

The zoning policy is effective in improving the weighted mean suitability of the residential land-use actor and reducing the cumulative area of residential sector flooded. However, the impact of the zoning policy varies across the different physical policies. When the floating houses (FloatH) and fort cities (FaC) policies are applied, the zoning policy results in a higher total cumulative damage. These actor-specific physical policies substantially improve the resistance of the residential sector to flood events, thus counteracting the also actor-specific zoning policy. The increase in total cumulative damage can also be attributed to the damages experienced by the other land-use classes, especially the industry sector that has relatively high damage factor. These land-use classes are left vulnerable in flood prone dike rings. This raises a flood risk transfer problem, which is a prominent ethical issue in flood risk management (Doorn, 2014a,b). Endogenising land-use dynamics enables the exploration of this risks transfer problem transparently.

Third, by endogenising land use change we enable a broader perspective in the evaluation of alternative climate adaptation plans. Here, we use the weighted mean suitability to evaluate the utility of each land-use class. Incorporating this indicator provides two benefits. First, this indicator can approximate the distributional impacts of policies (i.e., disaggregated, actor-based policy performance indicators). This intragenerational distributional problem has been one of the key ethical challenges in climate adaptation planning (Green, 2016; Kolstad et al., 2014). Based on this indicator, an aggregated system-level inclusivity indicator can be further developed in many ways, for instance by calculating the discrepancy between the better-off and the worse-off land-use actors. Second, we can explicitly explore the multi-actor trade-offs of policies. Analytical techniques derived from ongoing works on multi-stakeholder model-based robustness analysis can be adapted for this purpose (e.g., Herman et al., 2014; Trindade et al., 2017; Zeff et al., 2016).

The area of residential sector flooded and the cumulative damage to the agriculture sector can be categorised as actor-based indicators. However, acknowledging so could be misleading as we only see the utility from the environmental perspective. The concept underlying the utility-based land-use change model can help in better apprehending the utility of the land-use actors from environment, social, and economics perspectives. The same reasoning also applies to zoning policies. Practically speaking, we can set rules in the exogenous land-use scenarios in such a way that future new residential area does not sprawl in the flood-prone area. However, we would have missed the emerging bottom-up responses of the land-use actors. This in turn might result in a misleading policy conclusion especially if the study is done for regions where land-use functions are highly dynamic.

3.5.2. When does endogenising land-use dynamics become (ir)relevant?

We evaluate four factors that have the potential to influence the relevance of endogenising land-use dynamics: severity of future climate change, future socioeconomic development characterized as (de)urbanisation scenarios, society's responsiveness to climate events, and the nature of the policies that decision makers want to appraise. We evaluate them with regard to the changes in the magnitude of the policy performance indicators, when compared to simulation runs that exogenise the land-use dynamics. If the results do not differ much, endogenising land-use dynamics can be considered as irrelevant.

In more severe climate change scenarios, the G and the Wp scenarios, the impact of endogenising land-use dynamics is larger. In these scenarios, the frequency of flood events is generally higher. The more frequent flood events trigger the society to adjust their land-use pattern. In the land-use change model, it is assumed that different land-use classes responded to the flood events differently. A slightly higher flood sensitivity parameter value is given to land-use classes whose flood damage function was higher in the original Waas case (e.g., higher values for the residential and the industry sectors as their original flood damage function is larger). Consequently, when flood events occur, the residential and the industry land-use classes are more affected, in comparison to the agriculture and the greenhouses land-use classes. This triggers an agglomeration for the residential and the industry land-use classes. The agglomeration increases the number of dominant residential and industry land-use parcels while decreases the number of dominant agriculture parcels. In combination with the higher flood damage function to these land-use classes, the agglomeration results in higher total cumulative damage.

When urbanisation is expected in a particular area, surprisingly, endogenising land-use dynamics leads to a lower total cumulative damage in comparison to the exogenised case. This is explained by the spatial distribution of the new residential area in the exogenous land-use maps. The new residential area from the exogenous maps sprawls uniformly around the smaller cities in the delta, where the elevation is relatively low. Conversely, when the land-use dynamics are endogenised, the new residential area tends to sprawl near the large city in the southeast part of the delta (see Figure 3.2). This area in general has higher elevation, thus safer from flood. Therefore, the effect observed here cannot be generalised, as it is strongly influenced by the spatial pattern of the exogenous land-use maps. Nevertheless, the insight shows that by endogenising land-use dynamics we can observe the area where new residential land-use might potentially emerge. This information can be used to develop further zoning policies for reducing climate impacts. Such an approach is typical in the Dutch's flood planning context (De Moel et al., 2011).

The responsiveness of a society to climate events, characterised by the flood sensitivity threshold parameter, strongly affects the implication of endogenising land-use dynamics. A higher threshold results in indifferent outcomes for both the exogenised and the endogenised case. This suggests that endogenising land-use dynamics becomes more relevant in a society that is highly responsive to climate events (i.e. has low flood sensitivity threshold). As an example, endogenising land-use dynamics is relevant for climate adaptation planning in the Vietnam Mekong Delta, where extreme weather events have empirically been proven to be one of the key determinants in the people's land-use decisions (Kim and Le Minh, 2017). Failure in capturing such phenomenon in the integrated assessment model resembles the 'policy myopia' problem (Nair and Howlett, 2017), which in turn might result in misleading policy conclusions. Conversely, it is less relevant for climate adaptation planning in Alba town, Italy, where recurring flood events have not had significant influence to the land-use dynamics of the city (Luino et al., 2012).

The nature of the policies to be evaluated also plays a role in the relevance of endogenising land-use dynamics. If the benefit of a policy does not disproportionately affect certain land-use actors, endogenising land-use dynamics tends to give only marginal effect. We observe this in the performance of the dikes heightening measures and the room for the river, which benefits are experienced by all land-use actors. Consequently, as shown in Figure 3.7, the total cumulative damages resulting from the endogenised and the exogenised land-use dynamics do not differ much. If a policy targets specific land-use actors, such as in the case in fort cities and floating houses, the dynamics of the land-use actors affects the performance of the policy. Hence, the effect of endogenising land-use dynamics becomes more profound. This further emphasizes the importance of endogenising land-use change dynamics in models used to support equitable adaptation planning, as many policies to promote equity (for instance, subsidies or compensation policies) are often actor-specific.

3.6. Conclusions

Although models used for supporting climate change are becoming even more integrated (Harrison et al., 2016), future land-use maps are still often treated as an exogenous factor. Strong interconnectedness between land-use change and climate change has long been acknowledged (Dale, 1997). Ignoring the interaction between the environment and the society (in this case embodied by the land-use) can result in miscalculation of the impacts of adaptation and might limit the adaptation options that are considered. Motivated by these facts, this paper explores the merits of using utility-based land-use change model for endogenising land-use dynamics in a spatially explicit integrated assessment model.

Three implications of endogenising land-use dynamics have been identified: (i) changes in the performance of policies, (ii) the possibility of including land-use based zoning policies, and (iii) the inclusion of disaggregated, actor-level policy performance indicators. With respect to the first point, the ranking of policies did not substantially change while the absolute scores of the policy performance indicators did change in some cases. With respect to the second point, this approach enabled the evaluation of zoning policies. The performance of such policies has only been descriptively evaluated in separate independent studies, often neglecting the infrastructural policies. By using the approach presented here, the performance could be evaluated in a quantitative and integrative manner. Moreover, the land-use maps generated by the model can be used as a starting point to identify potential land-use specific policies, which are important for designing equitable adaptation plans. With respect to the third point, the weighted mean suitability was used to evaluate the actors' utility not only from the environmental perspective but also from the social and economics perspective. These indicators can be a starting point to evaluate the distributional impacts and equity performance of alternative policies.

We found three factors that might affect the implications of endogenising land-use dynamics in model-based decision support for climate adaptation described above. We evaluated the effect by observing how the policies performance indicators changed.

The analysis suggests that the implications of endogenising land use are more profound if (i) more severe climate change is expected, (ii) society is reactive or sensitivt to climate events, and (iii) some of the policies are targeting specific actor groups within the society. Special attention should be put to point (ii). In a society that is sensitive to climate events, changing land-use functions is one form of autonomous adaptation (see e.g., Ahmed, 2011; Smajgl et al., 2015). Failing to capture these dynamics may overlook the adaptive responses of the people, and thus may have a profound influence on the conclusions of the study.

Although endogenised land-use dynamics here are specifically investigated in the context of flood risk adaptation planning, the approach can be used for other climate adaptation contexts. The importance of dynamically adding land-use change in integrated assessment models has been put forward for watershed planning (Wagner et al., 2017; Zhang et al., 2018), ecological vulnerability study (Zhang et al., 2017), agricultural system (Li et al., 2018), and livestock production system (Havlík et al., 2014). In order to endogenise land-use dynamics in other contexts, the key challenge is to identify the relevant states to be exchanged and the right time integration window between the land-use and the environment systems. This study has shown merits of making land-use dynamics endogenous in a theoretical case study as a proof of concept. The challenge now is to apply this approach to a real world case study.

4

Accounting for multisectoral dynamics in supporting equitable adaptation planning: A case study on the rice agriculture in the Vietnam Mekong Delta

4.1. Introduction

Home to over 500 million people (Kuenzer and Renaud, 2012), the world's deltas are critical for economic activities and global food production. Human activities, such as groundwater abstraction, sand mining, and hydropower dam development, have altered the (bio)physical characteristics of deltas through various physical mechanisms including land subsidence, sediment starvation, discharge regime alteration, morphological changes, coastal erosion, and salt intrusion (Minderhoud et al., 2020; Renaud et al., 2013; Syvitski et al., 2009; Whitehead et al., 2019). The changes in the (bio)physical character of deltas affect people's vulnerability in multiple ways: changing hydrological regimes implies increasing flood hazard; reduced sediment supply means less aggradation of land and decreased soil fertility; coastal erosion and salt intrusion reduce the land's suitability for various crops, to mention a few. Vulnerability is further amplified

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by increasing exposure to natural hazards and weather extremes triggered by climate change and sea level rise (Chen and Mueller, 2018; Giosan et al., 2014; Kuenzer and Renaud, 2012; Moser et al., 2012).

Impacts of climate change and (bio)physical changes of the delta on human vulnerability vary across people, depending on their social, economic, and geographical background (Adger et al., 2009; Below et al., 2012; Call et al., 2017; Füssel, 2010a; Thomas et al., 2019). Climate change adaptation planning, however, often uses aggregated indicators, disregarding equity considerations (Kolstad et al., 2014; Stanton et al., 2009). For example, adaptation planning studies by Ahmed et al. (2017); Campos et al. (2016); Radhakrishnan et al. (2017); Ranger et al. (2013); Smajgl et al. (2015) all report on aggregated indicators such as flooded area, total area having a certain salt concentration, number of people exposed to flooding, total paddy yield, and total economic value in a flood prone area. If little to no attention is given to assessing which groups of the population are more affected, the recommended adaptation policies might fail to target specific vulnerable groups within the population. Such distribution-blind adaptation might reduce the vulnerability of one group of people at the expense of another (Atteridge and Remling, 2018).

There are two important elements that should be included when accounting for equity in climate change adaptation planning: the unit (what is being distributed) and the scope (to whom it is being distributed) of the distribution (Page, 2007). The unit of the distribution varies from physical entities such as flood risk and sediment supply, to socio-economic impacts such as farming profitability (Doorn, 2018; Suckall et al., 2018; Wild et al., 2019). The scope of the distribution is commonly defined by dividing population based on their attributes, such as income level or location (Harrison et al., 2016; Jafino et al., 2019; Sayers et al., 2018; Van Ruijven et al., 2015). Explicitly delineating the distribution of units to different groups within the scope allows us to identify which groups benefit and who suffers from adaptation policies. Such information can be useful for decision makers to reduce inequalities, e.g., by taking additional compensation policies for worse-off groups.

Several recent studies in model-based adaptation planning in deltas have touched on the issue of equity. Chapman and Darby (2016) distinguish impacts of alternative rice farming practices on the economic performance of small, medium, and large-scale farmers, at a household level. Kind et al. (2017) explore four different aggregation approaches for considering risk aversion and income distribution in flood risk management planning. These two studies, however, do not account for the influence of uncertain external developments. Since inequality can be influenced by both adaptation policies and uncertainties, focusing on just one factor (e.g. adaptation policies) at a time while keeping the other factor (e.g., climate change) constant could result in overlooking the complete picture of possible inequality patterns, resulting in what Juhola et al. (2016) termed 'maladaptation'. One example of research that accounts for both uncertainties and possible interventions is Ciullo et al. (2020), which explores alternative distributive principles for optimizing flood risk management options, while also considering uncertainties. Their focus, however, is the exploration of the impact of using different principles for aggregating distributional outcomes, rather than on the impacts of the interplay between uncertainties and interventions on inequality patterns.

To adequately support equitable climate change adaptation planning in deltas, a quantitative model needs to satisfy two fundamental requirements. First, the model has to account for the multisectoral dynamics in the delta. This is because uncertainties in climate change adaptation planning come from different systems, including the climatic, hydrological, (bio)physical, and the socioeconomic system (Aerts et al., 2018b; Dunn et al., 2019; Kuenzer and Renaud, 2012; Wong et al., 2014). Adaptation measures also come in various forms, targeting different parts of the systems, and potentially benefitting or harming different subgroups within a population (Atteridge and Remling, 2018; Begg et al., 2015; Smajgl et al., 2015; Ward et al., 2020). The co-evolution between these systems may thus give rise to distinctive inequality patterns. The second requirement is that the model has to have an explicit representation of the different subgroups within the scope of the distribution. The specification of the subgroups has to be made on an appropriate dimension, so that the model can provide actionable and targeted recommendations to reduce future inequalities. For instance, if one aims to look at spatial inequalities, then the model needs to be spatially-explicit. This allows analysts to look at the robustness of alternative policies not only across scenarios and across dynamics over time (Hadjimichael et al., 2020; Steinmann et al., 2020), but also across people and across space.

The main aim of this study is to investigate how the intricacy of uncertain exogenous developments, internal changes within the delta, and adaptation policies jointly affects future inequality patterns. We investigate future total output and equity performance of the rice agricultural sector in the Vietnam Mekong Delta (VMD) under various realizations of uncertainties and adaptation options as a case study. For the equity part, we observe the spatial distribution of rice farming profitability (the unit) across the different districts (the scope) in the upper VMD. Being the world's third largest delta, the VMD provides 55% of the total rice production of Vietnam and contributes to more than 85% of the country's rice export (GSO, 2019; Toan, 2014). The VMD faces both uncertain climatic and anthropogenic pressures (Duc et al., 2019; Dung et al., 2015; Manh et al., 2015), which, in interaction with adaptation policies, affect flood risk, land-use change, land subsidence, and the deposition of nutritious sediments.

To capture the multisectoral dynamics affecting rice farming profitability in the VMD, we develop a spatially-explicit integrated assessment model. We combine existing detailed physical models with a cellular automata-based land-use change module and a rice farming profitability module. The model encapsulates the co-evolutionary dynamics influencing the livelihood of the rice farmer. These dynamics include changing flood regime, soil fertility, sedimentation and natural nutrients replenishment, human-induced land subsidence, economic-based fertilizer application, as well as behavioral land-use change. Using the model, we assess the efficacy of alternative adaptation policies using both aggregated and disaggregated indicators. We look at both aggregate total output (i.e., total rice production) and equity (i.e., Gini coefficient) indicators, as well as disaggregated inequality patterns (i.e., rice farming profitability at a district level) under different uncertain futures. Our study shows how equitable climate change adaptation planning in deltas can be supported by systematically exploring the inequality patterns resulting from complex interactions between adaptation options and different futures, enabled by a spatially-explicit computational representation of the multiple interacting subsystems in the delta.

In the next section we explain in more details the background of our case study area, which is the Vietnam Mekong Delta. In section 4.3 we outline the methodology that we followed in this study; the model conceptualization, the model evaluation, and the experimental setup. The results are presented in section 4.4. In section 4.5 we reflect on the limitations of our approach and how, despite the limitations, the findings of our study can still be meaningful to the discussion on climate change adaptation planning in the Vietnam Mekong Delta. We conclude with broader implications for supporting equitable climate change adaptation planning in section 4.6.

4.2. Study area

The large (inter)annual variability in rainfall, river discharge and tidal regime, in combination with human interventions, makes the VMD a physically dynamic delta (Gugliotta et al., 2017; Unverricht et al., 2013). From a biophysical point of view, the VMD is divided into three zones: downstream, midstream, and upstream (see Figure 4.1). Each zone faces different challenges; salinity intrusion due to sea level rise downstream, annual monsoon flooding upstream, and increasing flood hazard due to increasing runoff and higher river levels midstream (Eslami et al., 2019; Huong and Pathirana, 2013; Smajgl et al., 2015; Tri, 2012; Van et al., 2012). Human interventions including hydropower dam construction, human-induced land subsidence, and sand mining further complicate the dynamics (Hecht et al., 2019; Hoang et al., 2019; Minderhoud et al., 2019; Triet et al., 2017).

Most rice farming activities take place in the upstream zone where salt influence is minimal and freshwater availability is higher. We therefore focus our analysis to the two provinces in the upstream zone: Dong Thap and An Giang. The choice is motivated by three reasons. First, unlike provinces in the downstream zone, farmers in Dong Thap and An Giang do not face significant salt intrusion from the sea. Therefore, it is foreseen that these provinces will still be the main rice production hub in the delta in the foreseeable future (Mekong Delta Plan Consortium, 2013). Second, unlike provinces in

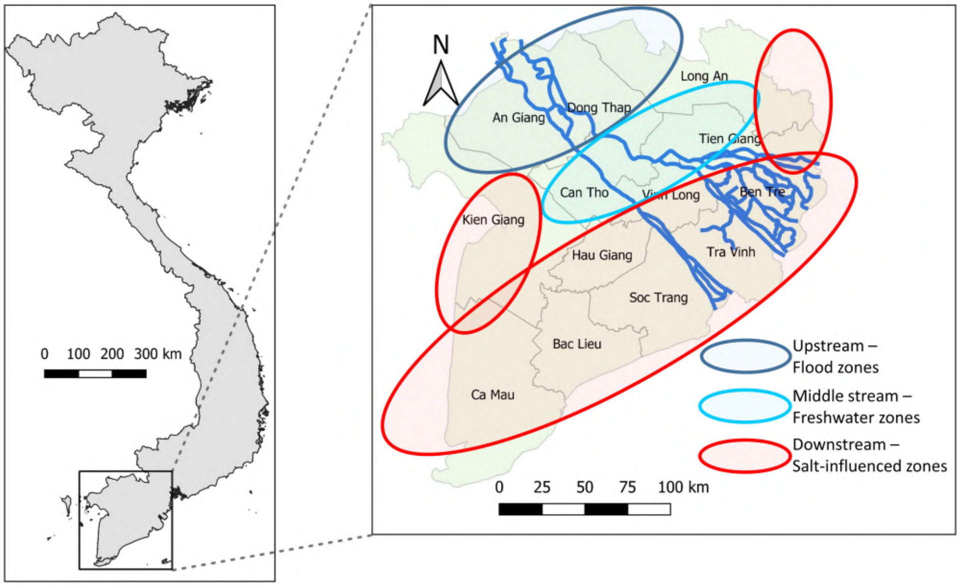

Figure 4.1: Left panel: map of Vietnam. Right panel: three different hydrological zones and 13 provinces in the Vietnam Mekong Delta. The blue lines are the branches of the Mekong river. In this study we focus on the upstream zone.

the middle stream zone, farmers in Dong Thap and An Giang still have to face annual flooding in the monsoon season. This makes the biophysical aspect of the upstream zone more dynamic compared to the middle stream zone. Third, these provinces are the first areas where high dikes were constructed and triple-rice crops were adopted. The land-use change in these provinces is among the most dynamic ones in the region (Ngan et al., 2018).

Rice farming in Dong Thap and An Giang has undergone a major transition in the past decades. This transition started after the establishment of the ‘Doi Moi’ policy in 1986, when the government pushed investments for agricultural intensification (Garschagen et al., 2012; Käkönen, 2008). Before 1986, farmers mainly relied on rainfed rice where the paddy fields were cultivated only once per year. Later, water management infrastructure, especially low dikes and irrigation channels, enabled farmers to adopt double-rice cropping. The winter-spring crop starts in December right after the monsoon season while the summer-autumn crop is grown between April and July (Ngan et al., 2018; Son et al., 2013). The monsoon season starting in July brings annual flooding so the paddy fields are inundated from August through October. Since the early 2000s, the government has been pushing further intensification by upgrading the low dikes (about 2 m high) to high dikes (about 4.5 m). High dikes prevent fluvial flooding of the paddy fields during the annual monsoon. So, farmers can grow a third crop between August and October, often called the autumn-winter crop.

Today, there is growing evidence that the increase in total rice production, thanks to the high dikes, comes at the expense of sustainability and exacerbates inequalities among farmers (Chapman and Darby, 2016; Chapman et al., 2016; Käkönen, 2008; Tran et al., 2018b). Preventing annual floods from entering the paddy fields reduces the natural supply of nutrients to the field. Over time, this means that farmers have to buy ever larger quantities of fertilizer for the same yield. Previous study has assessed the distributional implications of the high dike policy to a single illustrative farmer with different farm sizes (Chapman and Darby, 2016). A regional plan, however, requires more than just a single farmer assessment. Hence, in this study we center our attention to the spatial inequalities resulting from different scenarios. This enables us to provide a spatially explicit and more targeted recommendations on how to reduce future inequalities. In addition to calculating spatially distributed impacts, we also assess the delta's total agricultural output and equity through aggregated indicators.

4.3. Methodology

To explore both aggregated and distributional impacts of adaptation policies under different futures, we need to ensure that the relevant dynamics that give rise to distributed impacts to rice farming profitability are taken into account. Failure to include multisectoral dynamics and the interactions between them may lead to under- (or sometimes, over-) estimation of the impacts of policies and uncertainties (Jafino et al., 2019; Wagner et al., 2017). Therefore, we need a model that captures both the (bio)physical and the socioeconomic aspects of the delta. In the case of rice agriculture in the Vietnam Mekong Delta, the relevant (bio)physical aspects include, among others, the changing flooding regime, future sediment budget, as well as the various (bio)physical-focused adaptation policies (Chapman et al., 2016; Hoang et al., 2019; Triet et al., 2018). The socioeconomic aspects include land-use change decisions of the farmers, societal preferences of future farming practices, as well as farming profitability accounting (Ngan et al., 2018; Tran et al., 2021, 2018b).

The model we develop follows a theory informed meta-modeling approach (Davis and Bigelow, 2003; Haasnoot et al., 2012, 2014). This approach aims at simplifying and coupling detailed physical models while maintaining the performance of the original models. We combine both statistical and process-based approaches to meta-modeling (Razavi et al., 2012). The choice of the approach to represent the different systems depends on the availability of the complex model and statistical relationships, the possibility of simplifying physical processes, and the fitness to our model purposes.

Meta-modeling has been used for supporting climate change adaptation planning especially when the intention is to explore uncertain futures and alternative adaptation policies (Haasnoot et al., 2014; Hamilton et al., 2015; Lempert et al., 2003). The integrative nature of the meta-modeling approach makes it highly suited for representing the complexity of the agricultural sector in the VMD and its interdependencies with other sectors such as hydrology, land-use change, and nutrient cycling. Furthermore, the meta-model developed in this study has a spatially explicit representation of the system, so that it fits for the purpose of exploring future spatial inequality among farmers in different areas.

4.3.1. Model conceptualization

The integrated assessment model comprises two groups of modules as shown in Figure 4.2. The biophysical modules include the main pressures on the agricultural sector, namely sedimentation and inundation dynamics, as well as the main response variable, namely rice yield. The socio-economic modules include the calculation of farming profitability, which is aggregated at a district level, and the dynamics of land-use change due to the farmers' response to the changing environment. Table 4.1 lists each individual module.

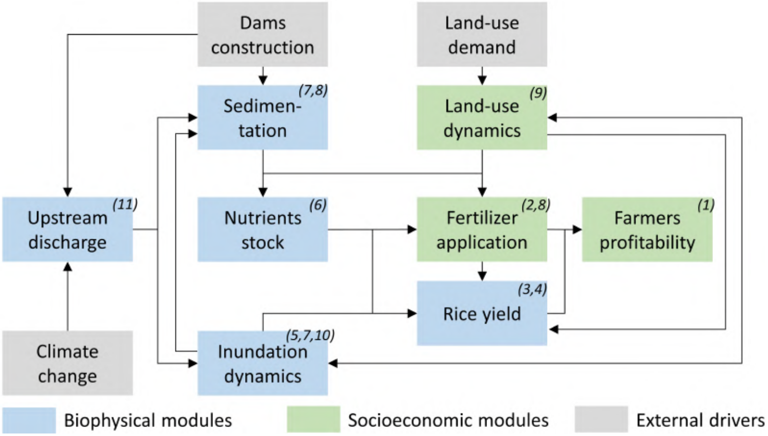

Figure 4.2: Conceptualization of the integrated assessment model. The numbers correspond to modules described in Table 4.1.

Farming profitability, which is the final output of the model, is calculated based on the farmers' income from selling rice and cost of purchasing fertilizer. The rice yield is determined by how much nutrients are available, both from fertilizer and from sedimentation. Therefore, letting the rice fields flood brings the benefit of replenishing the natural nutrients in the soil, although it prevents farmer for having a third crop throughout the year. The sediment budget that enters the VMD is determined by the magnitude of river discharge and the presence of upstream dams in Cambodia. A higher degree of upstream dam development traps more sediment upstream, thus reducing the expected benefits of intentional flooding in the VMD. Dam construction could also offset the climate change impacts of increasing discharge of the Mekong river

Table 4.1: Modules of the integrated assessment model, and the applied modeling approaches

No	Processes	Modeling approach	Description	Source of model equations and parameter values
1	Rice farming profitability calculation	Process-based	Simple equation of income and cost	Tran et al. (2018b)
2	Fertilizer application	Statistical + Process-based	Statistical modeling of average fertilizer use + cause-effect relations of yield deficit	Tran et al. (2018b);Chapman et al. (2016)
3	Rice yield	Statistical	QUEFTS rice yield model	Witt et al. (1999)
4	Rice yield damage due to inundation	Statistical	Cause-effect relations + lookup function	Triet et al. (2018)
5	Inundation dynamics	Statistical	Simplification of complex physical-based hydrological model in the Mekong Delta	Dung et al. (2011); Triet et al. (2018)
6	Nutrients stock dynamics	Process-based	Stock and flows structure	Chapman and Darby (2016)
7	Floodplain sedimentation	Statistical	Simplification of complex physical-based sedimentation model in the Mekong Delta	Manh et al. (2015); Manh et al. (2014)
8	Nutrients contents in sediment and fertilizer	Statistical	Statistical information from experiments	Tan et al. (2004); Manh et al. (2014)
9	Land-use dynamics	Process-based	Cellular automata land-use change model	White et al. (1997); Van Delden et al. (2011)
10	Land subsidence	Statistical	Statistical observation of past land subsidence in the Mekong Delta	Minderhoud et al. (2018)
11	Upstream discharge	Statistical + Process-based	Synthetic hydrographs from global model PCR-GLOBWB + correction for upstream dam development scenarios	Lauri et al. (2012); Sutanudjaja et al. (2018)

(Triet et al., 2020). Furthermore, we include a behavioral land-use change component where farmers can decide what kind of farming practices they want to adopt. However, different land-use classes induce varying rates of land subsidence, which in turn increase the flood risk in the delta. A more detailed explanation of the model is provided in Appendix B.

All processes except for maximum annual upstream discharge generation are spatially explicit with a cell size of 200m x 200m and a time step of one year. We consider the presence of monoculture rice farming, but also other forms of land-use such as aquaculture, fruits plantation, mixed shrimp-rice farming, and urban area. However, as displayed in Figure 4.3, rice farming dominates the land-use of the upstream VMD. The model is run for a period of 38 years from 2012 to 2050, while the period between 2002 and 2012 is used for model evaluation.

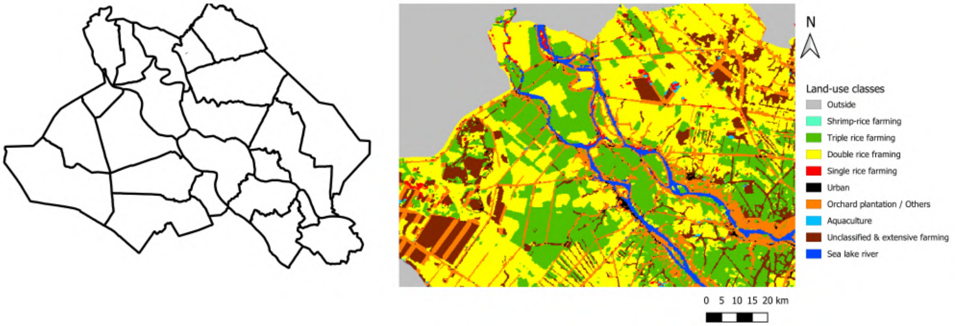

Figure 4.3: Left panel: boundaries of districts in Dong Thap and An Giang, two provinces in the upper Vietnam Mekong Delta. Right panel: land-use map of the case study area in 2011 (GAEN-View, 2013; Sakamoto et al., 2009). The two branches of the Mekong river stretch from the northwest to the southeast.

4.3.2. Model evaluation

To evaluate the adequacy of the model, we focus on whether the model is fit for its purpose of exploring inequality patterns. The fit for purpose approach begins by reflecting on the intended use of the model and continues with formulating evaluative questions that guide the adequacy of the model in fulfilling its purpose (Gramelsberger et al., 2020; Haasnoot et al., 2014). Given that the model will be used for exploring the total output of the agricultural sector and the emerging inequality among farmers under different scenarios, the main evaluative question for the model is: does the model produce credible outcomes and responses to external drivers that are within the boundary of past studies and historical data?

There are two elements to the main evaluative question. The first relates to the realism of the model, i.e., the agreement between the model outcomes with past studies and historical data. The second element is to evaluate the structural adequacy of the model through investigating if the model produces reasonable outcomes given changes in inputs. We adapted the behavior testing procedure in Van Delden et al. (2010) for this. This involves varying the inputs to the model, formulating hypotheses on how the model would behave, and evaluate if the model behaves accordingly. The guiding questions for both model realism and structural adequacy assessments as well as the results to these questions are presented in Table 4.2.

Table 4.2: Summary of fit for purpose evaluation of the model. Detailed results for each guiding question are discussed in Appendix B

Main question: Does the model produce credible outcomes and responses to external drivers that are within the boundary of past studies and historical data?

Evaluation elements	**Guiding questions / hypotheses**	**Results**
Model realism; to what extent the outcomes of the model comply with past studies and observations	Does the model produce the heterogeneity of rice farming profitability?	Although not the entire range of surveyed annual profitability is captured, farm profits calculated from the model (40-70 million Dong) are still within the boundary of surveyed profit (20-80 million Dong).
	Does the model capture the variation of rice yield between the different cropping seasons?	The averages of the modelled yield of each cropping season corresponds well to the historical observation (7 ton/ha for Winter-Spring crop, 5 ton/ha for Summer-Autumn crop, 4 ton/ha for Autumn-Wintner crop), although the range of the modelled yield is generally larger than the observation.
	Does the model produce a reasonable magnitude of annual floodplain sedimentation?	The floodplain sedimentation rate is adequately captured with an average deviation of less than 10%. An exception is for large flood events, where the maximum sedimentation is slightly underestimated by the model.
	Does the model yield a similar pattern of annual maximum water level in the study area?	Historical observations reported in previous studies and the model show a comparable temporal behavior of annual maximum water level at Tan Chau and Chau Doc hydrological stations between 2002 and 2012. In most of the years, the deviation from historical data is less than 10%.
	Does the model capture a sufficient location and pattern accuracy of land-use change processes?	The model simulates land-use change with high pattern accuracy, as measured by clumpiness index. The overall location accuracy is also relatively high (Kappa statistics of 0.793). Lower accuracy is observed for marginal land-use classes such as aquaculture.
Structural adequacy; to what extent changes in model outcomes given changes in model inputs are reasonable	Increase in annual peak discharge would increase the number of flood-induced damaged crops.	At an extreme scenario where the annual peak discharge increases by 60%, around 263% increase of damaged crop is observed.
	Reduction in sediment supply from upstream would also reduce rice farming profitability.	At an extreme scenario where upstream sediment supply decreases by 60%, average profitability of all farms also decreases by 8%. Double-rice farmers experience a bigger lose with an average of 11%, while triple-rice farmers are barely affected.
	Rapid expansion of triple-rice cropping without adequate dikes construction would increase the flood-induced damaged crops.	A rapid expansion of triple-rice cropping system while maintaining the standard dikes construction leads to 26% increase in total flood-induced damage to crops.

In light of Table 4.2, we conclude that the model is sufficiently fit for purpose. Regarding realism, the model sufficiently mimics historical behavior. However, the full spectrum of farming profitability is not captured by the model. One explanation is that the market price dynamics for rice are not accounted for. Regarding structural adequacy, the model behaves as hypothesized. The impacts of increase in annual peak discharge amplify stronger than the impacts of sediment starvation and triple-rice expansion. A higher peak discharge results in wider inundation extent, and this directly affects the observed outcomes (i.e., flood-induced damage to crops). Reduction in sediment supply does not have direct consequences to farming profitability, as nutrients are supplied by not only sediment deposition but also by artificial fertilizer.

4.3.3. Experimental setup

We consider three uncertain factors that also have been accounted for in earlier studies related to climate change adaptation planning for the upper Vietnam Mekong Delta (Manh et al., 2015, 2014; Triet et al., 2020, 2018). Table 4.3 lists these factors as well as the adaptation policies considered in this study. For river discharge, two hydrographs are generated based on two moderate and high-end global emission trajectories of RCP4.5 and RCP8.5 from the Representative Concentration Pathways (RCPs) framework (van Vuuren et al., 2011). Although the plausibility of RCP8.5 has been questioned (Hausfather and Peters, 2020; Ritchie and Dowlatabadi, 2017), these two RCP scenarios have been often used for climate impact assessment in the VMD as they cover both expected and worst-case emission scenarios (Dang et al., 2020; Hoang et al., 2019; Lee and Dang, 2018; Tan Yen et al., 2019).

Table 4.3: Uncertain factors and adaptation policies considered in the experimental setup. The detailed explanation of how uncertain factors affect internal variables is provided in Appendix B

Uncertainty and policy variables		**Possibilities**	**Internal variables affected**
Uncertain factors	Climate-induced river discharge	- RCP 4.5 - RCP 8.5	Inundation and sedimentation dynamics
	Upstream hydropower dam development	- Large development - Medium development - Small development	Sedimentation (reducing total annual sedimentation budget) and upstream discharge (reducing discharge)
	Societal preference over farming practices	- Expansion of triple rice - Shift back to double rice	Future land-use demand, affecting land-use dynamics
Adaptation policies	Hard infrastructural policies	- Further construction of high dikes - Deconstructing high dikes into low dikes	Inundation dynamics (high dikes prevent water level of up to 4.5m) and land-use dynamics (low dikes are not suitable for triple-rice farming)
	Soft policy	- Fertilizer subsidies	Fertilizer application (increasing seasonal fertilizer supply)

For upstream dam development, we consider three degrees of development: small, medium, and large. A higher level of dam development reduces both the annual sediment budget and the peak river discharge (Lauri et al., 2012; Manh et al., 2015). The large dam development, for instance, assumes that all 136 currently planned dams are constructed. For societal preference about different farming practices, we follow recent discussions on this topic (Nguyen et al., 2020; Tran et al., 2018b; Tran and Rodela, 2019). We consider two possibilities: continued agricultural expansion (triple-rice farming systems), and a shift to less intensive agricultural practices (double-rice farming combined with aquaculture and shrimp). These possibilities affect future land-use demand and development.

We consider three policies in addition to a baseline do-nothing policy: two different hard infrastructural adaptation policies, and one soft subsidy policy. The hard policies follow the different views as expressed in the recent debates on flood control: either more construction of high dikes (in accordance to the "Food Production Scenario" in the Mekong Delta Plan) or instead lowering them (Mekong Delta Plan Consortium, 2013; Triet et al., 2018). In the former we assume that all dikes are upgraded into high dikes, while in the latter we assume that all dikes are downgraded to low dikes. The soft policy is supporting farmers whose paddy field is far from the main branch of the Mekong river, as the sedimentation rate decreases with the distance to the river (Manh et al., 2014). We assume that this support is not in cash, but directly in the form of fertilizers: farmers receive 50 kilograms of fertilizer for each cropping season. Such farmers-targeted support is not new in the region. In the past ten years, three subsidy policies (Decree 42/2012/ND-CP, Decision 62/2013/ND-CP, and Decree 36/2015/ND-CP) have been enacted by the central government (Nguyen et al., 2020). All adaptation policies are assumed to be enacted from 2025 onwards.

We use a full factorial experimental design through which we explore all permutations of the uncertain factors and adaptation policies. The design results in 48 simulation experiments (2 river discharge scenarios, 3 dam development scenarios, 2 farming practices preference scenarios, and 4 alternative adaptation policies).

4.3.4. Analysis of model results

From the model we calculate two types of performance indicators. The first type is disaggregated indicators, i.e., district level farming profitability. From this indicator, we can observe the emerging spatial inequalities under different scenarios. Accordingly, farming profitability is aggregated for each of the 23 districts in Dong Thap and An Giang. As our aim is to assess farming profitability in a district relative to other districts in each individual scenario, while also understanding the degree of inequality in each scenario, the district level profitability in each scenario is scaled to the median. Specifically, in each scenario, we calculate the percentage deviation of each district's farming profitability from the median profitability in that scenario. The second type is aggregated indicators: total rice production as an indicator of total agricultural output and Gini coefficient among farmers as a proxy for equity. Total agricultural output is the sum of all rice production in the two provinces. This indicator is of importance to the regional government in order to ensure the adequate supply of rice. The Gini coefficient is calculated from the distribution of district-level average farming profitability.

4.4. Results

4.4.1. Disaggregated performance: inter-district inequality patterns

We began our analysis with the observation of spatial inequality across the 23 districts under different dam development, land-use demand, and river discharge scenarios, as well as under four alternative policies. The spatial inequality is presented in Figure 4.4.

First, we focus on the inequality that results from external developments without adaptation policies (Baseline column in Figure 4.4a-d). Large upstream dam development (lower left maps in Figure 4.4a-d) benefits districts located in the middle of the two branches of the Mekong river. In contrast, a small degree of dam development (upper left maps in Figure 4.4a-d) makes these districts relatively less profitable compared to other districts. There are three districts located to the north and three districts located to the south of the river that have relatively higher profitability under small dam development. Most paddy fields in these six districts are protected by low dikes only. Since low dike areas are regularly flooded, they receive nutrients from floodplain sedimentation during the monsoon. In combination with a small degree of upstream dam development, these six districts receive a relatively higher amount of nutrients from sedimentation. The constant large supply of natural nutrients (under the small dam development) along with the less exploitative double-rice system allow districts with low dike systems to outperform districts with high dikes because high dike districts tend to deplete their nutrient stock at a higher rate due to the triple-rice cropping.

The effect of different river discharge scenarios on inequality patterns can be seen by comparing Figure 4.4a with Figure 4.4c (RCP 4.5 vs RCP 8.5 with triple rice expansion) and by comparing Figure 4.4b with Figure 4.4d (RCP 4.5 vs RCP 8.5 with shift back to double rice). We see that the effect of different river discharge scenarios to altering the inequality patterns is relatively small. For instance, the six districts with the highest profitability under the small dam development and baseline scenarios (top left maps in Figure 4.4a-d) remain the most profitable ones irrespective of the river discharge scenario. The reason for this is that the annual maximum discharges under RCP 4.5 and 8.5 do not differ much during the simulated period of 2012-2050 (see Appendix B for details). Previous studies support this, as they show almost the same change in precipitation and evaporation, which are the two main drivers of river discharge, up to 2050 under both RCP 4.5 and 8.5 in Cambodia and the Vietnam Mekong Delta (Lee and Dang, 2018; van Oldenborgh et al., 2013). This also aligns with a recent study that finds that in the short to medium term, climate-induced discharge changes do not substantially increase flood risks in the delta (Triet et al., 2020).

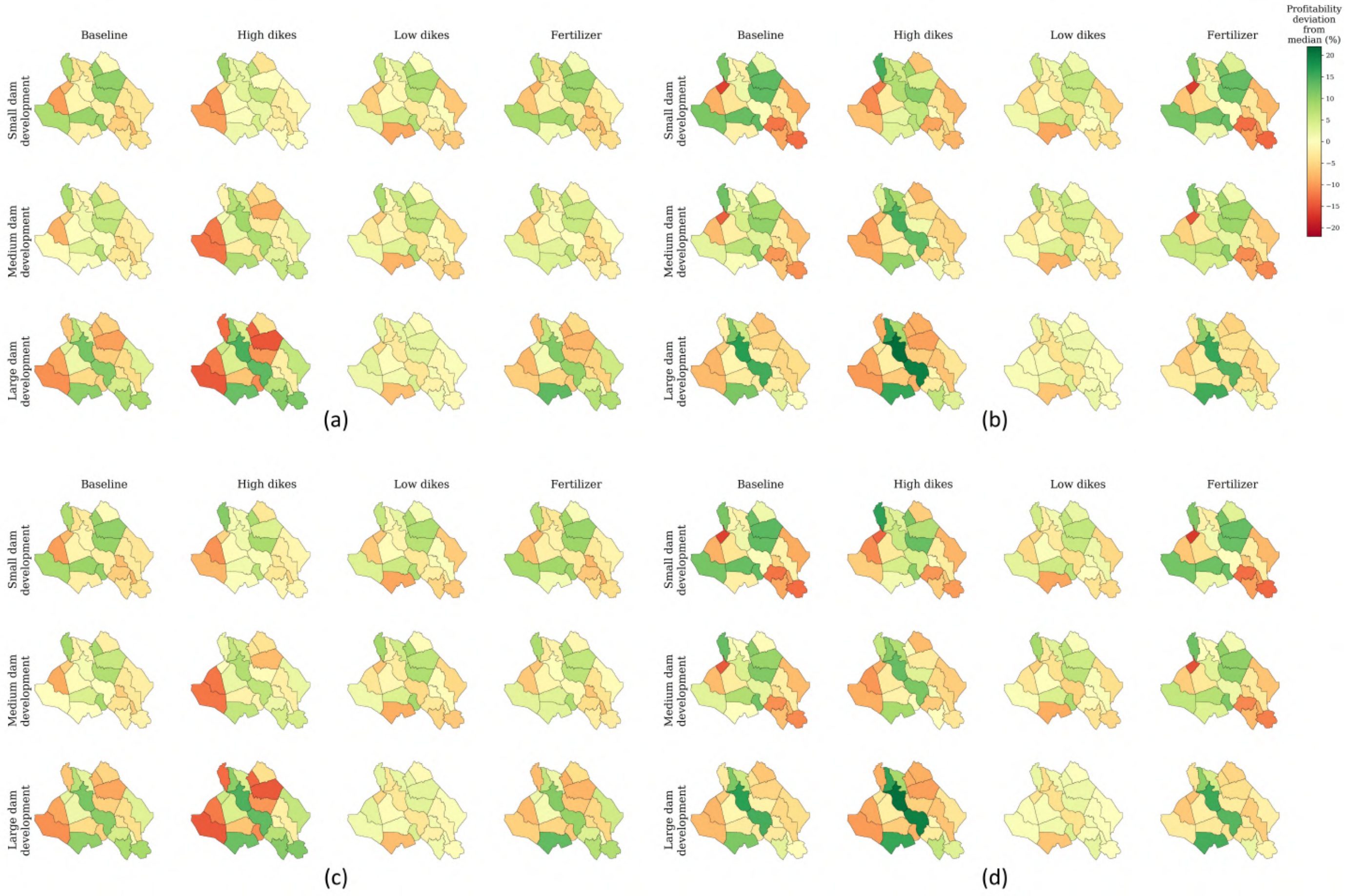

Figure 4.4: Relative profitability of rice farming at district level by 2050 under different scenarios and adaptation policies: (a) RCP 4.5 and triple rice expansion, (b) RCP 4.5 and shift back to double rice, (c) RCP 8.5 and triple rice expansion, (d) RCP 8.5 and shift back to double rice.

To assess the impacts of societal preference and land-use demand on inequality patterns, we compare Figure 4.4a with Figure 4.4b (different societal preferences under RCP 4.5), and Figure 4.4c with Figure 4.4d (different societal preferences under RCP 8.5). The effect is particularly noticeable for districts in the southeast and far east part of the case study area. For instance, under small dam development and RCP 4.5 river discharge, the relative profitability of these districts decreases when a shift back to double-rice happens (top left maps in Figure 4.4a and b). The effect of societal preference scenarios is less pronounced for districts alongside the river. The presence of low or high dikes in a district explains the different effects of the societal preference scenarios. Districts whose relative profitability is less affected are fully enclosed by high dikes, whereas districts with large relative profitability changes are only partially protected by high dikes. Land-use change is hence more subdued in high dike areas, since the suitability of a place for triple-rice farming is highly reliant on the presence of high dikes. Accordingly, the difference in spatial allocation of triple- and double-rice farming from the two societal preference scenarios is mainly seen in districts that currently still have low dikes (e.g., districts in the south east and far east part of the case study area).

Looking at the impact of each external development on inequality patterns under the do-nothing policy shows that upstream dam development has the largest influence. The inequality patterns change and differ substantially between the three dam development possibilities. The two different societal preferences affect only the land-use pattern of some districts while leaving the land-use pattern of other districts, especially those where triple-rice system is very dominant and has long been established, intact. The two river discharge scenarios also hardly affect the inequality patterns, as the discharges in both scenarios have similar magnitude and dynamics.

To illustrate the impacts of alternative adaptation policies to the inequality patterns, we first assume other factors to be the same (ceteris paribus principle). We look at the river discharge scenario from RCP 4.5, small dam development, and a continued expansion of triple-rice (top row in Figure 4.4a, also represented in Figure 4.5d). The high dikes policy prevents annual flooding from entering all rice fields. This in turn precludes sedimentation on double-rice paddy fields and without this free natural nutrient supply this reduces the relative profitability of the six most profitable districts under the baseline adaptation scenario (districts in Cluster 3 and 4 in Figure 4.5). The low dikes policy has the opposite effect. This policy is detrimental to districts which rely on high dikes for triple-rice farming (e.g. districts in Cluster 1 in Figure 4.5). The fertilizer subsidy policy, as expected, slightly raises the relative profitability of districts located far from the river. The fertilizer policy slightly reduces the relative profitability of districts between the river branches (as visible by comparing the fertilizer policy and the baseline policy in the top row of Figure 4.4a, also in as observed in districts in Cluster 1 and 2 in Figure 4.5d).

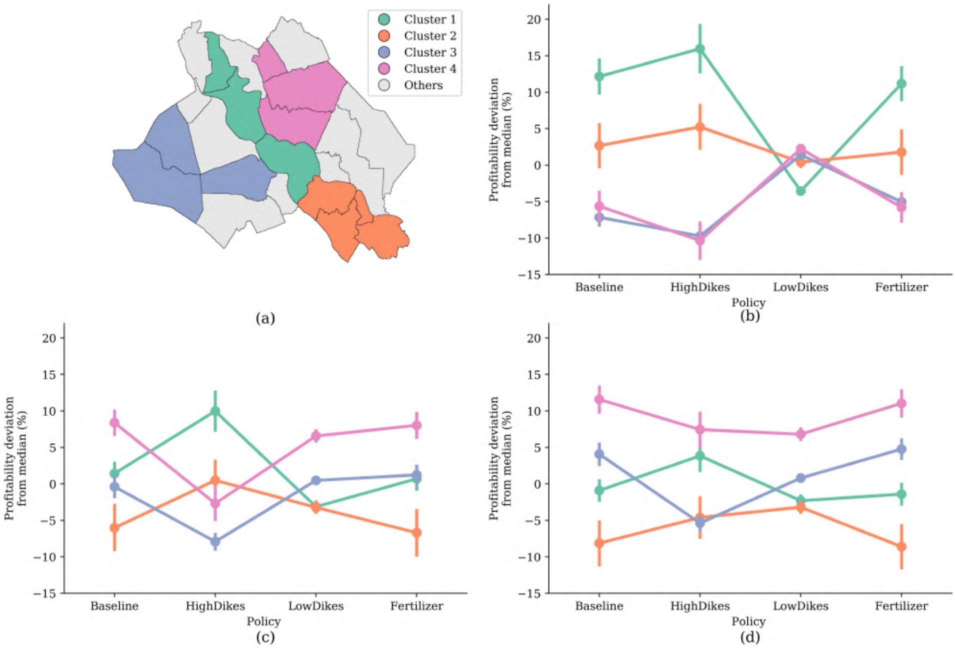

Figure 4.5: Profitability deviation of four different clusters of districts. Panel (a) shows the four representative clusters of districts. Panel (b), (c), and (d) show average profitability deviation under large, medium, and small dam development scenarios, respectively. The colors in panel (b)-(d) correspond to clusters of districts specified in panel (a).

The simulation results suggest that the impacts of external developments and adaptation policies cannot simply be analyzed in isolation from each other as the model shows non-linear responses of inequality patterns. For example, the high dikes policy yields relatively equal profitability across districts under small dam development scenarios, as seen through the convergence of the average profitability deviation in Figure 4.5d. In contrast, districts along the river largely benefit when a larger number of upstream dams is constructed (Figure 4.5b). If we specifically look at the average profitability deviation of districts in cluster 4, the low dikes policy benefits these districts under large dam development scenarios (Figure 4.5b), while it yields opposite impacts in medium and small dam development scenarios (Figure 4.5c and d).The difference in relative profitability of districts along the river and the other districts is even larger under the shift back to double rice scenario (Figure 4.4b, high dikes – large dam development).

4.4.2. Aggregated performance: total output and equity

We use total rice production as an indicator for total output and the inter-district Gini coefficient as an indicator for equity (Figure 4.6). We find neither a large correspondence nor a clear trade-off between these two indicators, as the effectiveness of the policies depends on the scenario. Some scenarios result in low total output but high equity performance, such as in case of the outcomes of the low dikes policy in the top-left part of Figure 4.6. Other scenarios lead to synergies of high total output and equity performance, such as those on the top-right part of Figure 4.6. Figure 4.6 also indicates which adaptation policies perform better than the others. For instance, in many scenarios the low dikes policy performs better than other adaptation policies in terms of equity, whereas the fertilizer subsidy policy performs better on the total output axis.

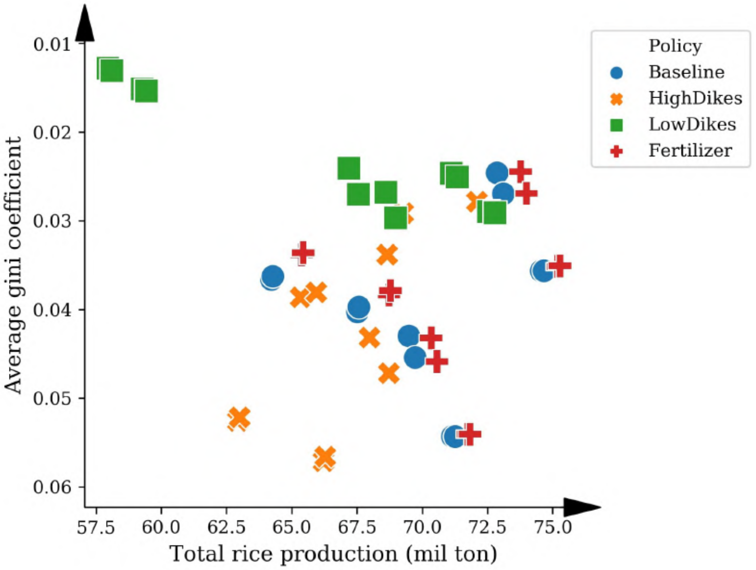

Figure 4.6: Equity (expressed by the district-level Gini coefficient) and total output (expressed by the total rice production) of the agricultural sector under different scenarios. The arrows on the axes represent the direction of desirability (low Gini implies high equity performance and high total production implies high total output performance).

We summarize the total output and equity performance of the alternative policies in Table 4.4. This table reveals four important things. First, upstream dam development is the most influential uncertain factor, with large upstream dam development generally worsens both total output and equity. Most scenarios (68.75%) involving large upstream dam development have relatively low total output and equity performance, while most scenarios (62.5%) involving small upstream dam development score better on both total output and equity. Hence, upstream dam development is a critical variable to be monitored continuously in order to ensure timely adaptation within the region. There are some exceptions to this observation. For instance, the equity performance of the fertilizer subsidy policy given RCP4.5 discharge and triple-rice expansion in case of medium upstream dam development is larger than in case of low upstream dam development. But it worsens again in case of large upstream dam development. A second exception is that the equity performance of the low dikes policy is largest in case of large upstream dam development, but at the expense of total rice production.

Second, climate scenarios which affect the river's peak discharges have only small impacts on the performance of the adaptation policies within the considered time horizon until 2050. For instance, under small upstream dam development and triple-rice expansion, the shift from RCP 4.5 to RCP 8.5 only marginally changes the total output of the high dikes policy. Uncertainties about farmers' preferences, expressed as land-use scenarios, have a larger effect than the climate change induced river discharge scenarios, although not as large as upstream dam development. This implies that uncertainty about future human interventions such as upstream dam developments and future societal preference are more important for the performance of the agricultural sector than uncertainty about climate change impacts to river discharge.

Third, trade-offs between total output and equity turn out to be very dependent on the external development scenario that materializes. The low dikes policy under the large dam development scenario exemplifies a very strong trade-off: there is a very low Gini coefficient (high equity performance) but at the expense of a very low total rice production (low total output performance). The performance of the adaptation policies under the medium dam, RCP4.5, and triple-rice expansion scenario exemplifies a very weak trade-off instead. Here, a higher total output is always accompanied by a larger equity performance as well.

Fourth, the low dikes policy is found to be the most robust alternative across all scenarios. It always has high equity performance in all scenarios, although it yields relatively smaller total output especially in the large dam scenarios. The low dikes policy can be seen as a no-regret alternative since, unlike the high dikes policy, it does not lead to a lock-in. The fertilizer subsidies policy is not as robust as the low dikes policy, but it can still be a preferred alternative due to its adaptability and flexibility – the government can decide in each year if they are going to employ the subsidies.

Table 4.4: Summary of aggregated total output and equity indicators by 2050 across all scenarios. Scoring is presented on a relative scale where '–' refers to the 20% lowest performance while '++' refers to the 20% highest performance across all scenarios.

		Small dam				Medium dam				Large dam			
		Baseline	HighDikes	LowDikes	Fertilizer	Baseline	HighDikes	LowDikes	Fertilizer	Baseline	HighDikes	LowDikes	Fertilizer
RCP4.5 + Expansion triple-rice	Inter-district gini	0	++	+	0	++	0	+	++	-	--	++	-
	Rice production	++	+	++	++	++	0	0	++	-	-	--	0
RCP4.5 + Back to double-rice	Inter-district gini	--	-	++	--	-	-	++	-	0	--	++	0
	Rice production	+	-	+	+	0	--	-	0	--	--	--	--
RCP8.5 + Expansion triple-rice	Inter-district gini	0	+	+	0	+	+	+	+	-	--	++	0
	Rice production	++	+	++	++	++	0	0	++	-	-	--	0
RCP8.5 + Back to double-rice	Inter-district gini	--	--	++	--	-	-	+	--	0	--	++	0
	Rice production	+	0	+	+	0	-	-	+	--	--	--	-

Overall, we find there is no simple preference nor ranking of alternative adaptation policies. A simple example here is the ranking of policies based on its equity indicator under the RCP4.5 and triple-rice expansion scenario (top rows in Table 4.4). Under small upstream dam development, the high dikes policy yields the best performance, followed by the low dikes policy. However, under medium upstream dam development, the baseline and fertilizer subsidy policy become the most preferable ones, followed by the low dikes policy, while the high dikes policy performs worst on equity. If dam development turns out to be even more intense, the low dikes policy takes the first place. This finding implies that which policy should be preferred depends on which external developments are materialized as well as on which performance indicator (either total output or equity) would be given priority by the decision makers. This emphasizes the need for an adaptive plan for coping with uncertain climatic and socioeconomic changes.

4.5. Discussion

4.5.1. Computational model to support equitable climate change adaptation planning

In climate change adaptation planning, future inequality is affected both by how uncertain factors play out and what adaptation measures are taken, requiring one to incorporate multisectoral dynamics. Including multisectoral dynamics requires one to expand the conceptual boundary of the model being used for analysis. This often comes at the cost of reducing the details and resolution of some of the systems through simplifications (Audsley et al., 2008; Davis and Bigelow, 2003). The model we develop in this study is no exception. As we try to make use of existing complex physical models and statistical relations, the integrated assessment model has some limitations worth noting.

The first limitation concerns the dynamics between the double-rice and triple-rice farming. The total demand of each farming type is fully exogenous. One improvement could be to make this demand internal in the model, as this demand in reality might react to factors such as average profitability over time. Furthermore, there also exists the possibility of changing land-use transition rules in the future. Such behavioural changes could be induced by, for instance, change in societal values or improvement in socioeconomic conditions (Malek and Verburg, 2020; van de Poel, 2018). A second simplification relates to the deterioration of soil quality over time. The model approximates the deterioration through the depletion of soil nutrients stock. In reality, soil quality reduction is also triggered by other means such as increase in sulphite concentration and acidity (Tong, 2017; Tran Ba et al., 2016). A third potential improvement is to look beyond rice agriculture, and consider other higher value livelihoods such as aquaculture, fisheries, and fruits and vegetables (Hoang and Tran, 2019; Pham et al., 2020). However, since these livelihoods have only been promoted and adopted recently (Tran et al., 2021), existing models and information regarding their impacts on the biophysical environment and the impacts of biophysical change to their productivity are limited.

Although including multisectoral dynamics unavoidably leads to simplifications in how subsystem are represented because of computational tractability and spatio-temporal alignment of the relevant processes, we still have to ensure that the resulting multisectoral dynamics model is suitable for answering the policy question at hand. For this purpose, we follow the fit for purpose approach for model evaluation. This approach has been promoted as an alternative to standard model validation approaches under three conditions (Haasnoot et al., 2014; Oreskes, 1998; Oreskes et al., 1994; Schwanitz, 2013). The first condition is when the phenomenon being modelled concerns an open loop system, that is, a system in which we have no ground truth to validate the model against. The second condition is when the model is being used to simulate situations that have not existed nor observed in the past. The third condition is when the model is being used to rapidly screen alternative policies under various uncertainties in a strategic decision-making context, rather than for detailed technical planning purposes. These conditions suit the nature of exploration of inequalities under different scenarios. We sometimes do not have exact historical data on some of the sectoral dynamics (e.g., measurement of soil fertility over time), while we need simulate scenarios that have not occurred in the past (e.g., people prefer to shift back to double rice) to investigate the emerging inequality patterns under different scenarios.

An important direction for future research in modeling multisectoral dynamics is improving the way in which model simplifications are accounted for in the entire analysis. One promising, but under appreciated, direction is that of the multi-resolution modeling (Davis and Bigelow, 1998; Hong and Kim, 2013). The core idea is to describe a system with a single model or a family of models involving different levels of resolution. Resolution here can encompass various dimensions of the system, such as process (e.g., detailed physical processes or stylized processes), spatial scale (e.g., small gridded cells or aggregate district area), and time (e.g., monthly or annual). The goal is to enable users to zoom in and out, allowing them to specify and explore parameters at the resolution suitable for their purposes. Adopting multi-resolution modeling to the present context of exploring inequality patterns allows us to identify interesting combinations of adaptation measures and futures that could be analyzed in more detail using a sectoral model with higher resolution. For example, on the temporal dimension, we can explore the impacts of changing monthly temperature and precipitation pattern and how an alternative cropping calendar might be used to adapt to such changes. On the process dimension, we can explore how power asymmetry between farmers within the same dike ring could shape the decision of (de)constructing high dikes, eventually affecting the inequality in the entire region.

4.5.2. Insights for the Vietnam Mekong Delta

This study provides two important insights for agricultural adaptation to climate change planning in the upper VMD. First, we explore how inter-district spatial inequalities vary across scenarios. The variety is mainly observed between two groups of districts: those located along the two branches of the Mekong (districts in the diagonal line from the northwest to the southeast) and those located just to the north and to the south of the river branches. Districts in the first group are fully protected by high dikes since the late 2000s. Local farmers in these districts have adopted triple-rice farming, which is more exploitative in nature. Districts in the second group is only partially protected by high dikes, making swapping between triple and double-rice cropping easier. There are two conditions where districts in the first group become relatively better-off compared to districts in the second group: further construction of high dikes and large upstream dam development. Further construction of high dikes would nudge farmers in other districts to shift to triple-rice farming. However, since the transition would take some time, districts in the first category have an advantage to other districts as they already have adopted triple-rice farming. Large upstream dam development induces sediment starvation which reduces the relative advantage floodplain sedimentation in the monsoon season.

The second important insight is that upstream dam development is the most influential driver whereas climate-induced river discharge is less influential in affecting the VMD's agricultural sector. A negative correlation is observed here: the more upstream dams, the lower the total rice production in the VMD. The relationship between upstream dam development and equity is more complicated as this strongly depends on other uncertain factors and the adaptation policy. For instance, in case of a low dikes policy, increased upstream dam development reduces inequality in the VMD. For the fertilizer subsidy policy, medium upstream dam development results in the largest equity compared to either small or large upstream dam development. While upstream dam development is treated as fully uncertain in this study, in reality it can be a subject of negotiation with the Cambodian government. This emphasizes the importance of pursuing a catchment-wide approach to climate change adaptation planning in deltas through coordination with upstream countries. As for climate-induced river discharge, the temporal dynamics of the two RCPs do not differ much during the time horizon of our analysis. This variable might become more influential if we look at a longer time horizon, for instance until the end of the century.

4.6. Concluding remarks

In this study, we demonstrate the importance of accounting for multisectoral dynamics in model-based support for equitable climate change adaptation planning. This necessity comes from the fact that the interactions between future uncertainties and adaptation policies give rise to distinctive inequality patterns, and that uncertainties and adaptation may originate from multiple sectors. We reflect on how including multisectoral dynamics often comes at the expense of sacrificing details in modelling some parts of the system. Further, we describe how the fit for purpose approach can be useful in assessing the adequacy of such a quantitative model for decision support. Climate change adaptation planning of the agricultural sector in the upper Vietnam Mekong Delta is used as a case study. We explore the consequences of different scenarios of river discharge, upstream dam development, societal land-use preference, and adaptation policies to spatial inequalities as well as aggregated total output and equity performance. While previous studies mostly focus on either the aggregate total output of the agricultural sector in the entire region, or equity issues at an individual farm, in this study we assess both disaggregate equity and aggregate total output at a regional level.

We recognize three broader insights for model-based support for equitable climate change adaptation planning in deltas. First, the relationships between uncertainties and adaptation policies with equity and total output are complicated and non-linear. Different combinations of uncertain future developments and adaptation policies may lead to different inequality patterns. We also present how small changes in an uncertain factor, when compounded with different adaptation policies, can lead to different inequality patterns with different ’winners’ and ‘losers’. This implies that when offering model-based support for climate change adaptation planning, varying only one factor at a time (e.g., degree of upstream dam development) while keeping other factors constant would risk overlooking non-linear interactions effects. This again emphasizes that in the quantitative models, one needs to incorporate relevant multisectoral dynamics as well as interactions between the different systems that give rise to distinctive inequality patterns.

Second, equitable climate change adaptation planning should involve the consideration of not only total output but also equity indicators. Equity performance should be assessed both at an aggregate (e.g., using the Gini coefficient or other aggregation procedures) and at a disaggregate (e.g., the spatial inequality patterns) level. This is because, similar to Anscombe’s quartet (Anscombe, 1973), the same statistical summary (Gini coefficient) can result from completely different inequality patterns. Further, while the aggregated indicators are more practical for comparing the performance of alternative policies, the disaggregate indicators are useful to help in identifying ‘winners’ and ‘losers’ under each combination of adaptation measures and scenarios. Such information is valuable for planners to anticipate changing inequality patterns in advance and to prepare additional policies, such as redistribution measures, to ameliorate inequality. When doing equity analysis, it is important to carefully deliberate the choice of the unit and the scope of the distribution. In this study, we choose to look at spatial equity of socioeconomic variables. In other circumstances, one might need to look at other variables such as distribution of flood safety or environmental degradations.

Finally, given the non-linearity and interaction effects, static strategies are unlikely to have satisfactory performance across multiple scenarios. Instead, strategies that can be adapted over time in response to changing conditions and new information are likely to perform better across the ensemble of scenarios (Maier et al., 2016; Walker et al., 2013a). Such adaptive strategies are often conceptualized as adaptation pathways (Haasnoot et al., 2013). It involves the identification and implementation of short-term no-regret actions while continuously monitoring critical variables and system performance and adapting in response to this to avoid maladaptation. However, in order to make an adaptive delta plan equitable, one needs to move beyond looking only at aggregate indicators. The findings of this study have shown that one needs to also continuously monitor the distributional impacts to the different population subgroups.

5

A novel concurrent approach for multiclass scenario discovery: Exploring spatial inequalities in the Vietnam Mekong Delta under uncertainty

5.1. Introduction

Recent model-based studies supporting climate planning have advocated for assessing distributional outcomes of alternative policies (see e.g., Gourevitch et al., 2020; Kind et al., 2017; Rao, 2013). This is because evaluating policies using aggregate metrics can be misleading, as a policy that is optimal from an aggregate point of view might actually benefit some people at the expense of the others (Hansson, 2007; Rao et al., 2017; Sayers et al., 2018). Looking only from an aggregate point of view can introduce, or even exacerbate inequalities. Furthermore, there exists uncertainty in not only the magnitude and the spatial distribution of climate change, but also in the differential exposure, vulnerability, and adaptive capacity of the people and how these factors evolve over time (Green, 2016; O'Neill et al., 2017; Thomas et al., 2019). This makes it even

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This chapter is based on: Jafino, B. A. & Kwakkel, J. H. (2021). A novel concurrent approach for multiclass scenario discovery using Multivariate Regression Trees: Exploring spatial inequality patterns in the Vietnam Mekong Delta under uncertainty. Environmental Modelling & Software, 145, 105177, doi:10.1016/j.envsoft.2021.105177. The introduction of the Vietnam Mekong Delta case study (Section 5.3.1 and 5.3.2) is shortened, as it has been extensively explained in Chapter 4.

more crucial to assess ex ante the distributional consequences of climate adaptation and mitigation policies.

There are two types of analyses for assessing distributional outcomes. The first one is normative analysis. Here, the aim is to identify a policy that best satisfies a moral principle. For instance, in climate change mitigation, the polluters pay principle and the equal per capita entitlements are two often used imperatives for allocating mitigation responsibility (Gardiner, 2010; Okereke, 2010). In adaptation, the use of differentiated historical responsibility has been proposed for determining funding responsibility (Grasso, 2007), whereas 'putting the most vulnerable first' has been proposed for distributing benefits (Paavola and Adger, 2006). These principles can be operationalized for use in quantitative model-based studies. For example, Adler et al. (2017) operationalize the prioritarian principle (giving higher weights to outcomes experienced by worse-off people) for calculating the social cost of carbon.

The second type is explorative analysis. Rather than putting value judgements on whether the distribution of outcomes is morally acceptable, explorative analysis aims to identify groups who become better-off and worse-off because of the implementation of policies. There are various ways to define population subgroups. For example, Ciullo et al. (2020) look at the distribution of flood risk reduction benefits across people living in different locations (i.e., dike rings). By identifying potential 'winners' and 'losers', explorative analysis can help planners in anticipating unintended distributive consequences and ameliorating potential injustices, for instance by preparing targeted compensation measures to worse-off actors.

When performing explorative analysis, the analyst faces an interpretation problem arising out of two concerns (Jafino et al., 2021b). First, identifying inequality patterns requires calculating the outcomes experienced by individual actors, leading to a larger number of performance indicators. This sometimes requires a modification to the model structure (Rao et al., 2017), and how model outputs are treated (Franssen, 2005; Kasprzyk et al., 2013). Second, the fact that distributional outcomes can vary substantially under different futures necessitates the exploration of inequality pattern across a large ensemble of scenarios (Schweizer, 2018; Taconet et al., 2020). Taken together, the large ensemble of scenarios and the high dimensionality of the output space make it hard to distill policy-relevant insights about the different plausible modes of inequality patterns, and the associated policies and uncertainties under which the different modes arise.

Scenario discovery is an approach for deriving policy-relevant insights from large ensembles of simulation results (Bryant and Lempert, 2010; Groves and Lempert, 2007). Scenario discovery begins with generating simulation results database through running the model under a large number of scenarios (Bankes, 1993; Moallemi et al., 2020), and proceeds with identifying combinations of driving forces that lead to a certain pattern of model outcomes. Scenario discovery thus answers the question 'under which conditions or scenarios do the model outcomes behave in a certain way?'. Scenario discovery by now is a recognized approach to deal with deep uncertainty in model-based planning for climate change and to make sense of large-scale computational experiment (see e.g., Guivarch et al., 2016; Herman et al., 2015; Knox et al., 2018; Lamontagne et al., 2018; Moallemi et al., 2017; Rozenberg et al., 2014; Weaver et al., 2013).

Traditional applications of scenario discovery include policy stress testing and vulnerability analysis (e.g., Eker and van Daalen, 2015; Halim et al., 2015; Hidayatno et al., 2020; Shortridge and Zaitchik, 2018) as part of (Many Objective) Robust Decision Making (Bartholomew and Kwakkel, 2020; Kasprzyk et al., 2013). The main objective here is identifying the conditions under which a policy fails to meet its objectives. This requires users to set a threshold for classifying policy success. If the performance of the policy exceeds (or goes below, in case of a maximization problem) the threshold, the policy is deemed to fail in reaching its objectives. In this established application of scenario discovery, one applies a binary classification to the model output space (from the simulation results database) by dividing the output space into a set of cases where the policy performance meets the minimal requirement and another set of cases where it fails to do so. A rule induction algorithm is then applied to identify combinations of input parameters that lead to the vulnerable set of cases in the output space.

In this study, we investigate the merits of using multiclass scenario discovery, an extension of the standard binary-class scenario discovery, for performing explorative analysis of distributional outcomes. In multiclass scenario discovery the model output space is partitioned into multiple clusters and the input subspaces for each cluster are then identified. Multiclass scenario discovery is appropriate for the explorative analysis of distributional outcomes. As there might be numerous modes of inequality in the future, we cannot simply impose a binary classification on the distributional outcomes. Distinctive inequality patterns might emerge, but due to system complexity and nonlinearity, similar patterns might arise from completely distinct uncertainty and policy scenarios (Jafino et al., 2021a).

We explore two alternative approaches to multiclass scenario discovery. First, we adapt the cluster-then-identify approach as has been used in previous multiclass scenario discovery studies (Gerst et al., 2013; Rozenberg et al., 2014; Steinmann et al., 2020). In this approach, the clustering of the model output space is performed first, followed by the identification of input subspaces for each cluster separately. This can negatively affect interpretability because different clusters in the output space might be linked to overlapping subspaces in the input space. To address this, we propose and test the use of Multivariate Regression Tree (MRT) for multiclass scenario discovery. In this second approach, the output space clustering and input subspace identification are solved concurrently through the MRT algorithm. We apply both the established sequential and the novel concurrent approach for multiclass scenario discovery to an agriculture adaptation planning problem for the upper Vietnam Mekong Delta (VMD). We explore spatial inequality of district-level farms profitability resulting from different realizations of uncertainties and implementation of adaptation measures.

The rest of the paper is structured as follows. In section 2, we describe the two approaches of multiclass scenario discovery and explain further the concept of input and output space separability. In section 3, we provide the background of the case study and introduce the model that is being used. In Section 4, we present the results of the two approaches. In Section 5, we discuss the merits of each approach, i.e., their performance in terms of input and output space separability as well as the resulting scenario narratives identified by each approach. In Section 6, we summarize our main findings and insights.

5.2. Methods

5.2.1. Multiclass scenario discovery

There are a number of scenario discovery applications that extend the output space partitioning from binary classification to multiclass classification (Gerst et al., 2013; Kwakkel and Jaxa-Rozen, 2016; Rozenberg et al., 2014; Steinmann et al., 2020). A major difference between traditional scenario discovery and multiclass scenario discovery lies in the characterization of the output space. In traditional scenario discovery, the output space is partitioned into only two classes: those which are of interest and those which are not (Kwakkel et al., 2013). In contrast, in multiclass scenario discovery the output space is partitioned into more than two classes. Multiclass scenario discovery involves two tasks: the output space has to be partitioned into multiple distinct classes, and for each class input subspaces which are highly predictive for it have to be identified. The highly predictive input subspaces form the narrative behind each class in the output space.

For the first task (partitioning the output space), various approaches for specifying the classes have been used. Classification can be performed by either manually imposing a threshold on the outcome variables (e.g., Guivarch et al., 2016; Rozenberg et al., 2014), or by using a clustering algorithm to automatically identify the classes (e.g., Berntsen and Trutnevyte, 2017; Gerst et al., 2013; Moallemi et al., 2017; Steinmann et al., 2020). In the manual threshold approach, the analyst has full control over how the output space is partitioned, thus enhancing the interpretability of the resulting classes. However, the task becomes increasingly complex with increasing number of outcome variables. In contrast, clustering algorithms can handle a larger set of outcome variables but at the expense of worsening interpretability. For the second task (identifying highly predictive input subspaces), both the Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) and Classification and Regression Tree (CART) algorithms (Breiman et al., 1984) have been widely used. For multiclass scenario discovery, PRIM is iteratively and independently applied to each cluster of the output space (see e.g., Rozenberg et al., 2014). In contrast, CART can identify highly predictive input subspaces for multiple clusters of the output space simultaneously, by predicting the membership of each scenario in one of the identified clusters (see e.g., Gerst et al., 2013).

The partitioning of the output space and the identification of highly predictive input subspaces are traditionally performed sequentially. In this study, we propose the use of Multivariate Regression Tree (MRT) for multiclass scenario discovery to concurrently perform these two tasks. MRT is an extension of CART where multiple dependent variables are being used to characterize the impurity of a decision node (De'ath, 2002). MRT has previously been used for model-based analysis, such as for unraveling trade-offs and synergies between management objectives (Ndong et al., 2020; Smith et al., 2019). For multiclass scenario discovery, the input parameters of the simulation model become the independent variables of the MRT, while the outcomes of interest become the dependent variables. The leaves resulting from the tree then act as the clusters of the output space. The variables being used in each decision node and their corresponding splitting values form the narrative behind each cluster of output space.

Scenario discovery enables the extraction of policy-relevant insights (e.g., exploring plausible modes of inequality patterns) from large-scale computational experiments by making the large ensemble of simulation results interpretable. The interpretability of multiclass scenario discovery can be evaluated using three criteria. The first criterion is output space separability, which is similar to the objective of clustering algorithms (Hastie et al., 2009; Jain, 2010). After clustering the output space, members within the same cluster should have similar outcome characteristics (e.g., spatial inequality patterns), while members from different clusters should be dissimilar. The second criterion is input space separability (Steinmann et al., 2020), which focuses on the rule induction part of scenario discovery. Each class of outcome should originate from distinctive and non-overlapping subspaces in the input space. As illustrated in Figure 5.1, scenario discovery results are ideal if the identified input and output subspaces are completely separable, i.e., if each cluster in the output space is distinctive from the other clusters and is driven by distinctive subspaces in the input space. The third criterion is the resulting number of scenario narratives. Having a larger number of clusters generally leads to better output space separability (Hastie et al., 2009), but it comes at the expense of having more complicated narratives to be communicated to decision makers.

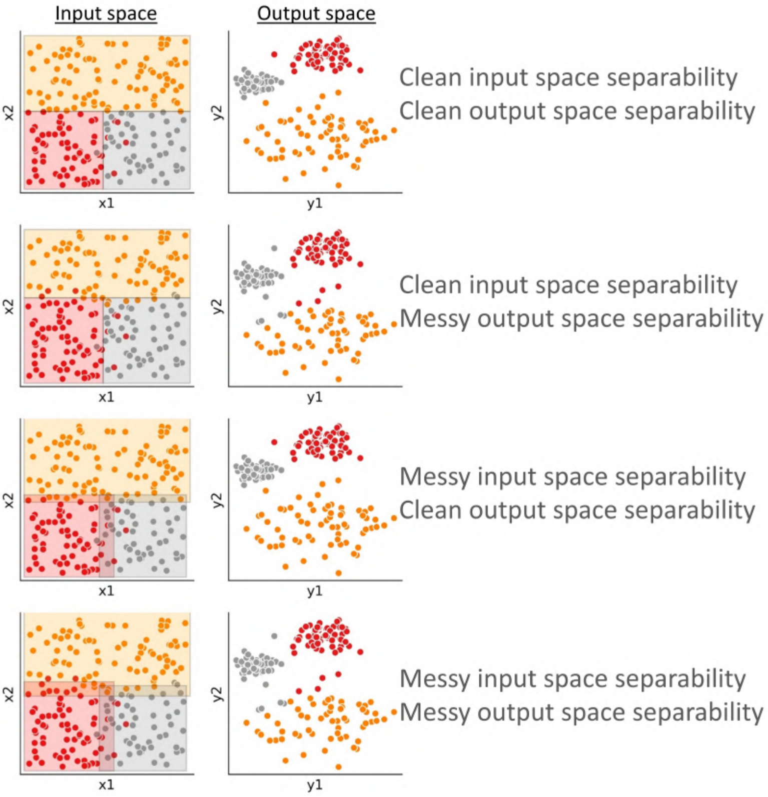

Figure 5.1: Illustration of input and output space separability. The color of the data points is based on the identified clusters in the output space. The shaded regions are the identified input subspaces from the rule induction algorithm. The output space separation in the second and fourth row misclassifies some of the orange cluster into the grey and red clusters. The input space separation in the third and fourth row is not clean as there is too much overlap between the induced subspaces.

5.2.2. Sequential approach: cluster-then-identify

Clustering phase

The clustering phase aims to find distinctive patterns of outcomes within the simulation results. Clustering performance is evaluated by the explained variance (Ketchen and Shook, 1996):

$$EV_k = 1 - \frac{\sum_{k=1}^{K} SSE_k}{SSE_{all}}$$

where EV_k is the explained variance of the algorithm with K clusters, SSE_k is the sum of squared error of members in cluster k, and SSE_{all} is the sum of squared error of the entire dataset. Explained variance generally increases with the number of clusters. The more clusters are used, the smaller the differences between members within each cluster will be. Put differently, higher explained variance implies more homogeneous membership within all identified clusters. To select the optimal number of cluster, explained variance is often used in combination with the elbow method (Ketchen and Shook, 1996). Here, we calculate the difference of the explained variance:

$$\Delta EV_K = EV_K - EV_{K-1}$$

We can then set a threshold T and determine the number of clusters where an additional cluster would yield $\Delta EV_K < T$ as an optimal number of clusters for the particular algorithm.

We consider five clustering algorithms that are commonly used in model-based analysis (Bandaru et al., 2017; Bárcena et al., 2015; Moallemi et al., 2018; Rohmer et al., 2018; Szekely and Rizzo, 2005): k-means clustering, k-medoids clustering, Gaussian mixture model, agglomerative clustering with complete linkage, and agglomerative clustering with average linkage. The combination of clustering algorithm and corresponding optimal number of clusters that yields the highest explained variance is selected for further analysis.

Input subspace identification phase

We adopt the boosted trees algorithm to induce subspaces conditional on each class of the output space (Trindade et al., 2019). Boosted trees build upon CART by generating an ensemble of classification trees, where each tree tries to minimize the impurity in the dataset by iteratively splitting the dataset into leaves (De'ath, 2007; Hastie et al., 2009; Schapire and Freund, 2012). A leaf is impure if it contains mixes of data points from different classes, or, in our case, simulation results from different clusters. We use the Gini impurity criterion:

$$I_G(m) = \sum_{k=1}^{K} p_{mk}(1 - p_{mk})$$

where $I_G(m)$ is the Gini impurity of leaf or node m, K is the total number of classes of the output space, and p_{mk} is the proportion of scenarios with class k in node m. In each iteration, a classification tree looks for all possible splits across the input features and selects the one that yields the highest reduction in impurity. Boosted trees employ an ensemble of weak classification trees through multiple boosting iterations. In each boosting iteration, the algorithm readjusts the weights of misclassified data that are to be inputted to the weak classifier in the successive iterations (Freund and Schapire, 1997; Hastie et al., 2009). Users control the algorithm by setting the maximum number of boosting iteration and limiting the complexity of individual trees (Pedregosa et al., 2011; Zhu et al., 2009).

The setup of boosted trees allows for calculating the relative importance of each input feature. In each splitting iteration, a classification tree uses one input feature to separate a parent node into two child nodes. The importance of an input feature can be estimated as a function of how often a given feature is selected as the splitting variable and how much impurity reduction is achieved. Specifically, the importance is measured by the normalized percentage of total impurity loss across all trees due to splits using the input feature. Finally, for scenario discovery, the most influential input features are mapped back to the identified clusters of the output space – a technique often coined factor mapping (Trindade et al., 2019). The factor maps can be used to visually construct rules or scenario narratives (i.e., combinations of input parameters) for each cluster of output space.

5.2.3. Concurrent approach: Multivariate Regression Trees

MRTs are an extension of univariate regression tree where multiple response variables are being used simultaneously to find candidate splits in each decision node (De'ath, 2002). In each iteration, MRT looks for the best split in the input features that leads to the largest reduction of impurity in the child nodes. For regression problems, the impurity of a node in terms of a single response variable is calculated as the summed Euclidean distance between each data point to the mean of the response variable. Accordingly, in MRT, the total impurity of a node (also termed the error of the node for regression trees) is calculated as the summation of the impurity of each response variable:

$$E_L = \sum_{n=1}^{N_L} \sum_{j=1}^{J} (y_{ij} - \bar{y}_{j(L)})^2$$

where E_L is the error or impurity of node L, N_L is the total number of data points in node L, J is the total number of response variables, y_{ij} is the value of response variable j from data point i, and $\bar{y}_{j(L)}$ is the mean of response variable j across data points in node L. The algorithm looks for the optimal split in the input space that yields the lowest sum of errors from the two child nodes.

In our application, the leaves from the tree will directly turn into the clusters of inequality patterns. This is because the splitting criterion in MRT is intended to minimize the similarity of outcome variables between the child nodes while maximizing the similarity within the child nodes. To maintain interpretability, it is important to balance the size of the tree with the purity of the tree. The size of the tree (the tree 'depth') in an MRT is externally determined by the user by specifying a stopping criterion, such as the maximum number of leaves, or the minimum impurity of the leaves (Breiman et al., 1984; De'ath, 2002; Pedregosa et al., 2011). We use a 10-fold cross validation technique to decide the appropriate depth of the tree (Larsen and Speckman, 2004). In each fold, the algorithm is trained on 90% of the data and the accuracy of the resulting tree is tested on the rest 10% of the data. The accuracy is indicated by the coefficient of determination score:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$$

where SS_{res} is the sum of squared distance between the predicted values and the actual values of the response variables, while SS_{tot} is the sum of squared distance between the actual values and the mean values of the response variables in the entire dataset. The accuracy of an MRT will increase with the depth of the tree. Hence, we also calculate the changes in accuracy and attempt to balance this with the complexity of the tree (Ndong et al., 2020; Smith et al., 2019). The selected tree depth is the one that has changes in accuracy smaller than a specified threshold T.

The resulting decision tree can be analyzed and visually inspected starting from either the leaves or the root (Smith et al., 2019). In leaves-first analysis, users begin with looking for the leaf that contains certain patterns of interest. The analysis then goes up the decision tree to understand conditions (i.e., combinations of input parameters and their values) that lead to the leaf of interest. In root-first analysis, users start from the very first decision node at the top of the tree, and go down the tree to explore a specific scenario. As their names imply, leaves-first analysis is a bottom-up approach to reading a decision tree while root-first analysis is a top-down approach. Note that leaves-first and root-first analyses are concerned with how we read the MRT results. Hence, the choice between these two does not alter the results of the algorithm itself.

Figure 5.2 summarizes how the two main steps in multiclass scenario discovery (i.e., output space partitioning and input subspaces identification) are carried out in the sequential and the concurrent approach. Through iteratively minimizing the impurity of the child nodes, the MRT partitions the output space to find distinctive patterns of outcomes. At the same time, the input features used to split each parent node as well as the splitting value of these features are used to construct narratives behind each final child nodes of the tree.

5.3. Case study

5.3.1. Adaptation planning in the upper Vietnam Mekong Delta (VMD)

In this chapter, we use the similar case study on agricultural adaptation planning in the VMD as used in Chapter 4. The upstream part of the delta – including An Giang and Dong Thap provinces (see Figure 5.3a) – is one of the main rice production hubs in the region. To facilitate further intensification of the agriculture sector, the government

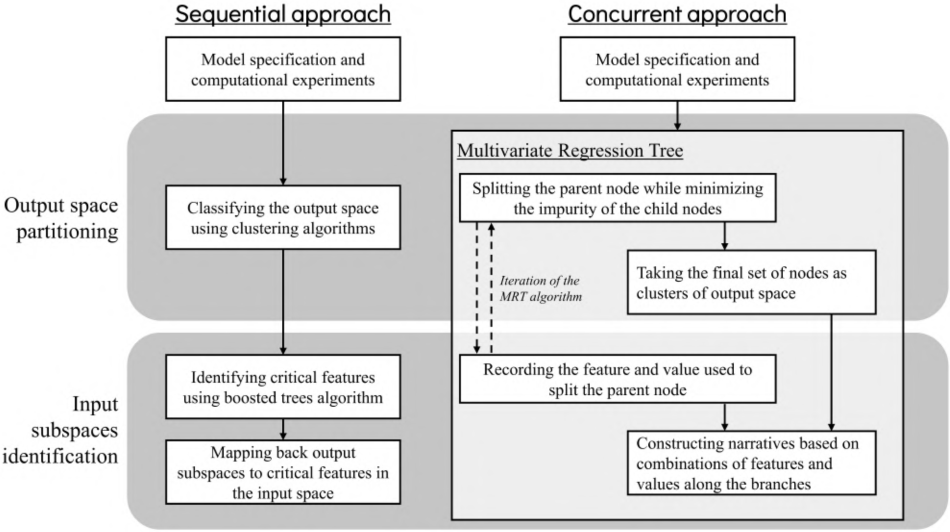

Figure 5.2: Schematic comparison of the sequential and the concurrent approach.

has been constructing high dikes of 4.5 m since the early 2000s, protecting the fields against monsoon flooding and thus enabling farmers to have a third cropping season in each year (triple-rice cropping, see Figure 5.3b). Recently, it was found that the high dikes expansion policy has unintended consequences for environmental sustainability (Garschagen et al., 2012; Tran et al., 2018b) and for inequality between richer and poorer farmers (Chapman and Darby, 2016).

Similar to the previous chapter, we evaluate the spatial inequality of farm profitability. Specifically, we look at how different spatial inequality patterns at a district level emerge from different combinations of anthropogenic pressure, climatic change, and implementation of alternative adaptation policies. This allows us to provide spatially explicit policy advice and administrative area-based recommendations for local decision makers. Our study complements previous inequality studies in the region that focus on the distributional outcomes from a household point of view (i.e., comparing poor and rich farmers at an individual household level) (Chapman and Darby, 2016; Chapman et al., 2016).

5.3.2. Integrated assessment metamodel

We used a spatially explicit integrated assessment model, as developed in Chapter 4, to simulate the profitability of the farmers in An Giang and Dong Thap provinces. The model operates with a spatial resolution of 200m where each cell is represented by a particular land-use function (e.g., single rice, double-rice, triple-rice, orchard plantation, or aquaculture). Profitability is then calculated for each cell. based on income from

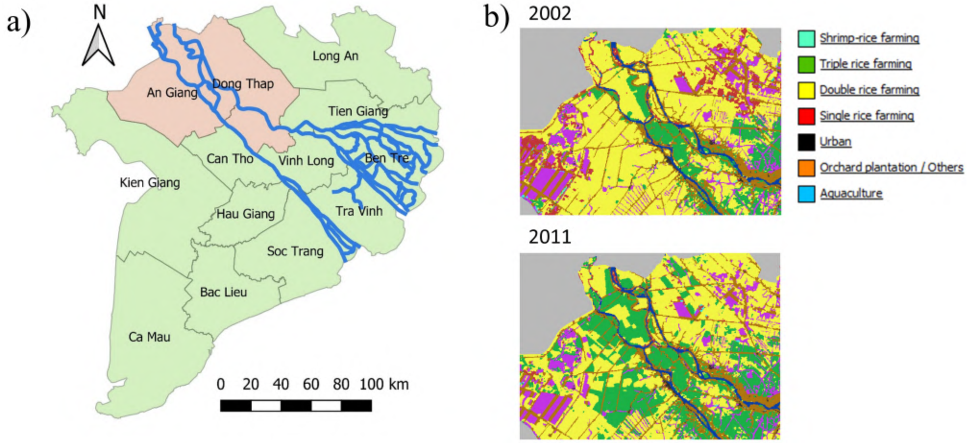

Figure 5.3: a) Provinces in the VMD, with the case study area highlighted in red and the Mekong river branches represented by blue lines; b) Land-use changes in An Giang and Dong Thap between 2002-2011 (GAEN-View, 2013; Sakamoto et al., 2009). The expansion of triple-rice farming indicates the construction of high dikes, as triple-rice farming systems are only possible in high dikes enclosed areas.

selling rice and cost of purchasing fertilizer. We assume that nutrients are the limiting factors of rice yield, which is the case in most Southeast Asian countries (Sattari et al., 2014; Witt et al., 1999). For a detailed description, see Chapter 4 and Appendix B.

Adaptation measures

We tested both 'hard' infrastructural and 'soft' non-infrastructural policies that affect the different modules within the model. The infrastructural policies are related to dike (de)construction. These policies are drawn from the recent flood control debates in the region: either further expansion of high dikes or deconstructing all established high dikes into low dikes (Käkönen, 2008; Tran et al., 2018b; Triet et al., 2020). These policies are applied in An Giang and Dong Thap independently, resulting in a total of four alternative policies. The first soft policy is a seeds upgrade policy. We assume that by using a better seed variety the crops become more resilient to floods. We model this by reducing the steepness of the stage-damage curve (Dutta et al., 2003; Triet et al., 2018), so that the same level of inundation results in a lower yield reduction. The second policy is fertilizer subsidies where 50 kilograms of free fertilizer are distributed to farmers in each cropping season. Free fertilizer is given to farmers located far from the river, as they get a significantly lower nutrients concentration from floodplain sedimentation (Manh et al., 2014, 2013).

Uncertainties

There are five key uncertain factors affecting the productivity of the agricultural sector in the upper VMD. The first uncertain factor is future annual peak discharge that affects flood risk. We use synthetic future hydrographs of the Mekong River, generated by a global hydrological model driven by climatic data from two scenarios (RCP 4.5 and 8.5) (Sutanudjaja et al., 2018; Winsemius et al., 2013). The second uncertain factor is the hydropower dam development upstream in Cambodia. This factor affects the annual peak discharge and reduces total sediment supply to the VMD as the dams trap the sediment upstream. We use five dam development scenarios as worked out by Lauri et al. (2012) and Manh et al. (2015).

The next two factors are the productivity gap among the three seasons. The winter-spring season that starts in December, just after the wet monsoon season, is the most productive season. The summer-autumn season and the autumn-winter season are less productive due to the limited water content in the soil in the former and the high degree of precipitation in the latter. In 2002, the summer-autumn season and the autumn-winter season in Dong Thap produced 38% and 50% fewer yield per hectare, respectively. In 2016, the productivity gap has been reduced to only 26% and 35% for the summer-autumn and autumn-winter season, respectively. In this study, we consider a wide range of plausible future productivity gap between 15-45%.

The last uncertain factor is the society's preference toward the different rice cropping system and the spatial plan for the region. This factor affects future land-use demand, which in turn is spatially allocated by the land-use change module. We consider four scenarios based on the competing narratives of agriculture intensification in the VMD as well as based on the Mekong Delta Plan (Mekong Delta Plan Consortium, 2013; Tran et al., 2018b; Triet et al., 2018): continuing intensification (higher triple-rice cropping demand and lower double-rice cropping demand), reverting to double rice (the opposite of the first scenario), rising non-rice preferences (higher demand for alternative livelihoods such as orchard plantation, aquaculture, and shrimp-rice farming), and increasing urbanization (higher demand for residential area).

Experimental setup

The setup of the case study is summarized using the XLRM framework (Lempert et al., 2003) in Figure 5.4. To allow for an exhaustive exploration of plausible combinations of uncertainties and policies, we apply full factorial sampling to uncertain factors that are categorical and ordinal, i.e., we sample all possible combinations of categorical and ordinal input factors. These factors include the six policy variables and some of the uncertain variables (i.e., river discharge and farming practice preference). We combine the full factorial sample with a Latin Hypercube Sampling of the productivity gap uncertainties, as the values for these uncertainties take a continuous range. This experimental setup results in a total of 43200 computational experiments. The exploratory modelling workbench (Kwakkel, 2017) is used to perform these experiments.

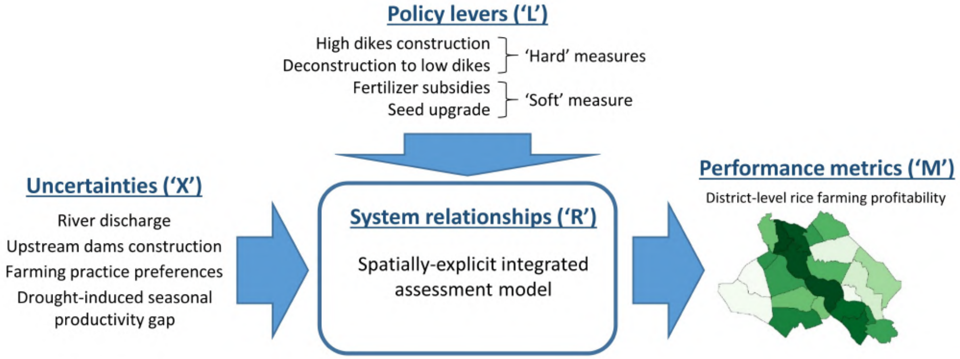

Figure 5.4: XLRM overview of the case study.

5.3.3. Post-processing of simulation results

The clustering phase in the sequential approach and the calculation of error in the concurrent approach require the computation of 'distance' between the outcomes of each scenario in the simulation results database. To avoid having one outcome variable dictating the distance calculation, the values of each outcome variable are usually normalized to 0-1 across the scenarios (e.g., Giudici et al., 2020; Smith et al., 2019). Normalization of each outcome variable across the entire scenarios when doing explorative analysis of distributional outcomes is problematic. The outcome variables are the outcomes for each district. By doing a normalization we lose sights of the relative performance of each district compared to all other districts within each scenario (see Figure 5.5a and b). Hence, we calculate instead the 'relative profitability' of each district, i.e., the 0-1 normalization is applied between the performance of each district within each scenario, instead of across scenarios (see Figure 5.5c). In this way we maintain the information regarding the relative 'winners' and 'losers' in each scenario. As a result, the clustering algorithm is forced to look for distinctive inequality patterns.

5.4. Results

5.4.1. Sequential approach

The first step in the sequential approach is clustering the output space into a number of representative inequality patterns. We test five alternative clustering algorithms while varying the number of clusters (see Appendix C for details). We find that the k-Means algorithm with seven clusters yields the most satisfactory performance which balances the explained variance and the number of final clusters. The remainder of the sequential approach is thus based on the results from this clustering setup.

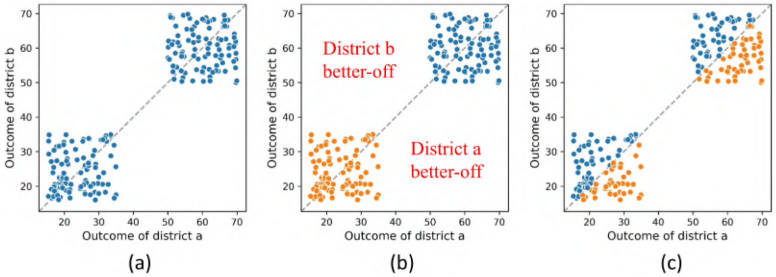

Figure 5.5: Illustration of the implication of normalizing across scenarios and within scenarios. (a) Outcomes for the two districts across 500 scenarios. (b) Clustering results when outcomes are normalized across scenarios. Here we see that in each cluster we have scenarios where both district b and district a is better-off. (c) Clustering results when the outcomes are normalized for each individual scenario. Here the resulting clusters have distinctive inequality pattern (district a is better-off in the orange cluster, vice versa).

Figure 5.6 shows the seven representative inequality patterns from each cluster of the output space. The representative scenario is taken from the medoid of the corresponding cluster, that is, the scenario which output has the smallest Euclidean distance to all other scenarios in the cluster. At a glance, we can see that cluster 2, 3, 6 and 7 have similar inequality patterns where three districts located around the mid-northeastern part of the region have a higher relative profitability of higher than 0.7. The patterns are different once we inspect them in more detail. For example, in cluster 3, the district located in the top northwestern part of the region is not relatively better-off. In cluster 6, this district is significantly better-off compared to the others (relative profitability = 1).

Next, we use the boosted trees algorithm to first identify the most critical input features that best explain the seven clusters of inequality patterns. Figure 5.6b shows the results of the input feature scoring. The most important input feature is the degree of upstream dam development, followed by three dikes construction policies: expansion of high dikes in An Giang, in Dong Thap, and reverting back to low dikes in An Giang. The other input features have substantially lower importance scores.

We use the four most important input features to map back the input space to the seven clusters of output space. The importance scores of these four features add up to 0.705, implying that these features contribute to 70.5% of the total impurity reduction in the entire ensemble of trees. Figure 5.6c shows the factor map for each cluster, where the cluster numbering corresponds to the seven inequality patterns in Figure 5.6a. Since three of the four most important features are related to dike construction policies, we combine them into a single axis (i.e., the vertical axis on Figure 5.6c). The numbers underlying the heatmap correspond to the fraction of scenarios in that particular cluster. For example, 20% of the 7879 scenarios in cluster 1 are scenarios with high upstream

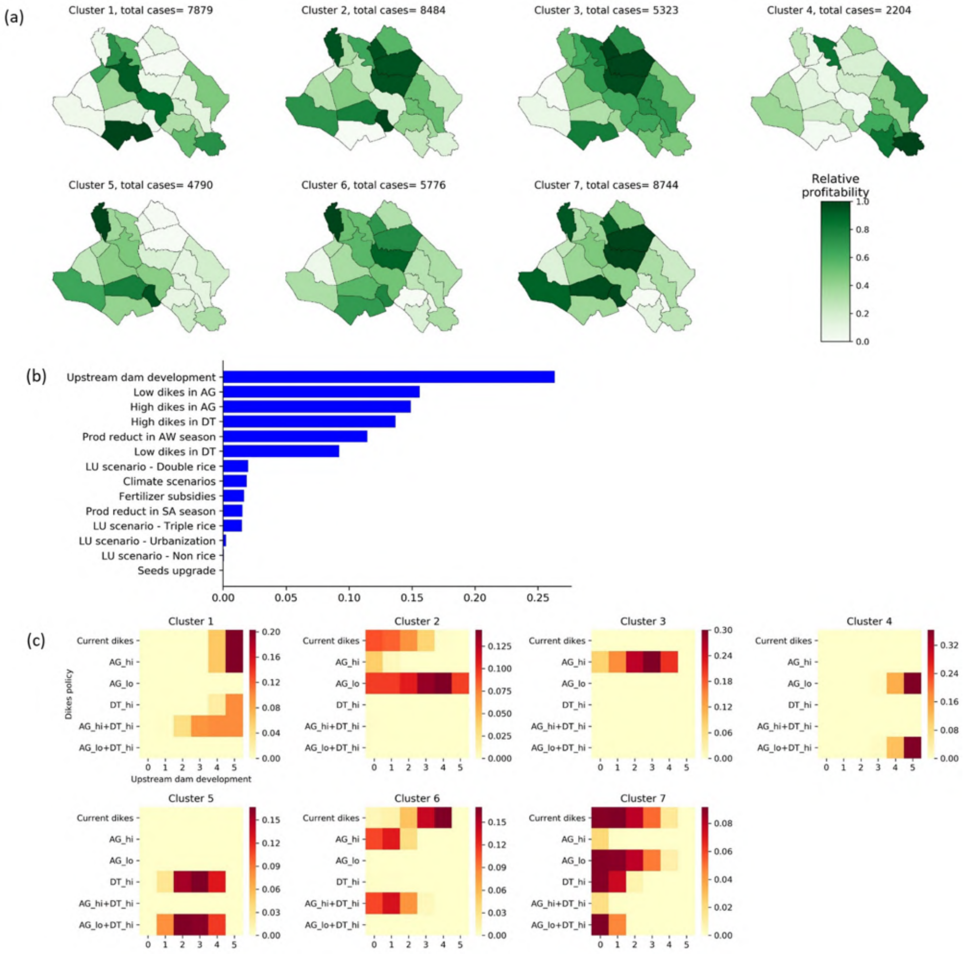

Figure 5.6: Results from the sequential approach: (a) representative inequality pattern from each cluster of output space and the number of scenarios in each cluster; (b) relative importance of the input parameters as identified by the boosted trees algorithm; (c) factor maps of the identified clusters of output space. AG_hi and DT_hi refer to further construction of high dikes in An Giang and Dong Thap, respectively. AG_lo refers to deconstruction of high dikes into low dikes in An Giang. The colorbar in each sub-figure refers to the fraction of total scenarios within that particular cluster.

dam development with current dikes configuration in the VMD and another 20% have a combination of high upstream dam development and low dikes policy in An Giang.

Figure 5.6c shows that cluster 1, which has one of the more distinctive inequality patterns (see Figure 5.6a), is primarily induced through a combination of high sediment trapping due to upstream dam development, and, either expansion of high dikes in

An Giang, or the preservation of current dikes. Inequality pattern as exemplified by cluster 4 is caused by the transformation of high dikes back into low dikes in An Giang together with a high degree of upstream dam development. Cluster 2 and 7, which have similar inequality patterns, emerge if upstream dam development is relatively low and either the low dikes policy in An Giang is enacted or the current dikes system is maintained. Further construction of high dikes in An Giang in combination with relatively low upstream dam development would lead to inequality patterns as depicted either in cluster 3 or 6.

What do these results imply for adaptation planning in the VMD? The most important insight is that the interaction between what the VMD government does (in terms of dikes (de)construction) and what the Cambodian government does (in terms of hydropower dams development) has non-linear effects on the emerging spatial distribution of farms profitability. For instance, a relatively small degree of upstream dam development would make provinces that expand their high dikes worse-off. This follows from comparing cluster 3 and 6 with cluster 5. In cluster 3 and 6, the high dikes policy in An Giang is enacted and this makes districts within An Giang relatively worse-off. In cluster 5, the high dikes policy in Dong Thap is also enacted and this leads to districts in Dong Thap becoming worse-off. This stresses the importance of having transboundary basin management in order to ensure equitable future for the VMD farmers.

5.4.2. Concurrent approach

The first step in the concurrent approach is growing the regression tree and selecting an appropriate tree size. We iteratively grow the tree from three to 40 leaves and observe the evolution of the cross-validation scores (see Appendix D for details). We find that the tree with 18 leaves yields the most satisfactory cross validation score and proceed with this tree size in the remainder of the concurrent approach. For visualization purpose, we separate the entire regression tree into two figures: Figure 5.7 and Figure 5.8 together make up the entirety of the regression tree.

The first splitting variable identified by the MRT is the expansion of high dikes in An Giang. Figure 5.7 shows the left branch of the tree (high dikes in An Giang is expanded) while Figure 5.8 shows the right branch of the tree (high dikes in An Giang is not expanded). The number of scenarios and the representative inequality pattern from all scenarios in each leaf are provided at the bottom of the figures. Similar to the sequential approach before, the medoid scenario in each leaf is assigned to be its representative inequality pattern. It is important to restate here that in each scenario the profitability of the districts is normalized between 0 and 1 where darker green color means higher relative profitability. Here, we illustrate how we can use either leaves-first or root-first analysis to interpret the results of the MRT. We will use root-first analysis to analyze the left branch of the tree and leaves-first analysis for the right branch of the tree.

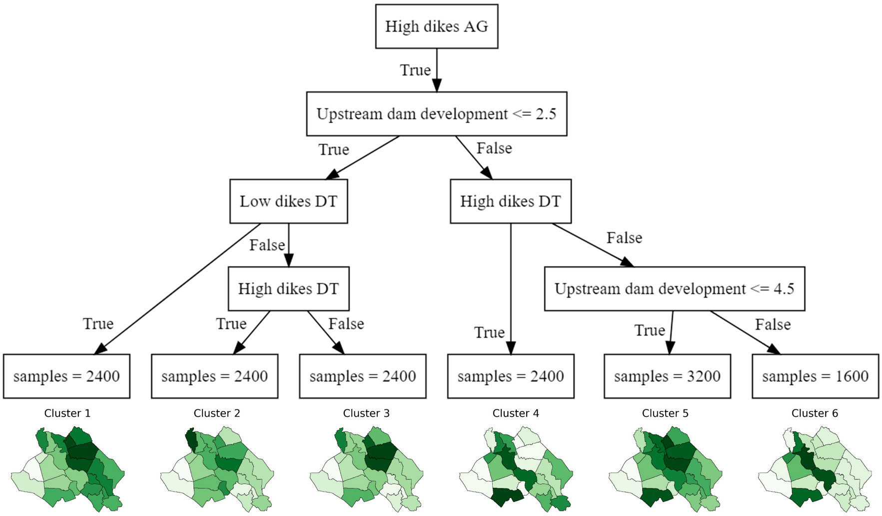

Figure 5.7: Left branch of the multivariate regression tree and the corresponding representative inequality pattern.

The left branch of the tree as shown in Figure 5.7 contains scenarios where the high dikes policy in An Giang is implemented. For illustration, we approach this side of the tree using root-first analysis. The subsequent decision node here is the degree of upstream dam development with a cutoff point of 2.5 (we have six levels of upstream dam development, with 0-2 being no to medium degree of upstream development and 3-5 being higher degrees of development). If upstream dam development is relatively small, the next deciding factors are the dikes policy in Dong Thap. Low dikes policy leads to inequality pattern in cluster 1, high dikes policy leads to cluster 2, while maintaining the current dikes distribution in Dong Thap leads to cluster 3.

It is interesting to compare cluster 2 and cluster 4, as, from the root-first perspective the only difference is the degree of upstream dam development. If high dikes are expanded in both provinces and many upstream dams are eventually built, districts alongside the river will become substantially better-off (cluster 4). However, a smaller degree of upstream dam construction will lead to a less striking difference in relative profitability (cluster 2). Cluster 6, although having a different narrative, has a similar inequality pattern as cluster 4. Even without expansion of high dikes in Dong Thap, a very large degree of upstream dam development in combination with high dikes policy in An Giang still make districts alongside the river better-off.

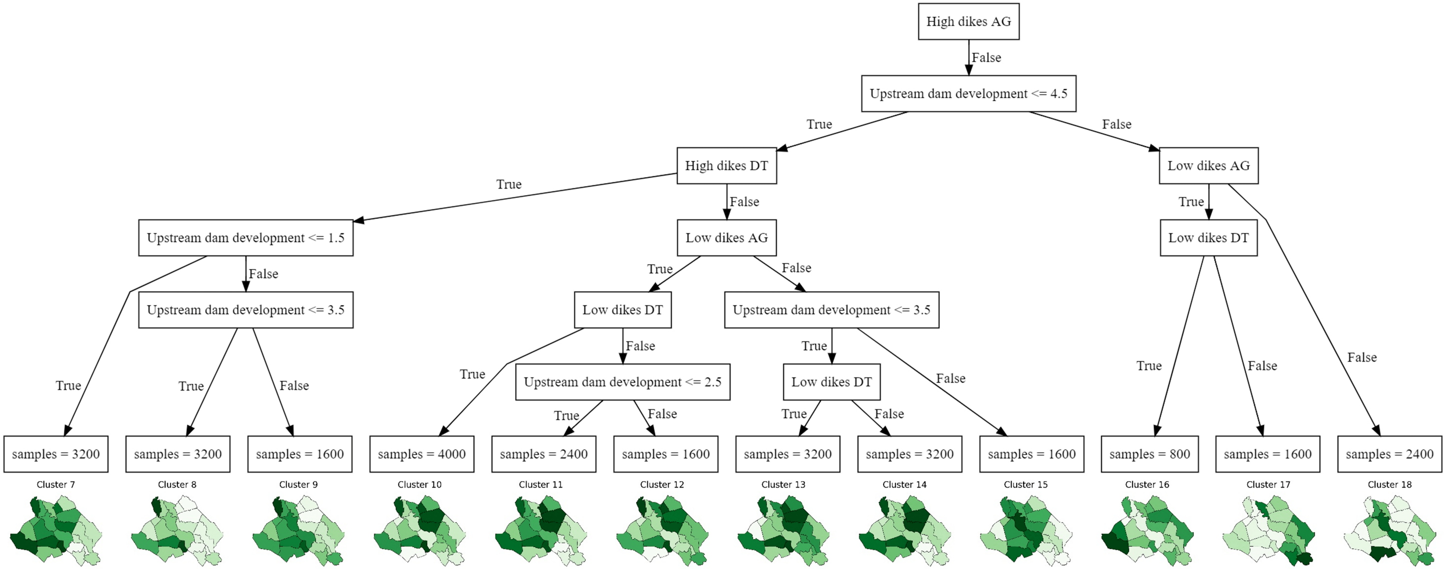

Figure 5.8: Right branch of the multivariate regression tree and the corresponding representative inequality pattern.

The right branch of the tree contains the remaining 12 leaves (Figure 5.8). We approach the interpretation of this branch by following leaves-first analysis. We focus on three visually distinct inequality patterns. The first pattern is typified by the higher relative profitability of districts alongside the river, as observed in cluster 15 and 18. Both clusters actually have a similar narrative where no dikes policy is taken, and upstream dam development is relatively large. The second distinct pattern is exemplified by cluster 8 and 9. In both clusters, districts located to the north of the river have smaller relative profitability. Both clusters have a similar narrative of medium degree of upstream dam development, and with high dikes being expanded in Dong Thap.

The third distinct pattern is observed in cluster 10-14 and cluster 16. The main pattern here is that there are three districts located to the north of the river, three districts located to the south of the river, and one district on the northwest corner of the region who are better-off. This pattern can emerge from multiple future conditions. For example, a condition for cluster 10-14 to materialize is no extremely high upstream dam development. However, Cluster 16 shows that even if all planned upstream dams are built, a similar inequality pattern could emerge if all dikes in both An Giang and Dong Thap are reverted back into low dikes.

What can the VMD government learn from the concurrent approach? Through combining both root-first and leaves-first analyses, we can clearly see that similar narratives could lead to distinctive patterns of spatial distribution, whereas at the same time similar distribution patterns could emerge from distinctive narratives. The decision tree can easily help the government in understanding plausible inequality patterns and pathways that lead to those patterns, and thus preparing additional measures to compensate worse-off districts.

5.5. Discussion

5.5.1. Input space and output space separability

The induced input subspaces though scenario discovery have a perfect separability if each subspace is mutually exclusive with the others. While traditionally this has been quantified through the density and coverage indicators (Bryant and Lempert, 2010), the use of these indicators is not applicable for sequential multiclass scenario discovery as presented here. This is because in the sequential approach we do not set a strict boundary on the identified subspaces. However, from a visual inspection, we can see that some of the identified subspaces are overlapping with each other (see Figure 5.6c). For example, the combination of current dikes and low to medium upstream dam development exists in the identified subspaces of cluster 2 and 7. In contrast, the concurrent approach produces completely separable input subspaces, as each end leaf has unique scenario narratives (i.e., combination of the scenario variables). Therefore, the concurrent approach leads to better input space separability compared to the sequential approach.

To quantify output space separability, we calculate the average Euclidean distance between the relative profitability of the 23 districts in all scenarios within each cluster (within-class dissimilarity) as well as between scenarios from different clusters (between-class dissimilarity). A better separability of output space thus entails low within-cluster distance and high between-cluster distance. From Table 5.1, we can see that neither approach is superior to the other. The concurrent approach has better within-cluster average distance compared to the sequential approach. This can be explained by the more granular separation of the output space, so that each cluster consists of more similar simulation results. In contrast, the sequential approach has better between-cluster average distance compared to the concurrent approach. This is explained by looking at the representative inequality patterns from the concurrent approach on Figure 5.7 and 5.8, where there are many clusters that have similar inequality patterns. To this end, it is interesting to observe in more details the (dis)similarity of the resulting narratives from the two approaches.

Table 5.1: Comparison of output space separability

	Within-cluster average distance	**Between-cluster average distance**
Sequential approach	2.997	6.329
Concurrent approach	2.628	6.007

5.5.2. Comparison of resulting scenarios

In this section we compare the clusters of inequality patterns from the two approaches as well as the narratives of drivers that lead to each cluster. First, we see that the clusters of inequality patterns from the concurrent approach have a higher degree of variation as there are several clusters that have a comparable pattern. However, most of the patterns identified from the concurrent approach are also present in the sequential approach. For example, the inequality patterns of cluster 4, 6, 15, and 18 from the concurrent approach are comparable to the inequality pattern of cluster 1 from the sequential approach. Table 5.2 lists the other pairs of similar inequality patterns identified by the two approaches.

Two exceptions worth noting are cluster 15 and 16 from the concurrent approach. In general, cluster 16 has a similar inequality pattern to cluster 2 from the sequential approach. However, the most profitable districts in cluster 16 are the two districts in the westernmost part of the region. Furthermore, the easternmost district is also slightly better-off than many of the other districts. Cluster 15 has similar inequality pattern to cluster 1 from the sequential approach. The difference is that many districts to the north of the river are also relatively better-off in cluster 15.

Table 5.2: Comparable inequality patterns their corresponding narratives of drivers from the sequential and the concurrent approach

Cluster from the sequential approach	**Comparable cluster from the concurrent approach**	**Narratives of drivers of inequality patterns from the sequential approach**	**Narratives of drivers of inequality patterns from the concurrent approach**
1	4, 6, 18	- High to very high degree of upstream dam development and high dikes in An Giang and/or Dong Thap - Very high degree of upstream dam development and maintaining current dike system	- Medium to high degree of upstream dam development and high dikes in An Giang and Dong Thap - Very high degree of upstream dam development and high dikes in An Giang - Very high degree of upstream dam development and maintaining current dike system
2	10, 12	- Low dikes in An Giang - Low to medium degree of upstream dam development and maintaining current dike system	- Low dikes in An Giang and in Dong Thap - Medium degree of upstream dam development and low dikes in An Giang
3	1, 3, 5	- Low to high degree of dam development and high dikes in An Giang	- Low degree of upstream dam development, high dikes in An Giang and low dikes in Dong Thap - Low degree of upstream dam development and high dikes in Dong Thap - Medium to high degree of upstream dam development and high dikes in An Giang
4	17	- Very high degree of upstream dam development and low dikes in An Giang	- Very high degree of upstream dam development and low dikes in An Giang
5	8, 9	- Medium degree of upstream dam development and high dikes in Dong Thap	- Medium degree of upstream dam development and high dikes in Dong Thap
6	2	- Medium to high degree of upstream dam development and maintaining current dike system - Low degree of upstream dam development and high dikes either only in An Giang or both in An Giang and Dong Thap	- Low degree of upstream dam development and high dikes both in An Giang and Dong Thap

7	7, 11, 13, 14	- Low to medium degree of upstream dam development and maintaining current dike system or low dikes in An Giang - Low degree of upstream dam development and high dikes in Dong Thap	- Low degree of upstream dam development in combination with either high dikes in Dong Thap or low dikes in An Giang - Low to medium degree of upstream dam development in combination with either low dikes in Dong Thap or maintaining the current dike system

Most of the narratives behind each inequality pattern identified by the two approaches are also comparable (see Table 5.2). For example, cluster 4 and 5 from the sequential approach have similar narratives to their counterparts from the concurrent approach. Since in the concurrent approach we do not limit our analysis to only four most important factors, this approach yields slightly richer and more detailed narratives for some of the clusters. In the concurrent approach, the low dikes policy in Dong Thap is identified as an important part of the narratives for some of the clusters (i.e., cluster 1, 10, and 16 from the concurrent approach).

The more aggregated results of the sequential approach conceal some diversity within the scenarios. For example, maintaining the current dike system in combination with a medium to high degree of upstream dam development is part of the narrative for cluster 6 from the sequential approach. However, the same narrative leads to different inequality patterns if we follow the decision tree from the concurrent approach (i.e., cluster 14 and 15). This is because combining the inequality patterns from cluster 14 and 15 of the concurrent approach will average out the profitability of districts that are better-off in each cluster, resulting in a more equal distribution as exemplified by the representative inequality pattern of cluster 6 from the sequential approach.

5.5.3. Reflection for practice

The comparisons above show that the concurrent approach outperforms the sequential approach. However, it comes with a caveat of having a larger number of final narratives. This raises the question of whether the benefit of better input space separability in the concurrent approach does outweigh the drawback of having more clusters and narratives. To answer this, we need to first revisit the main purpose of scenario discovery itself, which is to craft narratives about system outcomes under certain combinations of uncertainties/polices (Bryant and Lempert, 2010; Greeven et al., 2016; Lempert et al., 2006). In particular, attention needs to be given on the decision-making contexts, and on the use-case of the narratives generated from the multiclass scenario discovery exercise.

Past scenario discovery studies have a varying level of stakeholder involvement. Some studies indicate a relatively low degree of interactions with stakeholder (e.g., Hidayatno et al., 2020; Lamontagne et al., 2018; Moallemi et al., 2017). In these studies, the generated narratives are mainly aimed at defining plausible future pathways, which are to be used by other institutions for other contexts. Other studies indicate a more frequent and thorough interactions (e.g. Trindade et al., 2019; Hamarat et al., 2013; Groves et al., 2019). The aim of such studies is often more specific, such as for stress testing alternative policies and identifying vulnerabilities. Accordingly, narratives generated in such use-cases are used solely for the purpose of the project. The sequential approach, with a relatively lower number of narratives, is more suitable for the former type of use-cases (relatively little stakeholder engagement, narratives to be transferred for other contexts). The concurrent approach, with better separability performance but more narratives, is more suitable for the latter type of use-cases (more intense stakeholder engagement, more focused analysis).

In addition to the characteristics of the use-cases, there are two further important points to note with respect to the use-case of multiclass scenario discovery. First, an important strength of scenario discovery is to facilitate deliberation, and this obviously requires thorough engagements with clients and stakeholders. Accordingly, narratives from scenario discovery should not be shared as-is with stakeholders. Rather, the analyst should always be at the interface between the policy problem and the model used to support the policy analysis (Cuppen et al., 2021). So, the issue with having a larger number of scenarios is that the analyst might have to do more work to distill the message from the analysis before conveying it to others, and this can be done through consultation with the stakeholders.

Second, as some clusters from the concurrent approach have similar inequality patterns, presenting them simultaneously might not be appropriate. Without the help of the results from the sequential approach, the regrouping of similar clusters from the concurrent approach can be performed through either root-first or leaves first analysis (Smith et al., 2019). In leaves-first analysis, the key step is to identify clusters with similar representative inequality patterns. This can be done qualitatively through visual inspection (as done in Table 5.2) or through consultation with stakeholders. To aid this process, the analyst can calculate the average distance between any pair of clusters and combine those with relatively low distance. The final choice of the number of narratives should not be the analyst's call, but instead, decided in a participatory and interactive setting with stakeholders. If what is of more interest is the narratives, instead of the resulting inequality patterns, the root-first analysis can be followed instead.

5.6. Conclusion

Adaptation policies and uncertainties, and the interactions between them, almost unavoidably yield differential and unequal consequences to different people. The task of exploring future inequality patterns and understanding their drivers fits the nature of scenario discovery. In scenario discovery, one maps back the output space of a model (in this case, inequality patterns) with its input space (policy levers and exogenous uncertain factors). In this study, we contribute to the advancement of scenario discovery in two ways. First, we propose two novel criteria to evaluate the quality of multiclass scenario discovery results: output space separability and the number of resulting narratives. Second, we propose a novel concurrent approach for multiclass scenario discovery by using Multivariate Regression Trees (MRT).

Using agriculture adaptation planning for the Vietnam Mekong Delta as a case study, we demonstrate the application of both the established sequential and the novel concurrent approach for multiclass scenario discovery. We find that the concurrent approach performs considerably better in terms of input space separability. The MRT algorithm guarantees a perfect separation of the input space when clustering the simulation results. This, however, does result in a larger number of clusters of output space, and subsequently, narratives. While the sequential approach results in seven scenarios, the concurrent approach produces eighteen scenarios. Both approaches have a fairly comparable output space separability performance, with the sequential approach results in better between-cluster dissimilarity and the concurrent approach results in better within-class similarity. Despite the differences in performance, we show how most of the narratives and representative inequality patterns identified by the two approaches are similar, with some exceptions. The concurrent approach provides richer insights as it unravels two additional representative inequality patterns that are not captured by the sequential approach.

Based on the case study results, we argue for the use of the concurrent approach for future multiclass scenario discovery. The concurrent approach guarantees perfect input space separability without sacrificing too much in terms of output space separability. Furthermore, the concurrent approach captures richer more distinctive trade-off patterns between outcome variables (in our case, inequality patterns) compared to the sequential approach. One caveat is that the concurrent approach requires one to make extra effort to distill insights from these richer results.

In light of the presented results, we see several directions for future research. The first one is related to the selection of representative inequality patterns. In this study, we take a pragmatic approach by using the medoid scenario in each cluster. Other approaches include averaging the relative profitability of each actor across all scenarios in a cluster, or selecting the scenario which has the largest dissimilar inequality pattern relative to the other clusters (Carlsen et al., 2016). The second direction is assessing the limits and scalability of clustering when a higher number of stakeholders, which leads to a larger number of outcome variables, is considered. While alternative high-dimensional clustering techniques are available (Kriegel et al., 2009; Xu and Tian, 2015), their usefulness in the context of scenario discovery remains to be evaluated. The third direction is to assess the impacts of different spatial aggregations. As we aggregate farms profitability at a district level, within-district inequality is ignored. The statistical bias resulting from spatial aggregation, the modifiable areal unit problem (Fotheringham and Wong, 1991), can have profound implications for the emerging spatial pattern. Sensitivity or robustness analysis could be applied to understand the stability of the representative inequality patterns under different aggregation levels.

Inequalities can be viewed from various dimensions (across people in different locations (interregional), with different income, different socioeconomic background, or across actors) and variables (inequality of profitability, benefits from policies, exposure to and impacts of climate change) (Harrison et al., 2016; Jafino et al., 2021b; Rao et al., 2017). Irrespective of the dimension of inequality, there is still a methodological need to explore plausible inequality patterns to support equitable adaptation planning. For the purpose of showing the merits of multiclass scenario discovery for this methodological need, we used one dimension of inequality (interregional inequality of profitability). Without loss of generality, the sequential and concurrent approaches could be applied to other conceptualizations of inequality, as we only need to slice the population differently based on our variables of interest. However, it is important to highlight the limitation of this approach. In planning for climate change, distributional consequences can be seen from intra-generational (between people, and assuming they live within the same generation) and intergenerational (between generations) perspectives (Jafino et al., 2021b). Multiclass scenario discovery is more applicable for exploring intra-generational, but not intergenerational inequalities. The topic of discounting is more applicable for the latter, with recent works proposing alternative discounting methods that account for equity (Asheim, 2017; Dietz and Asheim, 2012). Yet, as noted in Chapter 2, one can also theoretically turn an intergenerational problem into a multiobjective problem, for instance by representing the impacts experienced by each generation as a separate outcome indicator.

6

Evaluating the distributional fairness of alternative adaptation policies: A case study in Vietnam's upper Mekong Delta

6.1. Introduction

Attention to justice in climate change adaptation planning has increased in the past years (Byskov et al., 2019; Pelling and Garschagen, 2019). There are several reasons for this. Firstly, physical consequences of climate change vary across space, resulting in different exposure and impact to people in different places (Green, 2016). Secondly, people exposed to the same degree of climate change may experience different actual impacts because of differences in vulnerability and adaptive capacity (Thomas et al., 2019). Thirdly, adaptation policies are likely to unequally affect different people, thus reinforcing existing or introducing new inequalities (Atteridge and Remling, 2018). Despite all this, the assessment of adaptation alternatives often still uses aggregated indicators where the costs and benefits of alternatives are aggregated across people, space, and time (Kolstad et al., 2014). Such blind aggregative assessments obfuscate the distributional impacts to different groups of people.

Two dimensions of justice are relevant: procedural and distributive justice. Procedural justice is concerned with how decision-making processes are organized (Bulkeley

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et al., 2013; Schlosberg, 2009). In procedural justice, higher degrees of recognition, inclusion, participation and transparency in decision-making processes are advocated for (Chu et al., 2016; Hügel and Davies, 2020). Procedural justice reflects on how institutional arrangements for adaptation governance could be improved to realize a more inclusive decision-making process (Holland, 2017). Distributive justice is concerned with how the benefits and costs of adaptation policies are distributed across stakeholders (Grasso, 2010a). The questions here include: how are the burdens and benefits of climate change currently distributed? Who gains and who loses from adaptation? How could burdens and benefits of adaptation policies be distributed more fairly?

Distributive justice research can be further divided into explorative and normative. Explorative studies assess how burdens and benefits of adaptation *will* be distributed by identifying who gains and who loses, and how this is affected by climatic and socioeconomic uncertainties (see e.g., Chapman and Darby, 2016; Gold et al., 2019; Triet et al., 2020). In contrast, normative studies are concerned with how burdens and benefits *should* be distributed and to what extent alternative policies meet standards (Grasso and Markowitz, 2015; Muller, 2001). Here, moral principles are used as a guidance to design requirements for (prescriptive) and to assess the fairness of (evaluative) equitable adaptation policies. While both prescriptive and evaluative normative analyses are paramount in mitigation studies (Dooley et al., 2021; Klinsky et al., 2017), this is not yet the case in adaptation studies. Normative studies in the adaptation domain are largely prescriptive, i.e., aiming to prescribe what a just adaptation policy should look like (Graham et al., 2015; Paavola and Adger, 2006; Pelling and Garschagen, 2019). It is therefore an open question how to use multiple moral principles as yardsticks in evaluating the projected outcomes of adaptation policies. Moreover, how does uncertainty affect the policy preference rankings as produced by different moral principles? With the exception of a few recent studies, model-based quantitative analyses for supporting adaptation planning barely consider distributional effects and seldom reflect on the moral principle that implicitly underlies the aggregation of outcomes across people (Beck and Krueger, 2016; Rao et al., 2017).

In this paper, we show how to use multiple moral principles in performing a normative assessment of distributional outcomes in model-based adaptation planning under uncertainty. We first operationalize seven distributive moral principles often found in climate studies. Next, using agricultural adaptation planning in the upper Vietnam Mekong Delta (VMD) as a case study, we evaluate the performance of six alternative adaptation policies using these moral principles and analyze the change in rankings across them. Then, we evaluate the robustness of the rankings for each principle. Finally, we demonstrate how to identify scenarios in which two moral principles give reversed preference ranking.

The remainder of this paper is structured as follows. We introduce the theoretical background of this study in more detail in Section 2. Next, we introduce the distributive moral principles that we consider as well as the case study we apply these principles on. Section 4 presents the results of the case study, while in Section 5 we provide a more general reflection and conclusions.

6.2. Justice considerations in adaptation planning: some theoretical background

6.2.1. Moral philosophy and distributive justice

The concept of justice originates from the field of ethics and moral philosophy (Kolstad et al., 2014). Moral philosophy is concerned with rationalization of ethical judgements (Rachels and Rachels, 1986). It tries to answer the question of what constitutes a morally justifiable action. Two paradigms dominate the discussion: consequentialism (outcome-based) and deontology (rights-based). Consequentialist arguments uphold that the moral righteousness of an action should be judged by its consequences (Sen, 1979; Smart and Williams, 1973). Deontological arguments prioritize rights over outcomes so the moral righteousness is inherent in actions without considering the consequences (Alexander and Moore, 2020).

Within both paradigms, various moral principles for distributive justice have been articulated (Ikeme, 2003). Moral principles dictate how a unit of interest should be ideally distributed among people (e.g., how flood risks should be distributed among people living in different locations). For example, the no envy principle demands an equality of consumption where no agent would prefer another agent's consumption bundle. Some principles are concerned with the distribution of not only the outcomes and/or consequences. For example, the meritocracy principle is concerned with the initial distribution (for instance, equal access to education), but not with what the final distribution of outcomes (for instance, equal lifelong earnings). Other moral principles, such as total equality, have been defended on deontological grounds, for instance when deciding that affected stakeholders should have equal authority and participation in decision-making on local adaptation (Björnberg and Hansson, 2011).

6.2.2. Assessing distributional outcomes of adaptation policies

Adaptation policies inevitably have distributional effects for different groups within the population (Atteridge and Remling, 2018). These can be intentional consequences or unintended side-effects. Deliberately planned distributional effects are profound in the domain of flood risk adaptation where various compensation mechanisms have long been an inseparable element of adaptation policies, as physical measures such as levee heightening often have adverse consequences for some subgroups of the population (van Doorn-Hoekveld et al., 2016). Yet, even in such an established domain, unforeseen distributional impacts still abound. In the Vietnam Mekong Delta, reducing flood risk by constructing higher dikes turned out to be harmful for small-scale farmers

(Chapman and Darby, 2016), while also transferring flood risk downstream (Triet et al., 2017). This inherent complexity of adaptation planning emphasizes the importance of *ex-ante* accounting for distributive justice in adaptation policy planning.

Assessing distributive justice requires specifying the *unit* (what is being distributed?), *scope* (to whom is it being distributed?), and *shape* (what pattern of distribution is just?) of the distribution (Bell, 2004; Page, 2007). The *unit* of the distribution depends on context and application domain. For example, in flood risk management, the *unit* of the distribution typically is the expected annual damage or exposure to flood hazard. In adaptation planning for deltas, the *unit* ranges from physical variables such as flood risk (e.g., expected annual damage or expected casualties) to socioeconomic variables such as farmers annual income (Suckall et al., 2018). The *scope* of the distribution is defined by partitioning the population into relevant (sub)groups, for example by dividing the population based on their income (Hallegatte and Rozenberg, 2017), or based on where they live (Ciullo et al., 2019; Jafino et al., 2019).The *shape* is relevant for assessing the resulting distributional effects of alternative policies in comparison to what is considered just given a preferred distributive moral principle.

Incorporating distributive justice in the assessment of alternative adaptation policies can be supported by two types of analyses. Explorative analysis aims at investigating who wins and who loses under which circumstances (see e.g., Ciullo et al., 2019; Triet et al., 2020). Explorative analysis can guide planners in designing corrective actions. In contrast, normative analysis evaluates to what extent the distributional outcomes of an adaptation policy correspond to an ideal distribution as prescribed by a given moral principle. Explorative and normative analyses are complementary. While an explorative analysis identifies ‘winners’ and ‘losers’, normative analysis generates a preference ranking of adaptation policies based on a pre-selected moral principle.

Various distributive moral principles have been proposed for the specific context of planning for climate change. Many cost-benefit analyses of adaptation projects adopt a utilitarian principle (André et al., 2016; Watkiss et al., 2015), where the goal is to maximize the total benefits irrespective of how they are distributed across people. The ‘putting the most vulnerable first’ principle is often applied in studies that focus on fair adaptation to climate change (Burton et al., 2002; Paavola and Adger, 2006). Other moral principles which are gaining prominence in the climate justice domain include egalitarianism, prioritarianism, and Rawlsian difference (Adler and Treich, 2015; Ciullo et al., 2020; Johnson et al., 2007). These principles are, however, mainly applied only in the mitigation domain. For adaptation, these principles are being used but primarily to prescribe how adaptation strategies should be designed (e.g., more resources should be put for flood protection should for worse-off regions), but not to *ex-ante* evaluate the expected outcomes of concrete adaptation measures under different scenarios.

6.3. Methods

6.3.1. Alternative principles for distributive justice

To perform a normative analysis of distributional outcomes, we use seven moral principles that have been previously used in climate change research (Table 6.1). We operationalize these principles by deriving aggregation functions based on the normative ideas underpinning them. For example, the Rawlsian difference principle of bringing benefits to the least advantaged members of the society implies an aggregation function that looks at the outcome for the worst-off (Rawls, 2009). Strict egalitarianism demands total equality of outcomes across all individuals (Nielsen, 1979), hence the aggregation function concerns the discrepancy between the outcomes of the worst-off and best-off individuals. These aggregation functions compare the distributional outcomes of the alternative adaptation policies to produce a preference ranking amongst them.

There are two important things to note about the operationalization of the principles. Firstly, the absolute values of the aggregated outcomes are incommensurable across the different principles. Comparison across principles can only be performed by comparing the preference rankings produced by a principle. Secondly, the original conception of each principle might have specific units for which the principle is deemed applicable. For example, the utilitarian principle is concerned with utility (Posner, 1979). But utility is an abstract concept, and it is not necessarily a linear function of other measurable units. Nevertheless, applications of this principle often use the unit of interest in the planning context (e.g., expected annual damage) directly as utility (Du et al., 2020), whereas other studies transform the unit of interest into utility by using a concave function (Adler et al., 2017; Kind et al., 2017). The envy-free principle, in contrast, cares about the consumption bundle owned by individuals, but not about the utility gained from consuming the bundle (Varian, 1974). In this study, we interpret the principles more liberally; we use our unit of interest directly as the subject of the distribution.

Table 6.1: Distributive moral principles accounted in this study

Principles	**Description**	**Aggregation function**	**Theoretical underpinnings**	**Examples of application in the climate change domain**
Utilitarian	An action should maximize well-being and/or welfare of all affected individuals	$\sum_{i=1}^{n} u(x_i)$	Posner (1979)	Anthoff and Emmerling (2018); Fankhauser et al. (1997); Shardul and Samuel (2008); Thaler et al. (2018)
Strict egalitarian	Equality of outcomes – each individual should have the same level of welfare. An action should strive for such equal distribution of outcomes	$max(u(x_i)) - min(u(x_i))$	Konow (2003); Nielsen (1979)	Ciullo et al. (2020); Ikeme (2003); Johnson et al. (2007); Kaufmann et al. (2018); Thaler and Hartmann (2016)
Rawlsian difference principle	An action should bring benefits for the least advantaged individuals	$min(u(x_i))$	Rawls (2009)	Johnson et al. (2007); Kaufmann et al. (2018)
Prioritarian	The outcome of an action is a function of an aggregation of overall welfare with extra weights given to worse-off individuals	$\frac{1}{1-\gamma} \sum_{i=1}^{n} u(\frac{u(x_i)}{u(\bar{x})})^{1-\gamma}$	Arneson (2000); Parfit (1997)	Adler et al. (2017); Anthoff et al. (2009); Ciullo et al. (2020); Gourevitch et al. (2020); Paavola and Adger (2006)
Sufficientarian	An action should ensure that all individuals have secured enough welfare	$\lvert \{i \in n : u(x_i) \geq u(s)\} \rvert$	Shields (2012)	Ikeme (2003); Meyer and Roser (2010)
Envy-free	An action is morally just if no individuals prefer another individual's achievements and/or welfare	$\sum_{i=1}^{n} \sum_{j=1}^{n} max\left\{u(x_j) - u(x_i), 0\right\}$	Bosmans and Öztürk (2018); Konow (2003); Varian (1974)	Tol (2001); Grasso (2007); Ikeme (2003)
Composite principles	The outcome of an action should be evaluated against several moral principles (in this case, between utilitarian and egalitarian)	$w * f(\sum_{i=1}^{n} u(x_i))+$ $(1-w) * f(max(u(x_i)) - min(u(x_i)))$	Frohlich and Oppenheimer (1993); Konow (2003)	Schlosberg (2013); Wood et al. (2018)

where:
$u(x_i)$, welfare of individual i
$u(\overline{x})$, average welfare of all individuals
γ, inequality aversion factor
$u(s)$, minimum welfare threshold deemed sufficient
w, preference factor for utilitarianism compared to egalitarianism
$f(.)$, min-max linear normalization

6.3.2. Case study: Adaptation planning for rice farming in the upper Vietnam Mekong Delta

In this chapter, we use the similar case study on agricultural adaptation planning in the VMD as used in Chapter 4. We assess the distributional outcomes of six alternative adaptation policies for Dong Thap and An Giang, two provinces in the upstream VMD (see Chapter 4). More precisely, we evaluate the spatial distribution of farm profitability among farmers in the 23 districts in these two provinces. We use the same integrated impact assessment metamodel as developed and explained in Chapter 4. The metamodel combines flooding and sedimentation dynamics, soil nutrient stock dynamics, crop yield calculation, land subsidence, land-use change dynamics, as well as a farm profitability calculation module (see Jafino et al. (2021a)). Farm profitability, calculated at parcel level, is aggregated at district level, resulting in a total of 23 performance indicators. We further aggregate the performance indicators based on each principle as listed in Table 6.1. We then calculate the preference ranking of the alternative adaptation policies for each principle.

Alternative adaptation policies

In this study, we consider four hard infrastructural and two 'soft' policies. The infrastructural policies are related to dikes (de)construction: either further construction of high dikes in the currently low dikes area, or deconstruction of all high dikes into low dikes again. Each policy is applied in both An Giang and Dong Thap independently. These policies are inspired by recent discussions on sustainable flood control in the region (Tran et al., 2018b; Triet et al., 2020). The soft policies are upgrading seed and fertilizer subsidy. In the former policy, we assume that by using a higher quality seed variety, crops are more resilient to flooding. This policy thus reduces the steepness of the stage-damage curve (Triet et al., 2018), so that the same flood depth results in a lower fraction of damaged yield. In the latter policy, we distribute 50 kilograms of free fertilizer to farmers who are located far from the Mekong River. The motivation behind this is that the sediment concentration in the river declines proportionately to the distance from the main river. Hence, farmers located far from the river receive significantly fewer nutrients from the floodplain sedimentation process (Manh et al., 2015). All policies are assumed to be implemented from 2025 onwards.

Uncertainties

We consider five future uncertain developments that have substantial influence on the agricultural sector in the upper VMD. Firstly, the river discharge is changing due to climate change. We use synthetic hydrographs generated by a global hydrological model to obtain annual maximum upstream discharge at Kratie, Cambodia, under climate scenarios RCP 4.5 and 8.5 (Sutanudjaja et al., 2018). The second uncertainty is hydropower dam development in Cambodia, which reduces total sediment supply entering Vietnam and the annual maximum peak discharge. We use five upstream dam development scenarios developed by Lauri et al. (2012) and Manh et al. (2015). The third and the fourth uncertainties are the productivity gaps between the three different harvesting seasons. The winter-spring season after the monsoon (December-April) is the most productive season, followed by the summer-autumn season (April-July) and the autumn-winter season (July-December). In 2016, the yields in the summer-autumn season and the autumn-winter season were on average 26% and 35% lower than that of the winter-spring season. Here, we consider a wider bandwidth of productivity gaps of 15-45%. The fifth uncertain development is land-use change dynamics. Based on recent reports and studies (Mekong Delta Plan Consortium, 2013; Triet et al., 2018), we consider four scenarios: continuing intensification of triple-rice farming system, shifting back to double-rice, increase of alternative agricultural livelihoods (e.g., orchard plantation and aquaculture), and large-scale urbanization.

6.3.3. Experiment and analysis setup

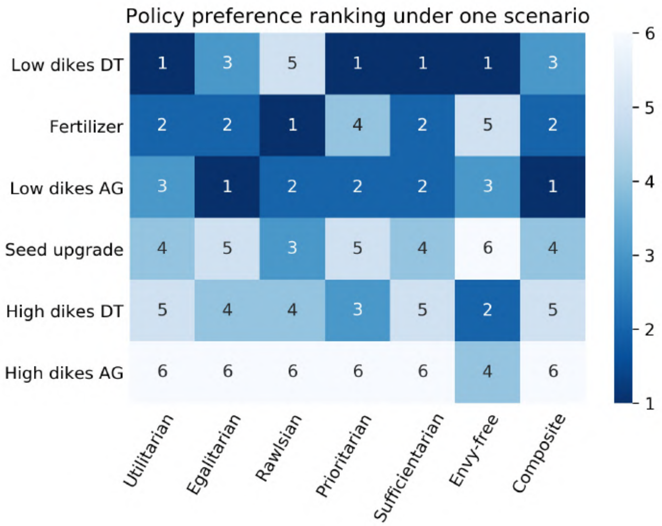
To systematically explore the uncertainty space, we use Latin Hypercube Sampling to generate 1200 future scenarios. Each scenario corresponds to a unique combination of values for each uncertain variable. We then perform four analyses. Firstly, we analyze the policy preference ranking under a baseline scenario to illustrate how the choice of different moral principles affects this ranking. The rank of each policy is determined by the aggregation of the district-level farm profitability using the functions specified in Table 6.1. Secondly, we evaluate the robustness of the ranking across all scenarios. Specifically, we look at how the rankings vary under each principle across all 1200 scenarios. Thirdly, we assess the agreement of rankings between each pair of principles across all scenarios using the Kendall's Tau-b coefficient. For each pair of principles, Kendall's Tau-b coefficient equates the rankings from all pairs of alternative policies and takes a value between 1 (completely similar rankings between the two principles) and -1 (completely opposite rankings). The fourth analysis is aimed at identifying the uncertain conditions under which two moral principles yield conflicting results, i.e., when Kendall's Tau-b coefficients between them are negative. We use dimensional stacking (Kwakkel, 2017), a scenario discovery technique (Bryant and Lempert, 2010), to identify uncertainty subspaces that have a high concentration of scenarios with negative ranking correlations between any pair of moral principles.

Several moral principles require further parameterization. Firstly, the operationalization of the prioritarian principle involves an inequality aversion factor γ. This factor can have any positive value, with larger values implying more weight to priority for the worse-off. Previous studies took a value between 0 – 3 with 0.5 and 1 the most frequently used (Adler et al., 2017; Anthoff et al., 2009). In this study, we take a value of γ=0.5. Secondly, the sufficientarian principle requires setting a minimum threshold of annual farm profitability. We use an optimistic threshold of 70 million Vietnam Dong (VND), which is the highest average annual profit as surveyed by Tran et al. (2018b). Thirdly, the composite principle requires setting the weighting factor w which indicates the preference given to the utilitarian in comparison to the egalitarian principle. We use a value of 0.33 here, implying less emphasis on the utilitarian principle.

6.4. Results

6.4.1. Policy preference ranking under a baseline scenario

To what extent do policy preference ranking changes when different distributive moral principles are used? To answer this question, we compare the ranking of the policies under a baseline scenario assuming low upstream dam development, continuation of triple rice expansion, and a river discharge regime resulting from the RCP 4.5 climate scenario. The result is presented in Figure 6.1.



	Utilitarian	Egalitarian	Rawlsian	Prioritarian	Sufficientarian	Envy-free	Composite
Low dikes DT	1	3	5	1	1	1	3
Fertilizer	2	2	1	4	2	5	2
Low dikes AG	3	1	2	2	2	3	1
Seed upgrade	4	5	3	5	4	6	4
High dikes DT	5	4	4	3	5	2	5
High dikes AG	6	6	6	6	6	4	6

Figure 6.1: Preference ranking of alternative policies under a single scenario, with 1 as the most preferred and 6 as the least preferred. DT stands for Dong Thap while AG stands for An Giang.

Overall, there are no pairs of principles that yield identical ranking. Also, there is no pairs of principles with completely reversed rankings. Some pairs of principles do have quite dissimilar preference rankings, despite having the same most preferred policy (e.g., utilitarian and the envy-free principle). Other pairs of principles have a relatively large degree of ranking agreement (e.g., utilitarian and the sufficientarian principles). The egalitarian and composite principles also result in a quite similar ranking, although the policies with seed upgrade and high dikes in Dong Thap are ranked in reversed order. This is explained by the fact that in the composite principle, we assigned substantial weight to the egalitarian principle (0.67).

Another way to interpret the result in Figure 6.1 is by looking at the performance of a policy across the different principles. Further expanding high dikes in An Giang is the least preferred alternative, except for the envy-free principle. In contrast, low dikes in Dong Thap performs best in most principles, except according to the Rawlsian difference principle, in which it is the second worst performing policy. The policy with low dikes in An Giang, despite ranking first in only 2 principles, does not rank lower than third when we look at all other principles. These rankings thus indicate which policies perform well (or bad) under different distributive perspectives.

6.4.2. Robustness of ranking across future scenarios

How do uncertainties influence the ranking of policies for the different distributive moral principles? To answer this question, in Figure 6.2 we vertically stack the rankings of the policies across all the 1200 scenarios. Each vertical line shows the ranking of the policies under one scenario. Figure 6.2 shows that there is no policy that is always ranked the same under all scenarios for any of the principles. For example, the policy that performs best according to the prioritarian principle in the largest number of scenarios is the policy with low dikes in Dong Thap. However, this policy is ranked first in only 61% of the scenarios, and ranked last in about 14%. According to the egalitarian and the Rawlsian principle, the policy ranked first under the baseline scenario (low dikes in An Giang and fertilizer subsidy, respectively) stays first in just over a third of all scenarios (around 35% and 38%, respectively). According to the sufficientarian principle, all policies have comparable performance in 15% of the future scenarios.

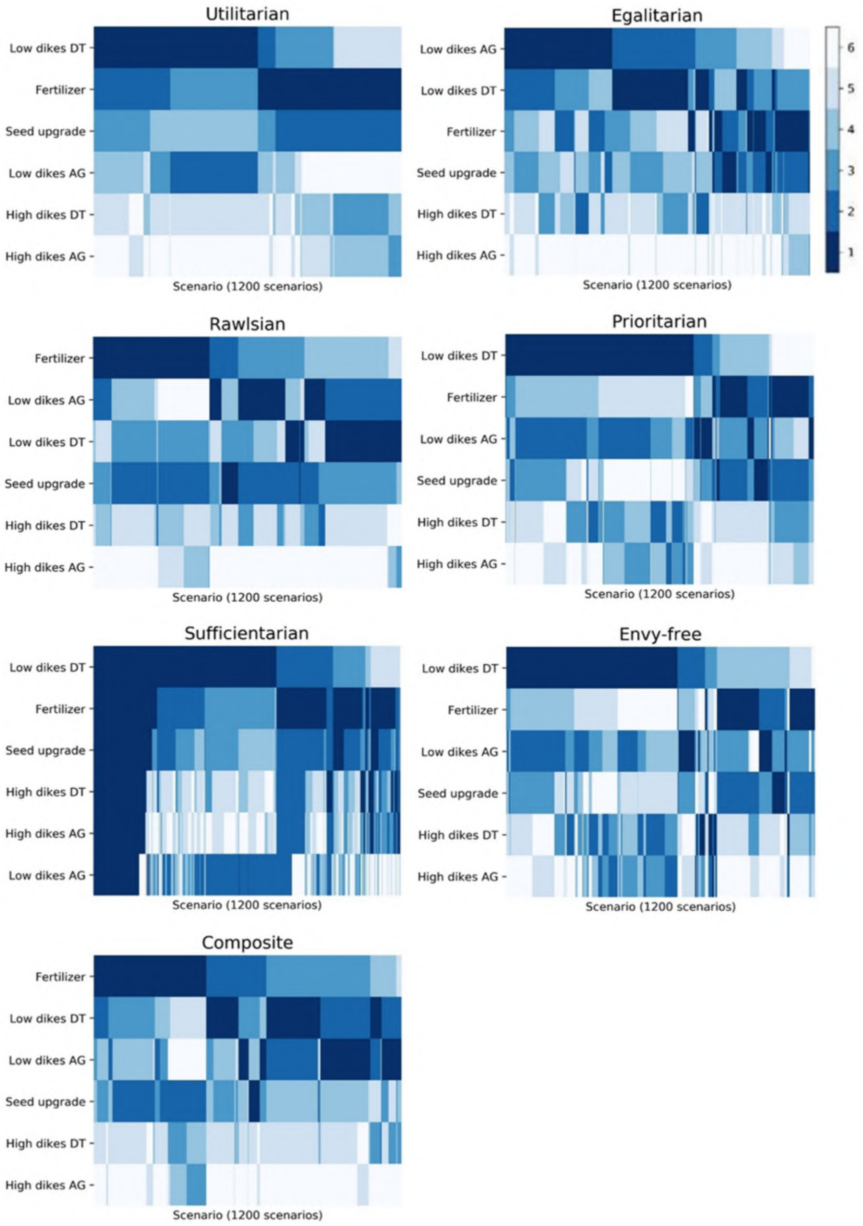


Figure 6.2: Ranking of policies across all 1200 scenarios based on seven distributive moral principles. All rankings are illustrated as stacked color lines, with each vertical line designating the ranking of policies under one specific scenario. For each principle, the policies are ordered based on how often they perform the best across the scenarios.

From Figure 6.2, we can draw more generic conclusions about the ranking stability of each distributive principle. For example, the results for the utilitarian principle can be classified into two groups. The first group contains 640 scenarios in which the policy with low dikes in Dong Thap performs best, whereas in the second group of scenarios (the other 560 scenarios) the policy with fertilizer subsidy performs best. Within the first group, the policy with fertilizer subsidy ranks second in 47% of the 640 scenarios while the policy with low dikes in An Giang ranks second in the rest of the scenarios. In the second group, the seed upgrade policy ranks second in most (88%) of the 560 scenarios in this group. In this second group, the policy with low dikes in Dong Thap (which is the most preferred option in the first category) ranks fifth in almost half the cases (47%).

Overall, the utilitarian principle has the most stable ranking. This is evidenced by the fact that the results for the utilitarian principle show the least changes of ranking compared to the other principles (see Figure 6.2). As a comparison, for the envy-free principle, in scenarios where the policy with low dikes in Dong Thap performs best (56% of all scenarios), the second most-preferred policy varies widely across the scenarios. In the remaing 44% of scenarios, the best performing policy is any of the other five policies. This underscores that, when we move away from a strict utilitarian perspective, the preference ranking of the policy is strongly affected by uncertainties.

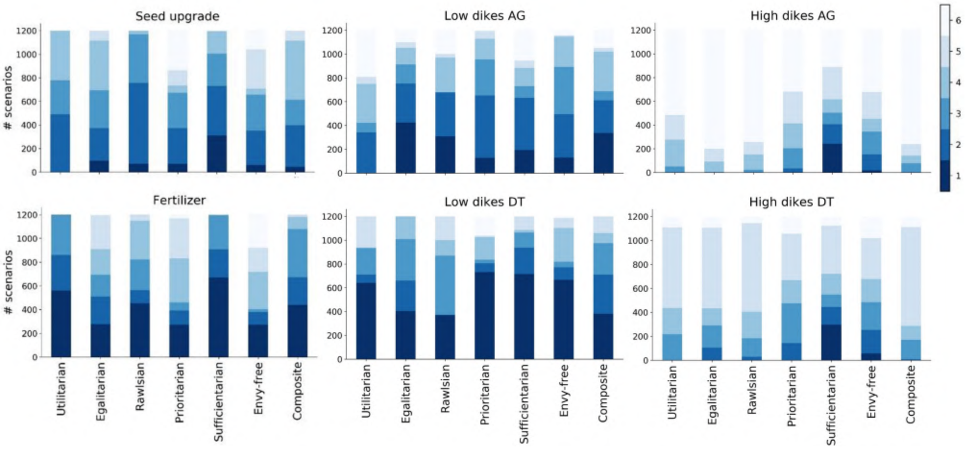


Figure 6.3: Histogram of rankings of each policy across all 1200 scenarios.

We can also analyze the results from the perspective of the policies (Figure 6.3). The policy with low dikes in Dong Thap, although performing best according to many distributive principles under the baseline scenario (Figure 6.1), ranks first in 53%, 61%, 60%, and 56% of the scenarios according to the utilitarian, prioritarian, sufficientarian, and envy-free principles, respectively (Figure 6.3). The next policy that ranks first in many scenarios across all principles is the fertilizer subsidy and low dikes in An Giang, although these policies do not perform well according to the prioritarian and the envy-free principle. High dikes policies rank low in most scenarios across all principles. From the perspective of the policies, we can identify the most robust performer across all moral principles and scenarios, which is the policy with low dikes in Dong Thap.

6.4.3. Agreement of ranking across scenarios

To what extent are the policy preference rankings according to each principle correlated, in the sense that they are in agreement with the rankings according to all other principles? To answer this, Figure 6.4a presents the distribution of Kendall's Tau-b coefficients across all 1200 scenarios as kernel density for each pair of principles. To facilitate a more direct comparison across all pairs of principles, Figure 6.4b highlights the median values of the Kendall Tau-b.

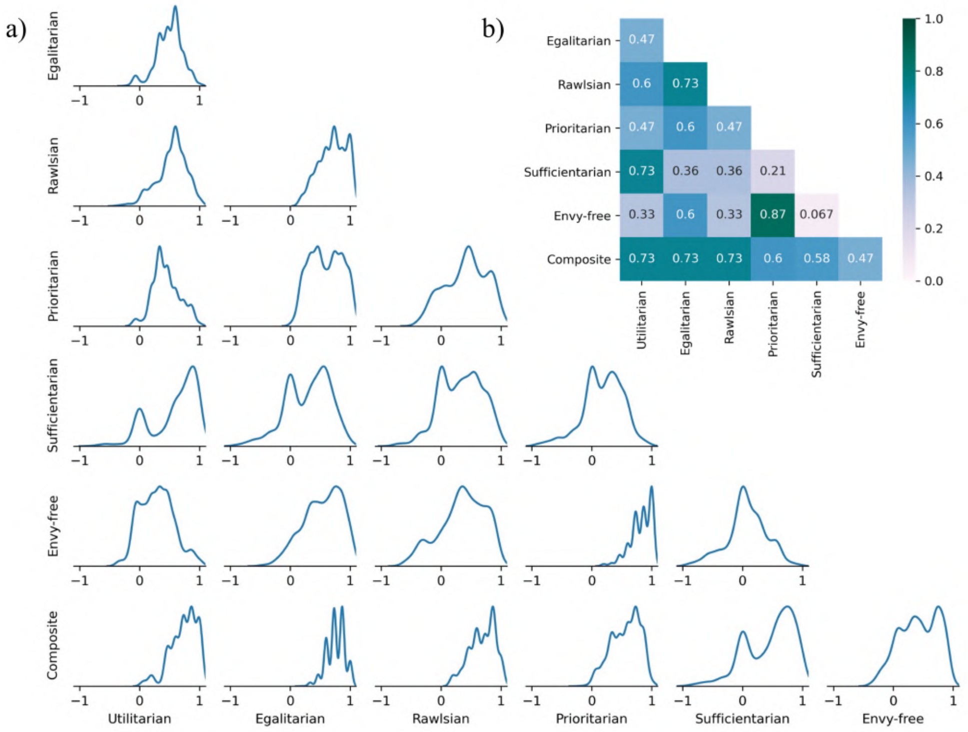


Figure 6.4: a) The distribution of Kendall Tau-b across all 1200 scenarios for each pair of distributive moral principles. The median value of the distribution is printed at the top left of each subplot. b) The same median values of the Kendall Tau-b, presented as a heatmap.

There are some observations given Figure 6.4. Firstly, we see that only six out of the 21 pairs have a median Kendall Tau-b coefficient larger than 0.7. Two of these pairs are the composite principle with the utilitarian and the egalitarian principle, which is to be expected because the composite principle was defined as a combination of the utilitarian (33%) and the egalitarian (67%) principle. Preference rankings from the prioritarian and the envy-free principle, despite being dissimilar in the baseline scenario (see Figure 6.1), are quite homogeneous across all scenarios (median Kendall Tau-b coefficient of 0.87). In many pairs of principles (10 out of 21), the median ranking similarity is relatively low (less than 0.5), with the envy-free and sufficientarian principles yielding the lowest median Kendall Tau-b coefficient.

Secondly, distributive moral principles that have similar prescription for what is considered to be just have a high Kendall Tau-b coefficient across the scenarios. This is the case for the envy-free, egalitarian, and prioritarian principles – the three principles that aim to minimize inequality. The results for pairs of principles founded on different imperatives are more mixed. For example, the utilitarian and the sufficientarian principles have a fairly high rank similarity, while the envy-free and Rawlsian principles have a low rank similarity.

Thirdly, in general, the Kendall Tau-b coefficients are positive but for some scenarios the coefficients are negative. For example, Kendall Tau-b coefficients between the envy-free and the egalitarian principles have a negative value in 6.1% of the scenarios. In some scenarios, the Kendall Tau-b coefficients between the sufficientarian principle and the egalitarian, prioritarian, and envy-free principles even take a value of -0.93. This implies an almost reverse preference ranking when the distribution of the profitability is evaluated by either of the two principles.

6.4.4. Identification of scenarios with conflicting results

What, if anything, do the scenarios with negative Kentall Tau-b have in common? We take the sufficientarian and the envy-free principles as an illustration for answering this question. Rankings from these principles have negative Kendall Tau-b correlations in around 28% of the scenarios. Figure 6.5 shows the results of the dimensional stacking analysis of these scenarios. Brighter color indicates higher concentration of scenarios with negative ranking correlations. Negative correlations occur in scenarios with high productivity gap in the Summer-Autumn crop, medium to high productivity gap in the Autumn-Winter crop, and medium degree of upstream dam development. In contrast, the rankings from both principles tend to have non-negative correlations under scenarios with high degree of both dam construction and productivity gap in the Summer-Autumn crop, and scenarios with low degree of dam construction and productivity gap in the Summer-Autumn crop.

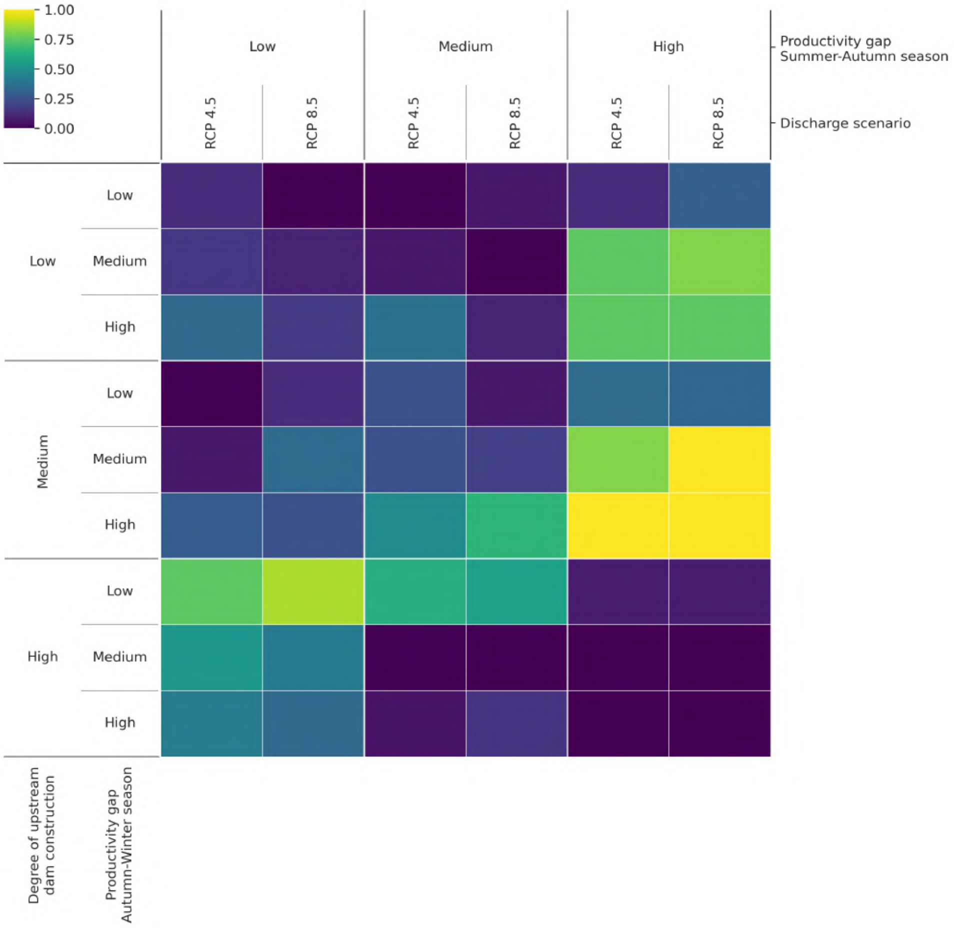


Figure 6.5: Identification of scenarios leading to negative ranking correlations between the sufficientarian and the envy-free principles. The colormap indicates the fraction of scenarios which ranking correlation is negative. For example, scenarios with high productivity gap in both summer-autumn and autumn-winter seasons, medium degree of dam construction, and discharge from RCP 8.5, result in negative Kendall Tau-b coefficients between rankings from the two principles.

Overall, this analysis shows that the realization of upstream dams in Cambodia and the decrease in agricultural productivity of the Summer-Autumn and Autumn-Winter crops are two critical variables to be monitored. These variables strongly influence the preference ranking agreement between the sufficientarian and the envy-free principle. This analysis also underscores the complex interplay between productivity reduction and dam construction. A high degree of productivity reduction for the Summer-Autumn crop causes conflicting ranking when upstream dam construction is low or medium. However, if most dams are eventually constructed, it would lead to similar rankings for both principles. In such scenarios, conflicting ranking would only emerge if the productivity gap is low both for the Summer-Autumn and for the Autumn-Winter crop.

6.5. Discussion and conclusion

Adaptation policies almost unavoidably have distributional consequences. Therefore, the assessment of adaptation policies needs to consider distributional outcomes. While many quantitative model-based adaptation studies focus on exploring the distributional consequences, research on normatively assessing the distributional outcomes is still limited. In this study, we evaluated the distributional outcomes of policies using seven moral principles. We operationalized these principles in order to create a preference ranking of alternative policies. We used the adaptation planning challenge of the upper VMD as a case study, for which we evaluated the distributional outcomes of district-level farm profitability. We evaluated how the preference ranking of the policies changes when different principles are being adopted, and how these rankings vary across scenarios.

There are various reasons for including multiple distributive principles when performing a normative analysis. Firstly, there is growing acknowledgement on the plurality of the conception of justice, i.e., there is no single justice principle that is universally applicable in all circumstances and across all generations (Konow, 2003; Taebi et al., 2020). Further, by accounting for multiple principles, one also enlarges the information base upon which adaptation decisions are taken (Sen, 2001). This reduces the possibility of creating unintended distributional consequences where certain people are unintentionally harmed by adaptation, which could be qualified as a form of 'maladaptation' (Juhola et al., 2016).

For the VMD case study, we found that the policy with low dikes in Dong Thap is the preferred policy according to four out of seven distributive moral principles in the baseline scenario. Even then, when a different distributive principle is being used (e.g., the Rawlsian difference principle), this policy could rank low (e.g., 5th) compared to the other policies. Across all 1200 scenarios, we found that this policy ranks first under the largest number of scenarios and across most distributive principles.

When looking at the principles, we observed that preference rankings for the utilitarian principle are not heavily influenced by uncertainties. In contrast, preference rankings from the egalitarian and the sufficientarian principles are strongly affected by uncertainties. Further, we investigated ranking agreement resulting from each pair of distributive principles across the 1200 scenarios. In general, principles that are derived from similar ethical imperatives (e.g., prioritarian, egalitarian, and envy-free principles) have high ranking agreement across scenarios. The agreement of rankings from principles derived from different imperatives is more mixed. Some pairs of principles were found to have large ranking similarity (e.g., utilitarian and sufficientarian principles) while others had small similarity (e.g., sufficientarian and envy-free principles).

Given that our findings may be case-study specific, what can we conclude and recommend? A first recommendation is to explicitly reflect on the distributive moral principle used to aggregate distributional outcomes, as well as the possible implications of using that principle. The utilitarian principle is often adopted without due consideration of its possible flaws. To identify which distributive principle is appropriate in a given case, participatory, qualitative, and survey methods can be used which aim to reveal the preference of affected stakeholders, for example as done by Lau et al. (2021) and Van Hootegem et al. (2020). Because societal norms could evolve over time, another recommendation is to evaluate the robustness of the policies across different principles, in addition to assessing robustness across scenarios (McPhail et al., 2020). Finally, since even the most robust policy might not be the most preferable under all principles, knowledge regarding under which principles a selected policy does not perform well could be very informative in reports about model-based policy analyses. This would warrant that decision makers are aware of the potential shortcomings of their policy from the perspective of certain principles.

7

Conclusions and recommendations

Although the importance of incorporating equity in planning for climate change is well recognized, its incorporation in adaptation planning for deltas is still lacking. Incorporating equity requires accounting for distributional outcomes to different groups of people. Hence, quantitative models – often used to evaluate the efficacy of alternative adaptation policies – can play a vital role in enabling equity considerations. Yet, recent studies incorporate equity only in an ad-hoc manner, as they mainly use one definition of equity. A comprehensive and systematic account of how quantitative models can support equitable adaptation planning suggests the need for modifications to both model structure and how model results are analyzed. Such an account, as well as examples of how it can be applied in realistic case studies were found missing.

In this research, I investigated how equity considerations can be systematically incorporated in model-based analysis for supporting equitable adaptation planning for deltas. This was carried out in three steps. First, I conducted a literature review on concepts related to climate ethics and justice, and model-based planning for climate change. This was aimed at understanding conceptual requirements for incorporating equity considerations in model-based adaptation planning. Second, I performed a proof-of-concept study of how to meet a subset of these requirements. I used the hypothetical Waas River, a case study often used to test new model-based analysis approaches, for this proof-of-concept. Third, I tested the applicability of approaches for incorporating equity considerations in quantitative models through a case study. In particular, I proposed approaches for performing explorative and normative analysis of distributional outcomes using a real-life case study of adaptation planning in the upper Vietnam Mekong Delta (VMD).

This chapter will first answer the research questions introduced in Chapter 1 based on the findings from Chapter 2 to 6. Next, a scientific reflection is provided with respect to methodological limitations and outlook for future research. The chapter ends with lessons for practice, in terms of how to incorporate equity considerations in adaptation planning for deltas and what can be learned to support equitable adaptation planning in the upper Vietnam Mekong Delta.

7.1. Answering the research questions

Based on the research gaps, the main research question was formulated as follow.

What is an adequate approach to model-based policy analysis for supporting equitable delta adaptation planning?

This main research question was divided into five sub-research questions:

1. *How can justice and equity be incorporated in quantitative models used to support planning for climate change?*

Drawing on concepts from distributive justice and climate ethics, requirements that a model should have to support equitable climate adaptation planning were formulated in Chapter 2. These requirements were drawn from the need to account for justice between different groups of people within a generation (intra-generational justice) and between different generations (intergenerational justice). In general, accounting for intra- and intergenerational justice in model-based adaptation planning requires (i) ensuring fair representation of actors and fair assessment of distributional outcomes in quantitative models, (ii) accounting for differential social vulnerability, (iii) promoting freedom of choice, especially for future generations, and (iv) ensuring the transparency of ethical preferences of decision-makers and stakeholders that are embedded in quantitative models. These four imperatives serve as the foundation for the modeling requirements.

The requirements were categorized using the XLRM framework. For performance metrics calculated through models (the ‘M’), incorporating justice and equity requires disaggregation of metrics based on the different stakeholders and their values, as well as disaggregation of the metrics over time. This could be further complemented through the aggregation of metrics based on different distributive moral principles. Methods from social choice and welfare theory can be adopted for this, as they provide guidance for operationalizing various moral principles. To allow for such analysis, the model structure (the ‘R’) should have an appropriate degree of disaggregated representation of actors. For policy levers (the ‘L’), incorporating justice and equity means designing actor-differentiated interventions, as different actors might experience varying levels of vulnerability. The freedom of choice imperative calls for an assessment of changes in policy space over time, as some adaptation interventions can have a strong path dependency either limiting or widening the available options of future generations. This can be supported through pathways approaches (as proposed by Haasnoot et al. (2013)), which explicitly account for sequences of decisions over time. Finally, as societal values could change over time, and planning for climate change is often long-lived, it is important to account for such normative evolutionary uncertainties (the 'X').

2. *What are the merits of endogenising land-use change dynamics in model-based support for delta planning?*
One way to have a more disaggregated representation of actors is by making the model spatially explicit and simulating the actor dynamics (e.g., through land use changes) over time. To this end, the merits of endogenising land-use change dynamics in model-based delta adaptation planning were explored in Chapter 3. I used the hypothetical Waas River case study to investigate two questions: what are the implications of endogenising land-use change dynamics to conclusions derived from a model-based analysis? Under what conditions does endogenising land-use change dynamics become (ir)relevant?

In answer to the first question, three implications were identified. First, endogenising land-use change dynamics does not substantially alter the preference ranking of alternative policies in terms of total flood damages. However, it leads to a change in the range of the policy performance's distribution across scenarios. Second, it allows for incorporating a wider range of policy alternatives, such as land-use zoning. Without integrating land-use dynamics, people's responses to such policies will not be appropriately captured. The third implication is enabling a more comprehensive assessment of distributional outcomes. The utility-based nature of the land-use change model allows one to evaluate the distribution of not only standard performance indicators such as flood safety, but also the stakeholders' overall utility. This utility could encompass diverse variables such as accessibility to key facilities, attractiveness of surrounding landscape, and social networks.

For the second question, three factors that influence the relevance of endogenising land-use change dynamics were evaluated in terms of their effect on the magnitude of policy performance. First, I found that endogenising land-use change dynamics has larger effect in more severe climate change scenarios. Second, I found that the higher the society's sensitivity to climate events in terms of changing land-use functions, the bigger the effect of endogenising land-use change will be. The combination of this factor with the previous one results in a more socially dynamic society due to more frequent and intense climate events. Without properly capturing societal dynamics, the projection of policy performance would be misleading (as also argued by Beckage et al. (2018)). The third influential factor is the distributional nature of the adaptation interventions. If adaptation interventions influence everyone in a similar way, the impact of endogenising land-use change dynamics will be minimal. In contrast, the performance of spatially targeted interventions such as dikes heightening – which are typical in delta planning – would noticeably change when land-use change is endogenised.

3. *To what extent do distributional outcomes of adaptation planning depend on adaptation policies and climatic and socioeconomic uncertainties?*
I used a case study of adaptation planning of rice farmers in Dong Thap and An Giang, two provinces in the upper VMD, to investigate the impacts of uncertainties and adaptation on distributional outcomes of district-level farms profitability. I developed an integrated impact assessment metamodel which fulfills some of the requirements proposed in Chapter 2. I found that distributional outcomes are not a simple summation of the impacts of uncertainties and adaptation policies. Interactions between them have non-linear effects on the distribution of outcomes. Even small changes in the scenario, when compounded with different adaptation actions, could lead to different distributional patterns. This implies that looking at the distributional impacts of uncertainties and adaptation separately, an approach often followed in previous studies (as done by Chapman and Darby (2016); Dang et al. (2020)), runs the risk of overlooking the non-linear impacts of these interactions. Further, not all uncertainties and adaptation actions have a similar influence on distributional patterns. Interestingly, I found that man-made interventions such as dikes expansion and upstream dam development in Cambodia have larger effects on spatial inequalities, compared to climatic uncertainties. One possible reason is that, because I looked at a small geographical scale and considered a relatively short time scale, the distributional impact of climate change across the farmers tended to be uniform.

It is important to note that while this sub-research question is context-independent, the answer provided so far is based on just one case study (i.e., adaptation planning for the upper VMD). The characteristics of the delta likely influence the sensitivity of distributional outcomes to adaptation and uncertainties. For example, based on findings in Chapter 3, one could hypothesize that in a less socially dynamic delta the distributional outcomes under different scenarios and adaptation would be less variable. Modeling choices could also influence the outcomes of the distributional analysis. In the VMD case study, for example, the inundation modeling was carried out through a simplified metamodel that neglected explicit hydraulic interaction between interventions taken in downstream and upstream regions. Modeling such interaction could have profound implication on the emerging distributional outcomes. Nevertheless, recent studies (e.g., Taconet et al. (2020)) at the global scale also show that interaction effects between uncertainties and adaptation have non-linear consequences on emerging patterns of inequality.

The finding that adaptation and uncertainties have non-linear impacts on distributional outcomes yields three broader implications for future model-based adaptation planning studies. First, for decision making under deep uncertainty, this finding underscores the importance of global, instead of one-at-a-time approaches to sensitivity analysis (Saltelli et al. (2019) also proposed the same approaches). Second, the finding emphasizes the need to include multisectoral dynamics – in addition to having disaggregated representation of actors – in quantitative models, so that uncertain factors that could have significant impacts on distributional patterns are accounted. This could be done by carefully selecting an appropriate level of model conceptualization and abstraction at an earlier stage of model development. Finally, supporting equitable adaptation planning requires evaluating not only aggregated inequality indicators such as the Gini coefficient, but also disaggregated outcomes to different people. This is because, similar to Anscombe's quartet (Anscombe, 1973), using only aggregated indicators obscures the distributional patterns of the outcomes.

4. *How to explore plausible patterns of distributional outcomes in adaptation planning under deep uncertainties?*

I explored the use of two approaches for multiclass scenario discovery for unraveling patterns of distributional outcomes under a wide range of deep uncertainty scenarios. Scenario discovery is a method commonly used for extracting insights from a large-scale computational experiment, by identifying subspaces in the input space that best explain the outcomes of interest. In multiclass scenario discovery, the simulation output space is partitioned into multiple (more than two) classes of interest. Through multiclass scenario discovery, distinctive patterns of distributional outcomes were identified, and the driving forces behind each pattern were then characterized. The first approach I considered is a sequential approach, which begins with clustering the distributional outcomes from a large-scale computational experiment, and continues with applying rule induction techniques for each cluster of distributional outcomes. This sequential approach is the *de facto* standard for multiclass scenario discovery. As a second approach, I proposed a concurrent approach. This approach utilizes the Multivariate Regression Tree (MRT) algorithm where the distributional outcomes become the multivariate dependent variables while the policy and uncertainty factors act as the independent variables for the algorithm. The algorithm generates branches of narratives from the independent variables while simultaneously looks for distinctive clusters of distributional outcomes.

I proposed three interpretability criteria to evaluate the performance of multiclass scenario discovery: output space separability, input space separability, and the number of resulting clusters. Output space separability evaluates the dissimilarity of distributional patterns between different clusters (more dissimilar is preferred) and the similarity within each cluster (more similar is preferred). Input space separability focuses on the extent to which the identified narratives behind each cluster are mutually exclusive from each other. A larger number of clusters tends to increase the burden of communicating the results to decision makers. From performing both the established sequential and novel concurrent approach for the VMD case study, I found that the sequential approach slightly outperforms the concurrent approach in terms of between-cluster output space separability, but it is slightly outperformed in terms of within-cluster separability. The concurrent approach results in perfect input space separability, as the nature of the MRT algorithm ensures binary and mutually exclusive splits of narratives. However, it comes at the expense of having a higher number of clusters. While the comparison of the output space separability might be case study dependent, the comparison of input space separability is generalizable, owing to the nature of the MRT algorithm.

Which approach one should use depends on the specific use-case and context, especially in relation to how the results would be used and communicated. The sequential approach is more suitable in situations where the generated narratives will be re-used by other agencies for other contexts and purposes. This is because the sequential approach produces fewer clusters and narratives. The concurrent approach is more appropriate in situations where the generated clusters and narratives are used only for a single specific context in which the analysis is conducted. The level of interactions with decision makers is another important consideration. Given that the concurrent approach produces a substantially richer picture of future distributional outcomes, it requires a relatively more intense interaction with decision makers. Having only minimal communications with decision makers will undermine the benefits of the concurrent approach.

5. *How can the use of multiple distributive moral principles in model-based support tools improve the considerations of equity in adaptation planning?*

To answer this question, I operationalized seven distributive moral principles for evaluating the performance of alternative adaptation policies: utilitarian (maximizing the utility of everyone), egalitarian (equality of outcomes), Rawlsian difference (benefits for the worst-off), prioritarian (extra weights given to worse-off stakeholders), sufficientarian (minimum threshold of utility for all stakeholders), envy-free, and composite principles (combining two or more individual principles). The ideas behind each principle were translated into aggregation functions that added up the profitability of all districts. In this way, the preference ranking of alternative policies could be determined. The change in the preference ranking when different principles are adopted was first observed for one baseline scenario, and then for a large number of scenarios, in order to understand the stability of the ranking. Conflicts and agreements of preference rankings between principles across the scenarios were also observed.

As expected, adopting different principles alters the preference ranking of the policies. In the VMD case study, the fertilizer subsidy policy ranks first based on the Rawlsian principle but performs second-worst on the envy-free principle. When seen across scenarios, the utilitarian principle yields the most stable preference ranking. In more than half of the scenarios, the low dikes in Dong Thap policy is the most preferred option, while fertilizer subsidy is the best performing option in the rest of the scenarios. In contrast, the most preferred option based on the egalitarian principle is more scenario dependent: low dikes in An Giang (most preferred in 35% of the scenarios), low dikes in Dong Thap (also around 35% of the scenarios), fertilizer subsidy (around 20% of the scenarios), and improving seed quality (around 5% of the scenarios). The similarity of rankings from two different principles across the scenarios was also evaluated. Overall, principles which have similar imperatives (e.g., prioritarian and egalitarian) have high ranking similarity across all scenarios, while ranking similarities for pairs of principles with different imperatives are more mixed.

Decision makers could have different preferences of justice, and this could change in different contexts (Van Hootegem et al., 2020). Hence, when performing normative analysis of distributional outcomes, it is important to first reflect on the justice principle appropriate for the case study and accepted by people in the case study area. In addition, justice preference could change over time. This again underlines the importance of using several distributive moral principles, even those which are presently not in line with the preferences of the decision makers. Each principle provides alternative views on what constitutes a morally justifiable distribution. Hence, evaluating the distributional outcomes of alternative policies against multiple moral principles would reduce the possibility of maladaptation (Magnan et al., 2016), as the various principles shed light on different potential unintended distributional consequences of the policies.

7.2. Scientific reflection

This research was motivated by the need to account for equity in model-based adaptation planning for deltas. While previous studies have made ad-hoc attempts to include equity considerations in model-based adaptation planning in general (Li et al., 2018; Thornton et al., 2010; Van Ruijven et al., 2015), and in model-based planning for deltas in particular (Aerts et al., 2018b; Ciullo et al., 2020; Kind et al., 2017), a systematic assessment of what is needed for model-based support for equitable adaptation planning so far has been missing. This research aimed to close this gap by understanding modeling requirements to account for equity, demonstrating the merits of fulfilling some of these requirements, and proposing two complementary model-based analyses to support equitable adaptation planning, namely explorative and normative analyses. In light of my research, I have several points that warrant further discussion.

First, fulfilling model requirements proposed in Chapter 2 requires a huge investment in model development. At the very minimum, disaggregated outcomes to different stakeholders should be calculable in order to assess intra-generational justice. To have a fairer representation of the stakeholders, their behavior should also be encoded in the model. In this thesis, I did this through a utility-based land-use change module. In Chapter 3, I discussed how under certain conditions, failure to include this endogenous behavior could lead to misleading outcomes. This could have subsequent implications for the outcomes of the distributional analysis as well. Including human behavior and external variables which influence it implies accounting for multisectoral dynamics through coupling and simplifying complex models. This is not a trivial exercise. As noted by Voinov and Shugart (2013), treating model coupling as a technical software exercise would produce ‘integronsters’ – models that are valid as software products but useless as decision-support tools. Overall, fulfilling the model requirements underlines the importance of assessing whether a model is fit for purpose (Haasnoot et al., 2014), for instance through devising evaluative questions that assess the adequacy of the model for answering policy questions.

Second, there are two critical choices related to the variable(s) for which the analyst wants to assess the distribution. The first choice is whether the historical distribution of the variable across stakeholders is considered. In the VMD case study, I simulated farms profitability starting from 2012. This approach is agnostic to the historical profitability of the farmers. In reality, it is likely that some farmers were initially better-off compared to others. These choices could therefore have procedural justice implications. The second choice is related to the temporal dimension: whether to look at dynamics over time, or at aggregation for the entire planning horizon. Here, I aggregated farms profitability across the entire planning horizon. To account for intergenerational justice, it is essential to look at dynamics over time. The distributional outcomes may look different when observed in the near- and long-term future, and aggregating temporal outcomes could obscure intergenerational trade-offs. Finally, Accounting for intergenerational justice could be further complemented with pathways approaches (Haasnoot et al., 2013; Wise et al., 2014). Through pathways, we can look not only at the evolution of the distributional patterns, but also at the change in the policy space over time. As noted in Chapter 2, evaluating how decisions today limit or extend available choices of future generations is one important way to include intergenerational justice considerations.

Third, the application of multiclass scenario discovery for supporting explorative analysis raises various follow up questions. In this research, I used an off-the-shelf algorithm (i.e., the Multivariate Regression Tree (MRT)) to concurrently account for input and output space separability. The MRT algorithm by default optimizes for maximizing output space separability, as the algorithm looks for orthogonal splits that result in the highest decrease in impurity of outcome variables (De’ath, 2002; Smith et al., 2019). A more suitable algorithm should be able to take into account all the three interpretability criteria (input space separability, output space separability, and number of narratives) and perhaps also allow for performing non-orthogonal splits on the simulation results database. The MRT algorithm could also suffer from the problem of multidimensionality. This is the case if distributional analysis is performed for an even larger number of stakeholders, as this would entail having a larger number of outcome indicators. High-dimensional data clustering algorithms are available to remedy this issue (Jain, 2010; Kriegel et al., 2009), although, as in other clustering algorithms, they focus only on output space separability. Further, the quality of the different approaches to scenario discovery is so far evaluated through quantitative metrics, but not through how prospective users of these results react to them (Parker et al., 2015).

Fourth, understanding who could potentially win and/or lose can have moral consequences. For instance, reflecting on the case study, one could imagine a situation where a district is expected to be worse-off in the future, owing to the implementation of certain policies or the realized climate change scenario. Such an analysis can be a self-fulfilling prophecy (Bafumi, 2011; Merton, 1948) if it leads to a decrease in investment in and attractiveness of that district. Without proper institutions and fair decision-making processes behind the application of the explorative analysis, the information of winners and losers could be gamed to the advantage of those with vested interests (Thomas and Warner, 2019). In Chapter 2, we indicated how this issue could be assessed from the angle of ethics of quantification (Saltelli and Di Fiore, 2020).

Fifth, normative analysis performed in this study (Chapter 6) assumes that the policies and principles are predetermined in advance. In other case studies, the policies might not be prespecified, but instead searched through an optimization routine (Herman et al., 2015). Research on using multiple moral principles in optimization, although growing, is still in its infancy (see e.g. Behbahani et al. (2019); Ciullo et al. (2020); Gourevitch et al. (2020)). In these studies, the different moral principles are independently translated into optimization problems, and the performance of the optimized policies is only compared later on. An alternative optimization setup, which is not yet explored, is to use the different moral principles in a multi-objective optimization setting, so that trade-offs between principles could be better explored. With respect to the principles, in Chapter 6 I assumed the principles to be applicable for the entire planning period (from the start to the beginning), while what principle is being preferred could change over time (van de Poel, 2018). What remains an open question is how to include uncertainties pertaining to dynamic change of the preferred principles.

Last, while this dissertation has been highly model-oriented, it is important to revisit the broader context of equitable adaptation planning. Assessing distributional outcomes is only one part of the story. Supporting equitable adaptation planning also requires ensuring the procedural fairness of the entire planning process, including model development and use. Adequate and fair stakeholder engagement is key for this. Ideally, all affected stakeholders should have sufficient influence, so that their interests can be well represented. Though, this could have multiple practical consequences. From a modeling point of view, involving more stakeholders could result in the need to have a wider conceptual scoping of the model, as we need include aspects that they find important, alternative measures they would like to consider, and different systems understanding. From a collective decision-making point of view, involving more stakeholders with varying interests could increase the possibility of decision deadlocks. Meanwhile, excluding relevant stakeholders is a recipe for disaster; it could overlook potentially significant impacts to some population subgroups. All these complications lead to the need to find a good balance between stakeholder engagement and decision-making authority. Fields of studies related to decision aiding and participatory modelling (as proposed by Pahl-Wostl (2002); Voinov et al. (2016)) and governance and institutional studies (as performed by Fung (2006); Pahl-Wostl et al. (2010)), could contribute to untangling this complexity.

7.3. Implications for practice

How do the findings in this thesis translate into practice, where resources to conduct proper equity analysis are often limited while interactions with clients are often more frequent? Here, four practical recommendations to include equity in adaptation planning for deltas are proposed. In addition, several policy-relevant insights for the VMD, which is the main case study in this thesis, are also outlined.

On models for assessing distributional outcomes

Accounting for equity is resource demanding, while resources for model development are often limited. Accounting for equity requires extending the conceptual boundary of the model. In Chapter 3, the original impact assessment metamodel was extended with a land-use change module, which is a complex model in itself. In Chapter 4, the importance of including multisectoral dynamics was emphasized. Fortunately, there were many complex, sector-specific models available from previous studies that could be used for the VMD case study. This might not always be the case, as for other case studies there might not be any sector-specific models available. For such cases, one could start small by choosing if he/she wants to focus on either equity across people or equity across values (see Chapter 2). This will determine the appropriate modeling formalism (i.e., the rules according to which a model is built, or the type of model) to use. For equity across people, the focus would be disaggregation of actors, and this could be apprehended by using spatially explicit models or agent-based modeling formalism (Filatova et al., 2013; Kelly et al., 2013). For equity across values, a more aggregated modeling formalism such as system dynamics would be more appropriate, owing to the simplicity of including multiple values in this formalism (Kelly et al., 2013).

Understanding preferred moral principles

This thesis has shown the wide variety of distributive moral principles (Chapter 6), and how they could be operationalized to assess the performance of distributional outcomes. People's preference towards certain principles is very domain, context, and culture dependent (Van Hootegem et al., 2020). Hence, in practice, the preference should first be elicited from the stakeholders. One way to do this is by designing questionnaires specifically aimed at eliciting stakeholder preferences (see e.g. Konow, 2001, 2003). Another way is to use readily available national survey data, which sometimes contain questions from which the society's distributive preference can be induced (see e.g. Van Hootegem et al., 2020). Quantitative information from surveys and questionnaires can then be confirmed to stakeholders through focus group discussions. Should resources for arranging questionnaires and surveys are not available, one can also organize workshops with stakeholders, where they are presented with commonly found distributive principles in the problem domain. In any case, due to the presence of normative uncertainties (Taebi et al., 2020, ; also discussed in Chapter 6), and in order to avoid unintended distributional consequences, normative assessment of distributional outcomes should always be accompanied with the use of more than one moral principles.

On explorative and normative analysis

This thesis has proposed two complementary types of analysis for supporting equitable adaptation planning. While here the explorative and normative analyses are performed in two separate studies, in practice they should be carried out together. Which should be carried out first depends on the objective of the study. If the goal is to identify the best performing policy (given certain distributive principles) and its performance across scenarios, the normative analysis should be performed first. The explorative analysis can then focus on exploring emerging inequality patterns only for the selected policies, instead of exploring all plausible patterns under all combinations of policies and uncertainties. If the goal is to understand distributional consequences of candidate adaptation actions and uncertainties, then the explorative analysis should come first.

Linking to adaptive pathways planning

As explained in Chapter 1, adaptive pathways planning is an emerging approach for long-term planning in deltas. In the Netherlands, this is encapsulated under the name of adaptive delta management (Klijn et al., 2015; Marchand and Ludwig, 2014). It has also been adapted and promoted worldwide, such as in the recent IPCC special report on sea level rise (Oppenheimer et al., 2019), UNESCO's Climate Risk Informed Decision Analysis framework (Mendoza et al., 2018), and the national guidance to coastal hazard in New Zealand (Lawrence et al., 2018). To support equitable planning, equity considerations could be integrated within the adaptive pathways planning cycle (see Figure 7.1). Of utmost importance here is the inclusion of distributional outcomes.

In the problem structuring stage, agreement regarding the scope of the distributional outcomes (distribution of what, and across who) should be made through stakeholder engagement and participation. Alternative moral principles could be used to aggregate distributional outcomes, in addition to the commonly used utilitarian principle. In the problem analysis stage, quantitative evaluation of alternative measures and uncertainties can be supported by a multisectoral model. Normative and explorative analyses should be conducted in this stage. Based on the explorative analysis, additional compensation measures for stakeholders anticipated to be harmed could be drafted in advance. In the strategy development stage, the performance of alternative pathways should be evaluated not only from an aggregate perspective, but also from the perspective of each actor (i.e., what would be the consequences of pathway *i* for actor *a*?). Accordingly, different signpost variables might have to be monitored for each actor. Lastly, in the final stage, the outcomes experienced by each actor should be monitored together with system-level outcomes. Note that specific adjustment to the framework presented here might be required for different case studies, but the general idea of including distributional outcomes and performing normative and explorative analysis holds true.

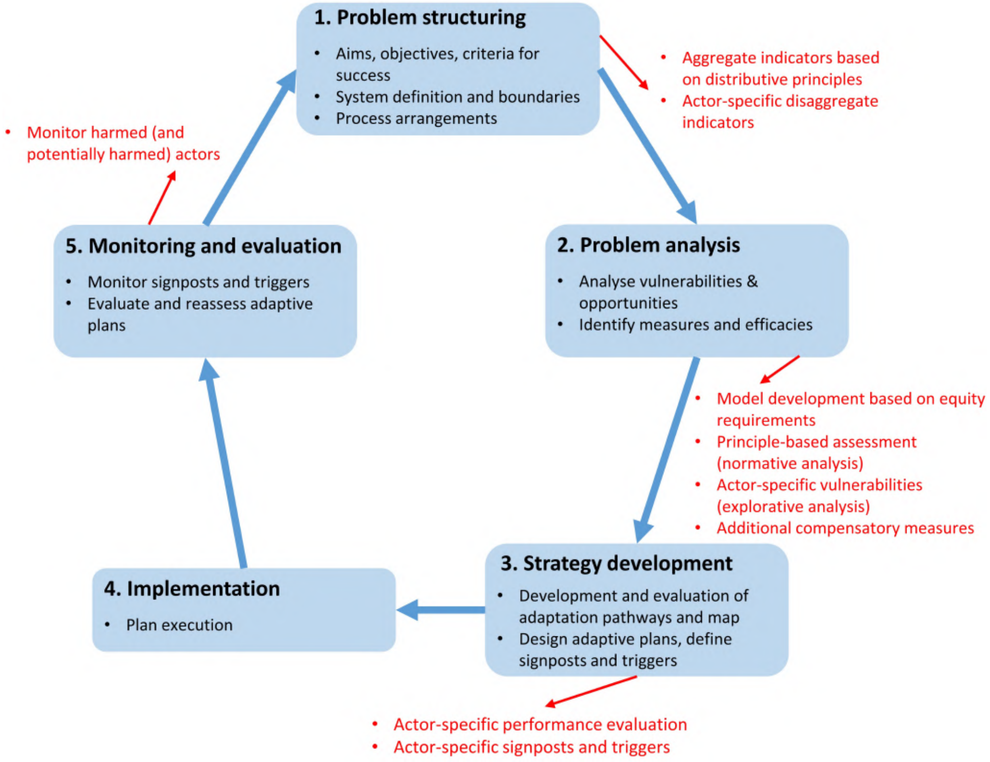


Figure 7.1: Integrating equity considerations into the adaptive delta management framework. The original framework, displayed as blue boxes, is adapted from Haasnoot et al. (2013) and Oppenheimer et al. (2019). The red texts indicate additional equity considerations required in each step.

Insights for the Vietnam Mekong Delta

Though the main contribution of this thesis is methodological, several policy-relevant insights emerge from using the VMD as the case study. First, this thesis found that man-made physical interventions have larger influence on both aggregate farm profitability (Chapter 4) and patterns of spatial distribution of farms profitability (Chapter 4 and 5). These interventions include dikes (de)construction in the VMD and upstream dam development in Cambodia. This finding aligns with suggestions from previous studies (Hoang et al., 2019; Manh et al., 2015; Nhan and Cao, 2019; Triet et al., 2020), which emphasize the importance of transboundary cooperation for safeguarding future livelihoods in the VMD. Second, overall, shifting back to living with the floods – for instance through deconstructing high dikes – is the best performing strategy across scenarios and principles. Though, it is important to acknowledge that under certain conditions, this strategy could perform relatively worse compared to the others (Chapter 6). Finally, this thesis found that in any future pathway, there are always ‘losers’ and ‘winners’ in terms of farms profitability. Depending on the realized scenarios, a different set of districts becomes better-off and others become worse-off (Chapter 4 and 5). This suggests the need to prepare for additional compensatory measures for worse-off districts, in addition to the current policy alternatives which are on the table.

A

Appendix for Chapter 3: Algorithms for calculating local suitability after flood events

We employ a simple utility function to define the local suitability of the land-use classes. All land-use classes have the same model structure, but with different parameters values. The utility of parcel c for land-use class j follows the logic below:

Algorithm 1: Calculation of local suitability

```
Calculate flood severity on parcel $c$ : $F_c = \beta_j * \frac{W_c}{0.5}$;
if $F_c < T$ then
    Utility of parcel $c$ for land-use $j$ : $S_{cj} = f(A_{cj})$;
else
    Calculate same-class utility on parcel $c$ for land-use $j$ : $E_{cj} = \alpha_j * \frac{A_{cj}}{900}$;
    Calculate accessibility utility on parcel $c$ for land-use $j$ : $D_{cj} = \gamma_j * d_{cj}$;
    Utility of parcel $c$ for land-use $j$ : $S_{cj} = f(E_{cj} - F_c + D_{cj})$;
end
```

where:

S_{cj}, Local suitability of land-use class j on parcel c

A_{cj}, Total area of land-use class j on parcel c (m2)

F_c, Perceived flood severity on parcel c

E_{cj}, Same-class utility on parcel c for land-use j

$D_c j$, Distance decay / accessibility utility on parcel c for land-use j

W_c, Average water depth on parcel c over a ten-year period (m)

T, Flood sensitivity threshold of the society

d_{cj}, Distance decay value of land-use class j on parcel c

α_j, Sensitivity parameter of land-use class j for the presence of the same land-use class within a parcel

β_j, Sensitivity parameter of land-use class j for the flood water depth

γ_j, Sensitivity parameter of land-use class j for the distance decay factor

B

Appendix for Chapter 4: Model description and validation

Model description

Farmers' profitability (module number 1 in Figure 4.2 and Table 4.1) is calculated based on a simple equation of profit and cost. An average selling price of 5000 VND/ton is used throughout the simulation period. The cost considered is the fertilizer cost, which contributes to around 25-40% of the total cost per cropping season (Thong et al., 2011; Tran et al., 2018b). On average, farmers apply 625 kilograms of fertilizer per hectare per season (module number 2 in Figure 4.2 and Table 4.1), although this number could vary between 400 and 1000 kg/ha/season (Chapman et al., 2016; Tran et al., 2018b). Higher fertilizer application is observed in old high dike areas, i.e., areas where high dikes have been constructed for more than 15 years. Surprisingly, no obvious differences in patterns could be observed with respect to rice yield per season between low dike and high dike areas. It is worth noting that we do not model individual farmers. Rather, farming activities and farm profitability calculation are represented in each of the 200m x 200m cells in the model.

We use the QUEFTS model to calculate the rice yield (module number 3 in Figure 4.2 and Table 4.1) in each cell in the model (Sattari et al., 2014; Witt et al., 1999). QUEFTS assumes that nutrient is the limiting factor of rice production. This assumption is suitable for tropical regions where other limiting factors such as water supply are less pressing issues. QUEFTS has been used for supporting site-specific nutrients management practices in multiple tropical countries including Vietnam (Dobermann et al., 2004). While nutrients are the limiting factor for the winter-spring crops, water availability seems to be a limiting factor for the two other seasons (i.e., summer-autumn and autumn-winter crops). We use a statistical relation based on Tan Yen et al. (2019)

for this. The yield of summer-autumn crops is generally 24% lower while the yield of autumn-winter crops is 30% lower than the yield of winter-spring crops. We use these scaling factors to calculate the yield of the summer-autumn and autumn-winter crops.

The soil nutrients module follow a simple stock and flow structure (module number 6 in Figure 4.2 and Table 4.1), with the nutrients availability in the soil as the stock (Chapman and Darby, 2016). Nutrients are supplied through both natural sediment deposition (for inundated cells, module number 7 and 8 in Figure 4.2 and Table 4.1) and artificial fertilizer application (for all cells). Therefore, if a cell is not inundated, nutrients come only from fertilizer. Since no reliable spatially explicit information is available on the fertilizer use, as a basis we take an average fertilizer use of 625 kg/ha/season as reported in Tran et al. (2018b). Which nutrients are available and which may be limiting depends on its origin (Manh et al., 2014; Tan et al., 2004). For instance, the average N, P, and K content in sediment are 4.9%, 1.9%, and 22.5% respectively. Nutrients in the soil are depleted at different rates depending on the cropping practices of the farmers. Evidently, the depletion rate is highest in a triple-rice system and lowest in a single-rice system. This stock and flow structure of the nutrients in the model comply with observations concerning increasing fertilizer use in old high dike areas (Tran et al., 2018a,b). The protection of the paddy fields from fluvial flooding also prevents sedimentation and hence reduces the supply of nutrients to the fields. In the long term, this results in reduced nutrient stocks. It eventually reduces the productivity (i.e., yield) of the crops and urges farmers to apply more fertilizer in the model.

The total sediment budget in a given year depends on the water level at the upstream VMD (module number 7 in Figure 4.2 and Table 4.1), which in turn is dependent on the upstream discharge at Kratie in Cambodia (module number 11 in Figure 4.2 and Table 4.1)). Specifically, we use the quadratic statistical equations provided by Manh et al. (2015) that calculate the total annual floodplain sedimentation in the dike-enclosed compartments in the VMD given the water level at Tan Chau (the upstream station of the VMD). In order to spatially distribute the total annual sediment budget (module number 7 in Figure 4.2 and Table 4.1), we make use of the simulation results of a complex spatially explicit sediment transport and deposition model provided in Manh et al. (2014). This complex model outputs the potential sedimentation rate on thousands of observation points along the rivers and irrigation channels. Overall, it shows that the sediment concentration is inversely correlated with the distance from the main rivers. Lastly, since sedimentation occurs only on inundated cells, we impose this potential sedimentation map with the flood map. The total sedimentation budget is then distributed on top of this inundation-corrected sedimentation map.

The inundation module (module number 5 in Figure 4.2 and Table 4.1) relies on a spatially explicit statistical relation that is constructed on the basis of complex hydrodynamic models in the VMD (Dung et al., 2011; Triet et al., 2018, 2017). The complex models provide the maximum inundation extent and flood depth for four exceedance probabilities of peak discharges at Kratie. Accordingly, the statistical relation is constructed for each cell in the model in a form of linear regression. The maximum annual discharge at Kratie (module number 11 in Figure 4.2 and Table 4.1) becomes the independent variable while the water level on each cell becomes the dependent variable. There are two flood events in each year: the 'July' flood and the 'all-year' flood. In the hydrodynamic model, the 'July' flood refers to the maximum flood extent due to the accumulation of rainfall only in July, right after the monsoon season starts. The 'all-year' flood refers to the maximum flood extent due to the accumulation of rainfall from July through late October. This distinction was made because the 'July' flood would affect the summer-autumn crop while the 'all-year' flood would affect the autumn-winter crop. The statistical relation for the 'all-year' flood is also used to determine the water level at Tan Chau, which then is fed to the sedimentation module of the integrated meta-model. In the complex hydrodynamic model, the 'July' flood

To calculate the flood damage to the agricultural sector (module number 4 in Figure 4.2 and Table 4.1), we depart from the crop damage logic applied by Triet et al. (2018). The crop damage due to inundation is divided into two categories. A cell belongs to the deep inundation category if the water level on that cell exceeds 0.5m. Deep inundation usually occurs longer than two weeks, incurring complete loss of the crop. If the water level is lower than 0.5m, then shallow inundation is assumed. Here, the field is inundated only for a short period of time. For this category, we apply an exponential function between the flood depth and the percentage of damage to the crop, with a maximum damage of 100% if the water level reaches 0.5m.

Land subsidence (module number 10 in Figure 4.2 and Table 4.1) due to various land-use functions complicates the flood risks further, as the flood depth deepens along with the decrease in the elevation of the area. We use the statistical relationship established by Minderhoud et al. (2018) to derive a subsidence rate for each cell based on its land-use function. Urban land-use induces the highest rate of subsidence of almost 20 mm/year. Subsidence rate of rice cropping activities is inversely correlated with the intensity of the farming system. Rain-fed single-rice has an average subsidence rate of 14 mm/year, while irrigated triple-rice cropping system induces only 8 mm/year of subsidence rate.

We model the land-use changes (module number 9 in Figure 4.2 and Table 4.1) for seven important land-use classes in the upper VMD (see Figure 4.3). We use the cellular automata approach to model land-use changes (Van Delden et al., 2010; White et al., 1997). In short, the approach allocates future demand of each land-use class based on the total potential map of that land-use class. The total potential map is calculated based on a combination of the neighborhood interaction factors, (biophysical) suitability, and zoning regulations. The biophysical suitability, especially the presence of high dikes, along with the neighborhood influence factor have been argued as the main driving factors of land-use change (Ngan et al., 2018; Sakamoto et al., 2009). It is important to note that we assume that farmers keep the same position and only decide what they cultivate – in the two provinces we observe, 90% of the area is already used for agricultural activities. The dynamics is between the contraction and expansion of different types of farming activities, which we treat as land-use demand scenarios.

Fit for purpose assessment

Considering data availability of main model inputs, which are upstream river discharge time series and historical land-use maps, the fit for purpose assessment of the integrated assessment model (IAM) is conducted by running the model over a time period of 2002-2012. Whenever sufficient information is not available for a particular variable, an earlier time frame is chosen. The rest of this appendix discusses the guiding questions and hypothesis presented in Table 4.2 of Chapter 4.

Does the model produce the heterogeneity of the farmers' profitability?
To answer this question, we compare the calculated profitability of all rice farmers in An Giang and Dong Thap between 2002-2012 with profits of surveyed farmers provided by Tran et al. (2018b). Figure B.1 displays the results of the comparison. While the modeling results are still within the boundary of the survey data, they do not capture the entire range of surveyed profits. Two reasons could explain this result. First, we do not consider the stochasticity and variability of rice selling price experienced by different farmers. Depending on their location and connection to rice brokers and markets, farmers would be paid differently for their yield (Stuart et al., 2018; Tran et al., 2018b). Second, on the cost side of the profitability calculation, we focus only on fertilizer cost. We do not consider, for instance, pesticide cost that could rise tremendously in case of pest outbreaks (Tong, 2017).

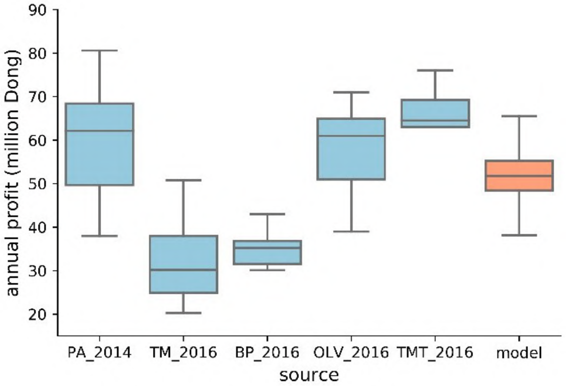


Figure B.1: Comparison of farmers' annual profit. Blue boxes are surveyed profits of farmers in various communes for different years, provided by Tran et al. (2018b)

Does the model capture the variation of rice yield between the different cropping seasons?

The seasonal yield from the IAM is compared with the seasonal yield reported by Tan Yen et al. (2019) for the same time period of 2002-2012. Figure B.2 shows the results of the comparison. The average calculated yield for each season matches with the average reported yield. However, the calculated yield has a larger spread for the winter-spring and summer-autumn season. This might be explained by the fact that the reported yields are the average values across all farmers, hence they miss the variability of actual yields. For instance, Tran et al. (2018b) report that at a household level the seasonal yield could be as high as 10 ton/ha.

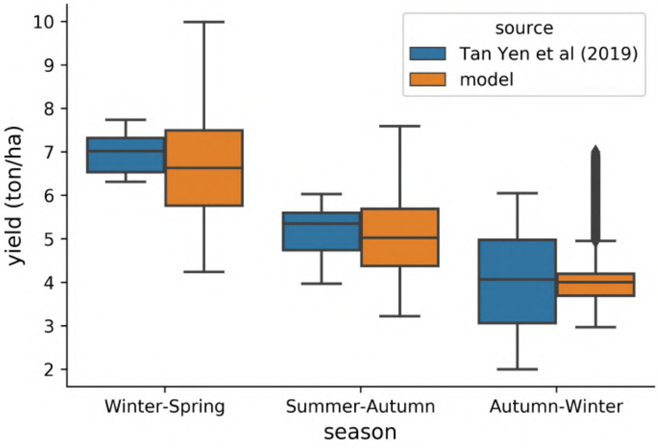


Figure B.2: Comparison of seasonal yield

Does the model produce a reasonable magnitude of annual floodplain sedimentation?

We compare the cell level annual floodplain sedimentation with the results of complex physical-based modeling by Manh et al. (2014). Figure B.3 displays the results of the comparisons for three different flood years: low flood (2010), normal flood (2009), and extreme flood (2011). As sedimentation rate is spatially explicit, three statistics are collected: the maximum, average, and minimum sedimentation rate across all pixels in the models. In larger flood events, particularly the 2009 and 2011 flood event, the IAM underestimates the maximum sedimentation rate by around 20%. Nevertheless, the calculated mean and minimum floodplain sedimentation for all flood events agrees quite well with the results of the complex model.

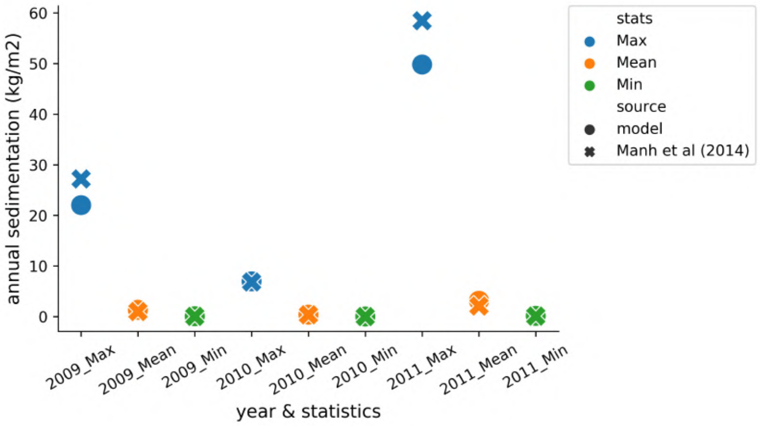


Figure B.3: Comparison of maximum, average, and minimum sedimentation at a cell level

Does the model yield a similar pattern of annual maximum water level at several hydrological stations in the study area?
We compare the annual maximum water level calculated by the IAM with the data reported by Triet et al. (2017) and Dang et al. (2016) for Tan Chau and Chau Doc hydrological stations that are located at the northern part of the study area. Figure B.4 presents the results of the comparison. The agreement between the calculated and reported annual maximum water level is quite high for extreme flood events (e.g., low flood years of 2010 and 2012 as well as extreme flood in 2011). A slightly lower agreement is observed for the annual maximum water level at Tan Chau in the normal flood year of 2007. Regardless of this, the IAM could replicate the overall temporal behavior of annual maximum water level quite well.

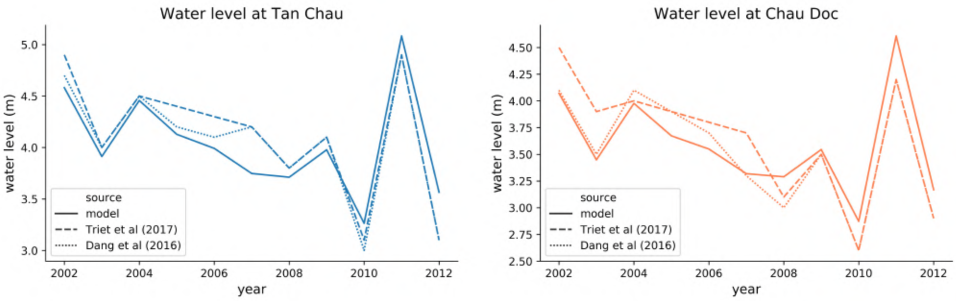


Figure B.4: Comparison of annual maximum water level at two hydrological stations in the study area

Does the model capture a sufficient location and pattern accuracy of land-use change processes?
Location accuracy concerns with the agreement (or in another term, correlation) between the simulated land-use map with the actual land-use map, whereas pattern accuracy measures the model's ability to mimic the overall landscape pattern of the actual map, rather than performing a cell-by-cell comparison as in the case of location accuracy (Brown et al., 2005; Van Vliet et al., 2013). We compare the simulated land-use map with the actual land-use map for year 2010 by calculating Kappa statistics (for allocation / predictive accuracy) and clumpiness index (for landscape / pattern / process accuracy) (Lin et al., 2020).

Table B.1 shows the results of the Kappa statistics and clumpiness indices. The Kappa statistics between two maps have a maximum score of 1, indicating a complete agreement between the two maps. The overall agreement between the simulated and actual land-use maps is almost 0.8, with the highest agreements observed for urban and orchard plantation land-use classes. The Kappa statistics for the two most important land-use classes, triple rice and double rice, are also quite high. The disagreement can be partly attributed to the micro behavior of some individual farmers who may change their land-use practices every other year due to various circumstances such as pest outbreaks. A very low predictive accuracy is observed for minor land-use classes, such as aquaculture, that cover less than 1% of the entire area.

Table B.1: Model evaluation results of the land-use change module

Location accuracy - Kappa statistics					
Overall	Triple rice	Double rice	Urban	Orchard plantation	Aquaculture
0.793	0.753	0.734	0.955	0.943	0.154
Process / pattern accuracy – Clumpiness index					
Maps	Triple rice	Double rice	Urban	Orchard plantation	Aquaculture
Simulated	0.872	0.82	0.559	0.763	0.665
Actual	0.874	0.855	0.525	0.749	0.547

The clumpiness index measures the degree of aggregation of certain land-use class, i.e., to what extent cells of the same land-use type are located next to each other. The index is 1 if a land-use class is maximally aggregated (the land-use class makes a single connected large patch), 0 if the land-use class is distributed randomly, and -1 if the land-use class is maximally disaggregated. The clumpiness indices are calculated for each important land-use class in the actual and the simulated maps. The more similar the clumpiness indices of the same land-use class from the two maps, the higher the pattern accuracy is. Table B.1 shows that the clumpiness indices of the main land-use classes for both the simulated and actual maps are in the same order of magnitude, implying a high degree of pattern accuracy. Marginal land-use classes – for instance aquaculture – again have a lower clumpiness index agreement.

Increase in annual peak discharge would increase the number of flood-induced damaged crops
We rerun the model for the entire fit for purpose assessment period (2002-2012) while increasing the upstream river discharge input by 20%, 40%, and 60%. We then compare the number of damaged crops due to inundation under each scenario. Figure B.5 shows the results of the comparison in violin plots, showing the distribution density of number of cells/farmers with certain crop losses due to flooding. Using the original upstream discharge data, most farmers experience crop losses of 0.5-1.5 tons. Higher upstream discharges rises inundation extent and flood depth, resulting in higher total losses. Non-linearity can be observed in this regard; increases of total crop losses from the 20%, 40%, and % higher discharge scenarios, when compared to the baseline scenario, are 263%, 158%, and 55% respectively.

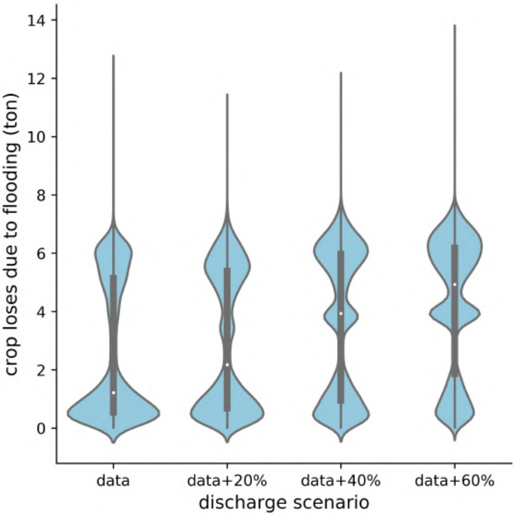


Figure B.5: Crop losses at a farmer level due to inundation

Reduction in sediment supply from upstream would also reduce farmers profitability
We rerun the model for the entire fit for purpose assessment period (2002-2012) while decreasing the sediment input from upstream by 20%, 40%, and 60%. We then compare farmers' profitability under each scenario. Figure B.6 shows the violin plots of the comparison. Under the default sediment load scenario, most farmers gain annual profits of around 55 million Dong. The violin plots flatten as the sediment supply decreases. The reductions of average profitability for all farmers under the 20%, 40%, and 60% less sediment load are 1.7%, 4%, and 8% respectively. Sediment load only

affects double rice-farmers, as triple rice farmers are protected by high dikes and not inundated (and thus no floodplain sedimentation at all). If we look at the reductions of average profitability only for double-rice farmers, the figures are 2.5%, 5.7%, and 11% respectively. The small impacts to profitability is because the use of artificial fertilizers that supply nutrients to the crops, aside from natural nutrients from the sediments. Since artificial fertilizers contribute more to the total nutrients supply, changes in sediment would have relatively lower impacts to profitability.

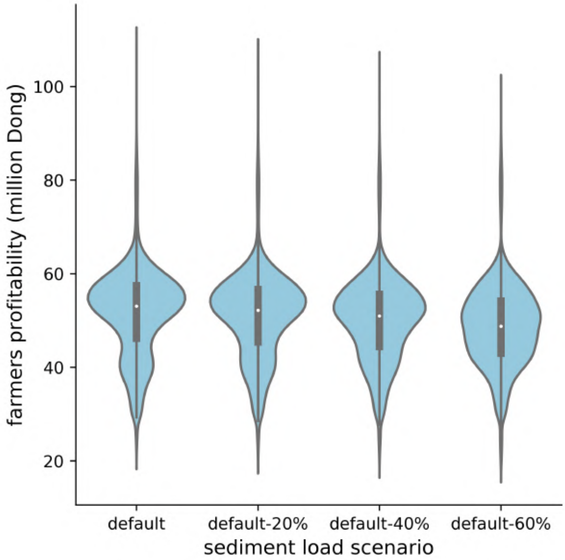


Figure B.6: Changes in farmers profitability due to reduction in sediment supply

Rapid expansion of triple-rice cropping without adequate dikes construction would increase the flood-induced damaged crops

We rerun the model for the entire fit for purpose assessment period (2002-2012) while increasing changing the land-use demand for triple-rice and double-rice farming systems. Historically, double-rice farming area decreases by 31% while triple-rice farming area increases by 175% over this time period. We develop an alternative rapid triple-rice expansion scenario where the double-rice farming area decreases by 50% whereas triple-rice farming area increases by 275%. By forcing this alternative land-use demand to the model, the land-use change module of the IAM then allocates the demand based on the neighborhood and suitability factors. We compare the number of damaged crops due to inundation under each scenario, assuming the high dike area is not expanded along with the rapid expansion of the triple-rice farming. Figure B.7 presents the result of the comparison. As a result of the rapid expansion the total losses increase by 26% compared to the baseline scenario. This is mainly explained by the expansion of triple-rice farms in the low dike area, which is eventually inundated during the monsoon season.

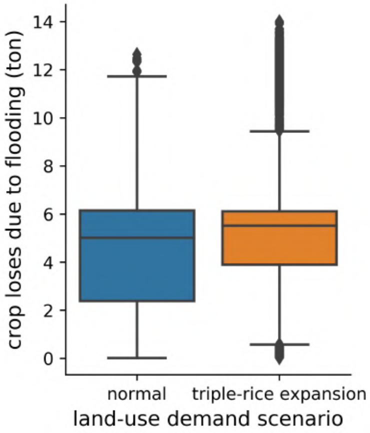


Figure B.7: Crop loses at a farmer level due to rapid triple-rice expansion

Uncertainties

This appendix discusses the three uncertain variables in the experimental setup: upstream discharges based on climate scenarios, dam development scenarios, and land-use demand scenarios based on societal preference over the different farming practices.

River discharges

Upstream discharge scenarios were obtained by running the global hydrological model PCR-GLOBWB 2 (Sutanudjaja et al., 2018) at the spatial resolution of 5 arcmin (10 km at the equator). The PCR-GLOBWB model is open source (`https://github.com/UU-Hydro/PCR-GLOBWB_model`) and has been used for various water-related change studies, such as the impact of land use change on water resources (Bosmans et al., 2017), groundwater depletion (de Graaf et al., 2017), as well as for current and future flood hazard and risk assessment (Ward et al., 2013; Winsemius et al., 2013). For this study, we used the standard parameterization of PCR-GLOBWB available at `https://opendap.4tu.nl/thredds/catalog/data2/pcrglobwb/version_2019_11_beta/pcrglobwb2_input/catalog.html`. However, unlike the standard setup used in Sutanudjaja et al. (2018) that implemented a simple travel-time characteristic solution, the PCR-GLOBWB simulation setup for this study used an advanced surface water kinematic wave routing scheme (see e.g., Winsemius et al., 2013). For this study, we forced PCR-GLOBWB with the ISI-MIP forcing data, consisting of five global climate models (GCMs), HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M, covering the historical period 1951-2005 and future climate period 2006-2099. For the future climate period, two different representative concentration pathway (RCP) scenarios are considered: RCP 4.5 and RCP 8.5. Based on these runs (in total, 10, runs from 5 GCMs and 2 RCPs), the upstream discharge time series were evaluated and extracted at the station Kratie.

Figure B.8 presents the median of the generated annual maximum discharge hydrographs at Kratie for the two climate scenarios, which is used as an input to the model. Figure B.8a shows that the RCP4.5 hydrograph has a similar exceedance probability graph with the historical observed time series (1924-2011), whereas RCP8.5 has relatively higher annual maximum discharges. Since our model is multi-temporal, a time series discharge is required. Figure B.8b shows the synthetic time series discharge between 2001 and 2050. Except for the time period of 2031-2040, RCP8.5 has relatively higher annual maximum discharges compared to RCP4.5.

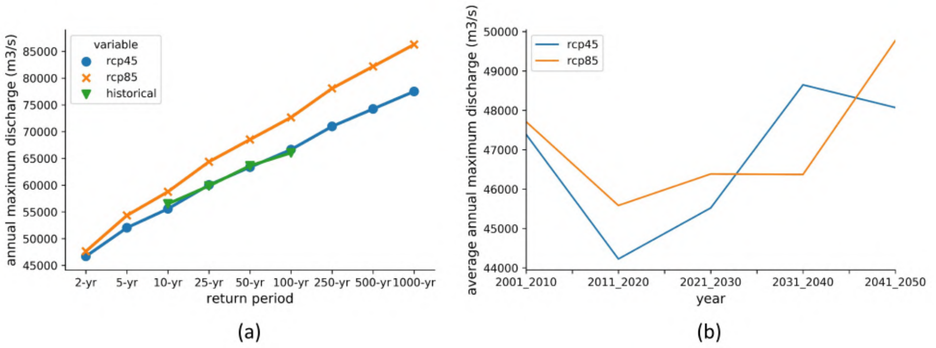


Figure B.8: (a) Historical and future (RCP4.5 and RCP8.5) exceedance probability analysis of annual maximum discharge at Kratie, (b) mean decadal annual maximum discharge at Kratie between 2001-2050.

Upstream hydropower dam development

Upstream dam development affects both the annual sedimentation budget through its sediment trapping efficiency (TE) rate, as well as the upstream discharge. Following the results of and Lauri et al. (2012) and Manh et al. (2015), we use three dam development scenarios: small (12% trapping efficiency), medium (53% trapping efficiency), and high (95% trapping efficiency) level of dam development. Based on a complex physical model Manh et al. (2015) formulated five fitted quadratic equations that calculate the total floodplain sedimentation under the different dam development scenarios (see Table B.2). The reduction in maximum annual discharge at Kratie, which is the input to the integrated assessment meta-model, is taken from Lauri et al. (2012).

Table B.2: Total annual floodplain sedimentation and reduction in maximum annual discharge under dam development scenarios. S refers to total annual sediment budget (million tons) while H is annual maximum water level at Tan Chau hydrological station (meter)

Scenario	**Annual sedimentation budget**	**Reduction in maximum annual discharge**
Small dam development	$S = 1.86H2 - 12.61H + 20.44$	4.94%
Medium dam development	$S = 1.06H2 - 9.41H + 16.12$	8.64%
Large dam development	$S = 0.12H2 - 0.84H + 1.51$	12.34%

Societal preference over farming practices

Preference over different rice cropping practices affect future land-use demand, which will in turn influence the land-use change dynamics. We develop two scenarios for this, resembling the two ongoing competing narratives in the region (Tran et al., 2019, 2018b; Triet et al., 2018). The first scenario assumes a continuation of agricultural intensification, implying a higher demand for triple rice farming in the future. The second scenario assumes the pursue of less intensive agricultural practices, implying a higher demand for double rice farming, shrimp-rice farming and aquaculture in the future.

C

Appendix for Chapter 5: Details of clustering results from the sequential approach

The first step in the sequential approach is determining the clustering algorithm and the number of clusters to proceed with. For each algorithm, we perform clustering with an increasing number of clusters from 2 to 21. We calculate the explained variance for each number of cluster (Figure C.1). By sweeping across different numbers of clusters we can observe the progression and the convergence of the explained variance. At the end of the iteration, i.e., with 21 clusters, the explained variance from all algorithms clusters converges to 0.8. As explained in the Methods section, we set a threshold T of 0.05 for the changes in explained variance in order to select an optimal number of clusters from each algorithm.

Note that the selection of the threshold T for the changes in explained variance is a subjective choice. We need to balance the explained variance of the selected number of clusters at which the threshold T is being met, the potential gain in explained variance when using a higher number of clusters, and the potential loss in interpretability when a higher number clusters is used. Table C.1 Explained variance of each clustering algorithm for the selected number of clusters shows the number of clusters from each clustering algorithm when the threshold T=0.05 is met and the corresponding explained variance. K-means algorithm yields the best performance. It performs slightly better than k-Medoids and clearly outperforms the other clustering algorithms. Its explained variance of 0.711 is also not too distant from the overall explained variance convergence of 0.8. Hence, in the remainder of this sequential approach we proceed with the 7 clusters of output space as identified by the k-Means algorithm.

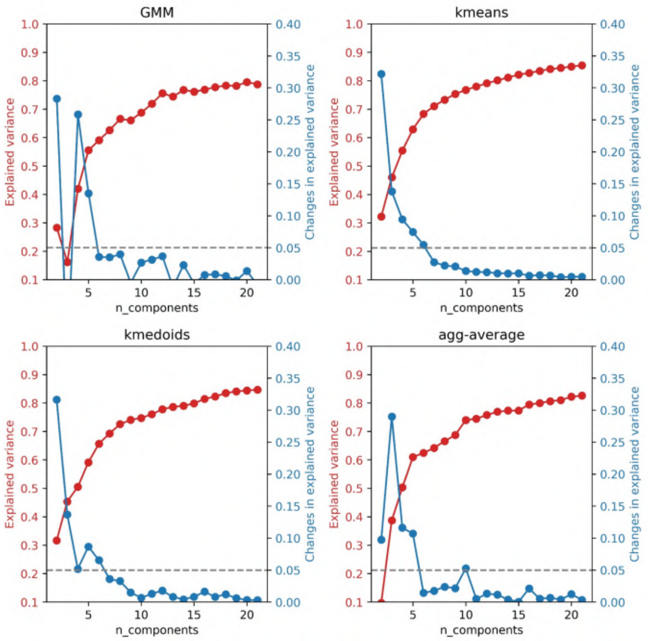


Figure C.1: Explained variance for varying numbers of clusters using five different clustering algorithms. The horizontal dashed line is the 5% threshold of delta/changes of explained variance used to determine the optimal number of clusters.

Table C.1: Explained variance of each clustering algorithm for the selected number of clusters

Algorithm	Selected number of clusters	Explained variance
Gaussian Mixture Model	7	0.626
k-Means	7	0.711
k-Medoids	7	0.693
Agglomerative clustering – complete linkage	7	0.619
Agglomerative clustering – average linkage	6	0.624

D

Appendix for Chapter 5: Details of tree selection in the concurrent approach

The concurrent approach begins with determining the size of the tree based on the evolution of the cross-validation scores. Figure D.1 shows the increase of the 10-fold cross validation scores. Similar to the clustering results in the sequential approach, the cross-validation score seems to converge to 0.8. As the score keeps increasing even after the tree has become quite complex, it is advised to set a threshold of increase in cross validation scores in order to select an appropriate tree size (Smith et al., 2019). We choose a threshold of 0.01 (dashed line on Figure D.1) and this threshold is reached when the number of leaves is 18.

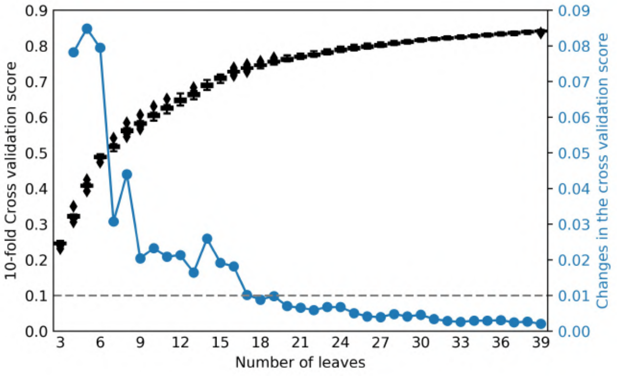


Figure D.1: 10-fold cross validation scores of the MRT. The left-hand y-axis corresponds to the boxplot of the 10-fold cross validation score. The right-hand y-axis corresponds to the changes in the cross validation scores. The horizontal dashed line shows the 0.01 threshold.

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Curriculum Vitae

Bramka Arga Jafino was born in Jakarta, Indonesia, on Jan. 4th, 1994. During undergraduate studies in Industrial Engineering at Universitas Indonesia (2011-2015), he conducted research on using an agent-based model to evaluate the performance of alternative natural gas vehicle transition policies for Jakarta. This led him to develop an interest in the field of model-based decision support, which he then pursued through graduate studies in Engineering and Policy Analysis at TU Delft (2015-2017). For his master thesis, he participated in a consultancy project with The World Bank, where he developed a transport network model to evaluate the criticality of freight transport network in Bangladesh.

Since October 2017, he is a PhD candidate at the Faculty of Technology, Policy, and Management, TU Delft. His research focused on developing model-based policy analysis approaches to support equitable adaptation planning, using case studies for the upper Vietnam Mekong Delta (VMD). This project combined integrated impact assessment modeling, exploratory modeling, and climate ethics and justice, to evaluate the distributional consequences of alternative adaptation policies as well as climatic and socioeconomic uncertainties in the VMD. Over the course of his PhD, he also participated in several consultancy assignments with The World Bank, primarily in projects related to simulation of climate change impacts on extreme poverty. In August 2021, he joined Deltares as advisor/researcher in flood impact modelling.

Publications and Presentations

Scientific articles related to this thesis

Published

1. **Jafino, B.A.** & Kwakkel, J.H. (2021). A novel concurrent approach for multiclass scenario discovery using Multivariate Regression Trees: Exploring spatial inequality patterns in the Vietnam Mekong Delta under uncertainty. Environmental Modelling & Software, 145, 105177.
2. **Jafino, B.A.**, Kwakkel, J.H., & Taebi, B. (2021). Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. Wiley Interdisciplinary Reviews: Climate Change, 12(4), e721.
3. **Jafino, B.A.**, Kwakkel, J.H., Klijn, F., Dung, N.V., Van Delden, H., Haasnoot, M. & Sutanudjaja, E. (2021). Accounting for multisectoral dynamics in supporting equitable adaptation planning: A case study on the rice agriculture in the Vietnam Mekong Delta. Earth's Future, 9(5), e2020EF001939.
4. **Jafino, B.A.**, Haasnoot, M., & Kwakkel, J.H. (2019). What are the merits of endogenising land-use change dynamics into model-based climate adaptation planning? Socio-Environmental Systems Modeling, 1.

Under review

1. **Jafino, B.A.**, Kwakkel, J.H., & Klijn, F. (Under review). Evaluating the distributional fairness of alternative adaptation policies: A case study in Vietnam's upper Mekong Delta. Climatic Change.

Other scientific articles

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1. **Jafino, B.A.**, Hallegatte, S., & Rozenberg, J. (2021). Focusing on differences across scenarios could lead to bad adaptation policy advice. Nature Climate Change, 11(5), 394-396.
2. Avner, P., Viguié, V., **Jafino, B.A.**, & Hallegatte, S. (2021). Flood protection and land value creation – Not all resilience investments are created equal. Policy Research Working Paper No. 9744. World Bank Group, Washington, DC.
3. Yap, J.R., **Jafino, B.A.**, & Verma, T. (2021). Equity principles highlight variations in road network criticality. Findings, June. https://doi.org/10.32866/001c.24900.
4. **Jafino, B.A.** (2021). An equity-based transport network criticality analysis. Transportation Research Part A: Policy and Practice, 144, 204-221.
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6. Hidayatno, A., **Jafino, B.A.**, Setiawan, A. D., & Purwanto, W. W. (2020). When and why does transition fail? A model-based identification of adoption barriers and policy vulnerabilities for transition to natural gas vehicles. Energy Policy, 138, 111239.
7. **Jafino, B.A.**, Kwakkel, J.H., & Verbraeck, A. (2020). Transport network criticality metrics: a comparative analysis and a guideline for selection. Transport Reviews, 40(2), 241-264.

Work in progress

1. Rentschler, J., Salhab, M., & **Jafino, B.A.** (Under review). Flood and poverty exposure analysis for 188 countries. Nature Communications.
2. Setiawan, A.D., Dewi, M.P., **Jafino, B.A.**, & Hidayatno, A. (Under review). Evaluating feed-in tariff policies for enhancing geothermal development in Indonesia. Energy Policy.

3. **Jafino, B.A.**, Rozenberg, J., Walsh, B., & Hallegatte, S. (In prep). Climate change impacts on poverty, inequality, and shared prosperity by the middle of the century: Projections and drivers across nations.
4. Cox, M., **Jafino, B.A.**, Koomen, E., & Kwakkel, J.H. (In prep). Inductive approach to scenario development in land-use change modelling.

Conference presentations related to this thesis

1. **Jafino, B.A.** & Kwakkel, J. (2021, April). Equitable adaptation planning under deep uncertainty for the upper Vietnam Mekong Delta. Presentation at the European Geosciences Union General Assembly 2021, Vienna, Austria.
2. Kwakkel, J. H., & **Jafino, B. A.** (2020, December). Informing the Design of Adaptive Policy Pathways in a Complex World: Considering multi-sectoral Dynamics and the Value of Deep Uncertainty Methods. Presentation at the AGU Fall Meeting 2020.
3. **Jafino, B.A.** & Kwakkel, J.H. (2020, November). Exploring multi-actor inequality patterns using scenario discovery: Comparisons of a cluster-and-classify approach with a multivariate regression tree approach. Oral presentation at the Decision Making Under Deep Uncertainty 2020 Annual Meeting.
4. **Jafino, B.A.** & Kwakkel, J.H.. (2020, September). A modified scenario discovery approach to explore inequality patterns in model-based adaptation planning. Oral presentation at the 10th International Congress on Environmental Modelling and Software, Brussel, Belgium.
5. **Jafino, B.A.** & Kwakkel, J.H.. (2020, May). A two-stage approach for assessment of distributional impacts in model-based delta planning: exploration of plausible inequality patterns and justice-based evaluation of policies. Oral presentation at the European Geosciences Union General Assembly 2020, Vienna, Austria.
6. **Jafino, B.A.** & Kwakkel, J.H. (2019, November). Using the scenario discovery approach to identify winners and losers of adaptation policies under uncertainties. Oral presentation at the Decision Making Under Deep Uncertainty 2019 Annual Meeting, Delft, The Netherlands.
7. **Jafino, B.A.**, Kwakkel, J.H., & Haasnoot, M. (2019, November). Exploring alternative moral principles for the ‘efficiency versus equity’ trade-offs in model-based policy analysis. Poster presentation at the Decision Making Under Deep Uncertainty 2019 Annual Meeting, Delft, The Netherlands.
8. **Jafino, B.A.**, Kwakkel, J.H., & Van Aalst, M. (2019, April). Evaluating the distributional impacts of water management strategies based on multiple lenses of justice: A case study in the Vietnam Mekong Delta. Oral presentation at the European Geosciences Union General Assembly 2019, Vienna, Austria.
9. **Jafino, B.A.** & Kwakkel, J.H. (2018, November). Towards incorporating inclusiveness in model-based support for long-term adaptation planning under uncertainty. Oral presentation at the Decision Making Under Deep Uncertainty 2018 Annual Meeting, Culver City, USA.
10. **Jafino, B.A.**, Kwakkel, J.H., & Haasnoot, M. (2018, June). How does endogenising land-use dynamics into an integrated assessment meta model affect the design of model-based adaptation pathways? Oral presentation at the 9th International Congress on Environmental Modelling and Software, Fort Collins, USA.
11. **Jafino, B.A.** & Kwakkel, J.H. (2018, April). Accounting for co-evolutionary interactions between human and water systems in a spatially explicit, loosely-coupled hydrological and land-use model. Poster presented at the European Geosciences Union General Assembly 2018, Vienna, Austria.

Other conference proceedings and presentations

1. **Jafino, B.A.**, Kwakkel, J.H. & Van Delden, H. (2019, December). Exploring plausible future land-use patterns: An application of the exploratory modeling approach in land-use modeling. Oral presentation at the 3rd International Land Use Symposium on ”Land use changes: Trends and projections”, Paris, France.
2. **Jafino, B.A.** & Kwakkel, J.H. (2019, November). Equity considerations in transport network criticality analysis. Oral presentation at the Decision Making Under Deep Uncertainty 2019 Annual Meeting, Delft, The Netherlands.
3. **Jafino, B.A.**, Kwakkel, J.H. & Van Delden, H. (2019, September). Identifying distinctive future land-use patterns that matter: An inductive model-driven scenario development approach. Oral presentation at the 21st European Colloquium on Theoretical and Quantitative Geography, Luxembourg.

4. Shinde, R., **Jafino, B.A.**, Kokosia, P., & van den Berg, J. (2016, December). Data Mining Algorithms for Improving the Efficiency of Governance in Dynamic Social Systems: Case Study of Indian Caste and Tribe Reservations. In Techno-Societal 2016, International Conference on Advanced Technologies for Societal Applications (pp. 249-263). Springer, Cham.
5. **Jafino, B.A.**, Soltani, P., & Pruyt, E. (2016, July). Saving Lives and Time: Tackling Transportation Induced Air Pollution in Jakarta. Conference proceedings of the 34th International Conference of the System Dynamics Society. Delft, The Netherlands.
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