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

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Abstract

The need for explicitly considering equity in adaptation planning is increasingly being recognized. However, quantitative evaluations of adaptation options often adopt an aggregated perspective, while disaggregation of results is important to learn about who benefits when and where. A typical example is adaptation of rice agriculture in the Vietnam Mekong Delta. In the past two decades, efforts focused on flood protection have mainly benefitted large-scale farmers while harming small-scale farmers. To investigate the distributional consequences of adaptation policies in the Vietnam Mekong Delta, we assess both aggregate efficiency and equity indicators, as well as disaggregated impacts in terms of district-level farmers profitability. Doing so requires an adequate representation of the co-evolutionary dynamics between the human and environmental systems which influence farmers profitability. We develop a spatially-explicit integrated assessment model that couples inundation and sedimentation dynamics, soil fertility and nutrient dynamics, and behavioral land-use change and farmers profitability calculation. We find that inter-district inequality responds in a non-linear way to climatic and socio-economic changes and choices of adaptation policies. Distinctive inequality patterns emerge from even slightly different combinations of policies and realizations of uncertain futures. We also find that there is no simple ranking of alternative adaptation policies, so one should make trade-offs based on the agreed preferences. Accounting for equity implies exploring the distribution of outcomes over different actor groups over a range of uncertain futures. Only by accounting for multisectoral dynamics can planners anticipate the equity consequences of adaptation options and prepare additional measures to aid the worse-off actors.

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Key Points:

- Understanding who wins and who loses under different futures can help planners in anticipating and ameliorating future inequalities.
- We show how inequality patterns are sensitive to external uncertainties and adaptation policies.
- Exploring inequality patterns requires accounting for multisectoral dynamics, which often has implications for the modelling choices.

Abstract

The need for explicitly considering equity in adaptation planning is increasingly being recognized. However, quantitative evaluations of adaptation options often adopt an aggregated perspective, while disaggregation of results is important to learn about who benefits when and where. A typical example is adaptation of rice agriculture in the Vietnam Mekong Delta. In the past two decades, efforts focused on flood protection have mainly benefitted large-scale farmers while harming small-scale farmers. To investigate the distributional consequences of adaptation policies in the Vietnam Mekong Delta, we assess both aggregate efficiency and equity indicators, as well as disaggregated impacts in terms of district-level farmers profitability. Doing so requires an adequate representation of the co-evolutionary dynamics between the human and environmental systems which influence farmers profitability. We develop a spatially-explicit integrated assessment model that couples inundation and sedimentation dynamics, soil fertility and nutrient dynamics, and behavioral land-use change and farmers profitability calculation. We find that inter-district inequality responds in a non-linear way to climatic and socio-economic changes and choices of adaptation policies. Distinctive inequality patterns emerge from even slightly different combinations of policies and realizations of uncertain futures. We also find that there is no simple ranking of alternative adaptation policies, so one should make trade-offs based on the agreed preferences. Accounting for equity implies exploring the distribution of outcomes over different actor groups over a range of uncertain futures. Only by accounting for multisectoral dynamics can planners anticipate the equity consequences of adaptation options and prepare additional measures to aid the worse-off actors.

1 Introduction

Home to more than 10% of the world's population, 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 increased the vulnerability 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). Vulnerability is further amplified by increasing exposure to natural hazards and weather extremes triggered by climate change and sea level rise (Chen & Mueller, 2018; Giosan et al., 2014; Kuenzer & Renaud, 2012; Moser et al., 2012). 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.

Climate change has heterogeneous impacts on different people, depending on their social, economic, and geographical background (Adger et al., 2009; Below et al., 2012; Call et al., 2017; Füssel, 2010; Thomas & Warner, 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), Ranger et al. (2013), Smajgl et al. (2015), Campos et al. (2016), and Radhakrishnan et al. (2017) 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.

Since little to no attention is given to assessing which groups of the population are more affected, adaptation policies rarely 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 & Remling, 2018).

There are two important elements that should be included when accounting for equity in 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 farmers' 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. Furthermore, from a political decision-making perspective, unequal distribution of outcomes can foster contestation and policy deadlock especially when the worse-off actors have substantial power in the decision-making arena (Gold et al., 2019; Trindade et al., 2019). Understanding distributional outcomes thus plays an important role in multi-actor planning processes.

Several recent studies in delta adaptation planning have touched on the issue of equity. Chapman and Darby (2016) distinguish impacts of alternative rice farming practices for the economic performance of small, medium, and large-scale farmers, at a household level. They uncover trade-offs between efficiency, i.e. maximizing total rice supply, and equity, i.e. income stability of farmers with different economic capacity. 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 as 'maladaptation'. One example of research that accounts for both uncertainties and possible interventions is the work of Ciullo et al. (2020), which explores several alternative distributive principles for optimizing flood risk management options for the Dutch-German Rhine, 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 the resulting inequality patterns.

A computational tool for supporting equitable delta planning needs to satisfy two fundamental requirements. First, the tool has to account for the multisectoral dynamics in the delta. This is because uncertainties in delta planning come from different systems, including the climatic (e.g., rainfall and drought dynamics), hydrological (e.g., flood and sedimentation regimes), biophysical (e.g., soil fertility and nutrients cycle), as well as the socioeconomic system (e.g., value and behavioral change, market dynamics) (Aerts et al., 2018; Dunn et al., 2019; Kuenzer & Renaud, 2012; Wong et al., 2014). Furthermore, adaptation measures also come in various forms, targeting different parts of the systems, and potentially benefitting or harming different subgroups within a population (Atteridge & 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 tool has to have a spatially-explicit representation of the delta. This requirement stems from the need to specify the scope of the distribution. The specification of the affected subgroups has to be made at an appropriate spatial scale (Ciullo et al., 2020; Shi et al., 2016), so that the tool can provide actionable and spatially-targeted recommendations to reduce future inequalities.

To showcase how the intricacy of uncertain exogenous developments, internal changes within the delta, and adaptation policies affects future inequality patterns, we investigate future equity and efficiency performance of the rice agricultural sector in the Vietnam Mekong Delta (VMD) under various realizations of uncertainties and adaptation options. 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 farmer 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 farmers' 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 efficiency (i.e., total rice production) and equity (i.e., Gini coefficient) indicators, as well as disaggregated inequality patterns (i.e., farmers profitability at a district level) under different uncertain futures. Our study shows how equitable delta planning 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 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. In section 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 adaptation planning in the Vietnam Mekong Delta. We conclude with broader implications for supporting equitable delta planning in section 6.

2 Study area

The large (inter)annual variability in rainfall, river discharge and tidal regime, in combination with human interventions, makes the Vietnam Mekong Delta (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 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 & 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).

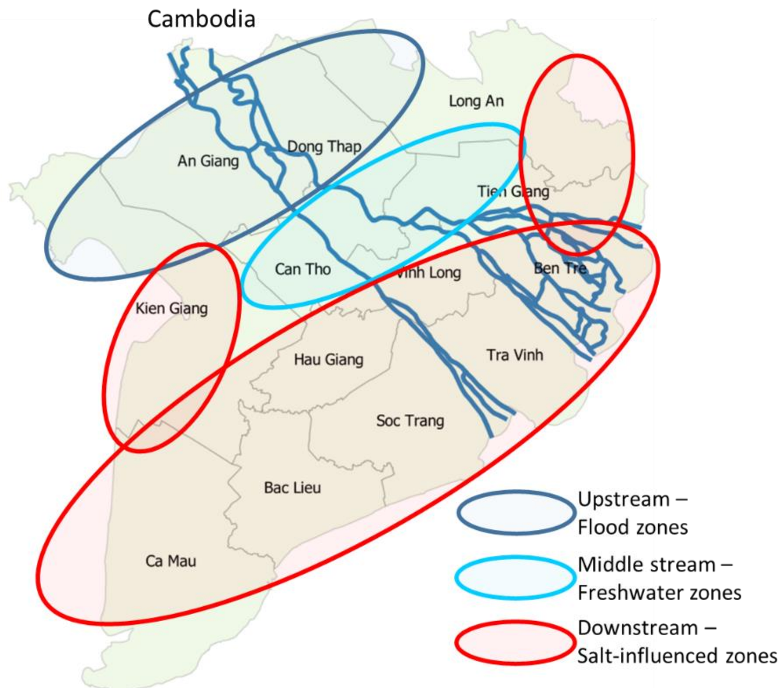

Figure 1. Three different hydrological zones and 13 provinces in the Vietnam Mekong Delta. The blue lines are the branches of the Mekong river. In this study we focus on the upstream zone.

Most rice farming activities take place in the upstream zone where salt influence is minimal and freshwater availability is higher. Furthermore, the fact that farmers in the downstream zone have started to move away from planting rice due to salinity intrusion (Ha et al., 2013; Nguyen et al., 2018) has put more pressure on the upstream zone to maintain the region's total rice production. 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 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 rain-fed 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 fosters inequalities among farmers (Chapman & Darby, 2016; Chapman et al., 2016; Käkönen, 2008; Tran et al., 2018b). Preventing annual floods from entering the paddy fields also 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 farmers with different farm size at a household level (Chapman & Darby, 2016). A regional plan, however, requires more than just a household level inequality 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 efficiency and equity through aggregated indicators.

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 farmers profitability are taken into account. Failure to include other sectoral 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, for this study we need a model that captures more than just one physical aspect of the delta (e.g., only the hydrological part). In the case of rice agriculture in the Vietnam Mekong Delta, the relevant dynamics include, among others the changing flooding regime, future sediment budget, societal preferences of future farming practices, as well as the various adaptation policies that touch upon different parts of the system.

The model we develop for this study contains not only the physical aspects of the delta, but also the spatially explicit socioeconomic aspects of farmers. Specifically, we develop an integrated assessment model that couples both biophysical and socioeconomic systems of the delta. The model follows a theory informed meta-modeling approach (Davis & Bigelow, 2003; Haasnoot et al., 2012). 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 adaptation planning especially when the intention is to explore plausible 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.

3.1 Model conceptualization

The integrated assessment model comprises two groups of modules as shown in Figure 2. The environmental 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 farmers' 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 1 enlists each individual module.

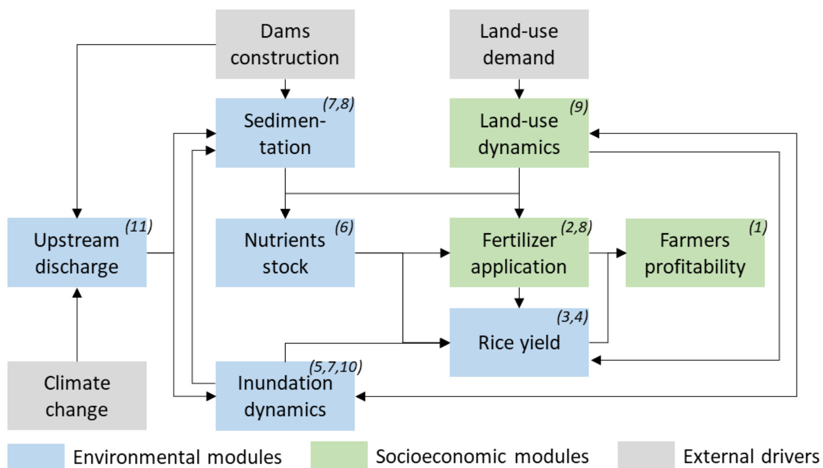

Figure 2. Conceptualization of the integrated assessment model. The numbers correspond to modules described in Table 1

Table 1. Modules of the integrated assessment model, and the applied modeling approaches

No	Processes	Modeling approach	Description	Sources
1	Farmers 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	Chapman et al. (2016); Tran et al. (2018b)
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	Manh et al. (2014); Tan et al. (2004)

9	Land-use dynamics	Process-based	Cellular automata land-use change model	Van Delden and Hurkens (2011); White et al. (1997)
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)

Farmers 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 also from sedimentation. Therefore, letting the rice fields flooded brings a 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 intended flooding in the VMD. Dam construction could also offset the climate change impacts of increasing discharge of the Mekong river (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 Supplementary Information S1.

The model is spatially explicit with a grid 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 3, rice farming dominates the land-use of the upstream VMD.

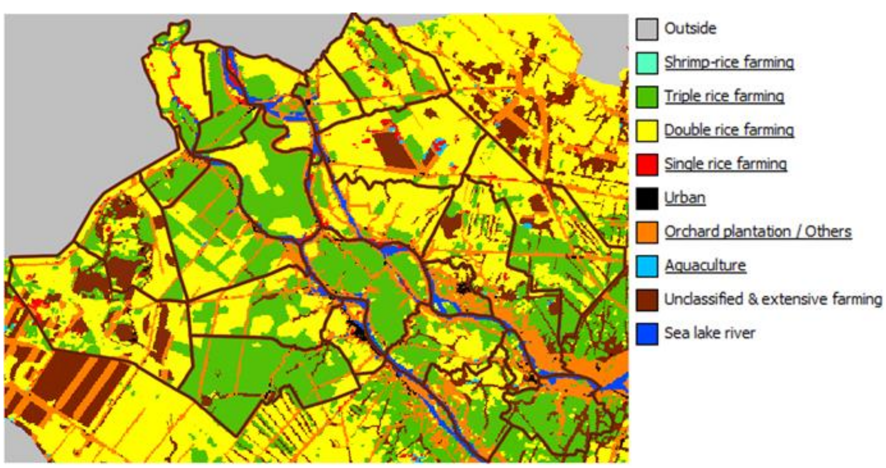

Figure 3. Land-use map of the upstream Vietnam Mekong Delta in 2011 (GAEN-View, 2013; Sakamoto et al., 2009a). The two branches of the Mekong river stretch from the northwest to the southeast. Underlined legends are land-use functions that are dynamically simulated in the model. Black lines are districts boundaries.

The spatial inequalities among farmers are assessed also at a district level. Accordingly, the profitability is aggregated for each of the 23 districts in Dong Thap and An Giang. In addition to this disaggregated profitability indicator, the model also calculates two aggregated indicators: total rice production as a proxy for efficiency and Gini coefficient among farmers as a proxy for equity. The model is then run for a period of 38 years from 2012 to 2050, whereas the period between 2002 and 2012 is used for model evaluation.

3.2 Model evaluation

To evaluate the adequacy of the model, we focus on whether the model is fit for its purpose of exploring plausible 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). The performance of the model is then assessed by the extent to which the model can answer the evaluative questions.

Given that the model will be used for exploring the efficiency of the agricultural sector and plausible inequality patterns 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 this 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 2.

Table 2. Summary of fit for purpose evaluation of the model. Detailed results for each guiding question are discussed in Supplementary Information S1

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 the farmers' profitability?	Although not the entire range of observed profitability is captured, farmer profits calculated from the model are still within the boundary of surveyed profit.
	Does the model capture the variation of rice yield between the different cropping seasons?	The average of the modelled yield of each cropping season corresponds well to the historical observation, 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 and its spatial heterogeneity are adequately captured. 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?	Both 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.
	Does the model capture a sufficient location and pattern	The model simulates land-use change with high pattern accuracy, as measured by clumpiness index.

	accuracy of land-use change processes?	The overall location accuracy is also relatively high. 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 farmers profitability.	At an extreme scenario where upstream sediment supply decreases by 60%, average profitability of all farmers 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 2, we conclude that the model is sufficiently fit for purpose. Regarding realism, we see that the model sufficiently mimics historical behavior. However, the full spectrum of farmers' profitability is not captured by the model. One explanation is that the market price dynamics for rice are not accounted for. Regarding structural adequacy, we observe that 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 farmers profitability, as nutrients are supplied by not only sediment deposition but also by artificial fertilizer.

3.3 Experimental setup

Table 3 enlists the uncertain factors and adaptation policies accounted for in this study. The three uncertain factors are climate-induced changes in river discharge, upstream dam development, and societal preference about different farming practices. For river discharge, two hydrographs are generated based on RCP 4.5 and RCP 8.5 (van Vuuren et al., 2011). 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 eventually constructed. For societal preference about different farming practices, we follow recent discussions on this topic (Nguyen et al., 2020; Tran et al., 2019; Tran et al., 2018b). 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 development. Further details on the three variables are provided in Supplementary Information S1.

Table 3. Uncertain factors and adaptation policies considered in the experimental setup. The detailed explanation of how uncertain factors affect internal variables is provided in Supplementary Information S1

Types	Variables	Possibilities	Internal variables affected
Uncertain factors	Climate-induced river discharge	- RCP 4.5 - RCP 8.5	Inundation dynamics (affecting inundation extent) and sedimentation (affecting total annual sediment

			budget)
	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	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)

We consider three top-down policies in addition to a baseline do-nothing policy: two different top-down adaptation policies, and one policy with only soft actions. 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; Tran et al., 2018a; 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 Results

4.1 Disaggregated performance: inter-district inequality patterns

We began our analysis with the observation of spatial inequality, in terms of farming profitability, across the 23 districts in An Giang and Dong Thap 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. Since the aim is to assess the profitability of farming in a district relative to other districts in each individual scenario, the district level profitability in each scenario is normalized between 0 and 1.

Figure 4. Relative profitability of rice farming at district level by 2050 under different scenarios and adaptation policies: (a) RCP 4.5 and expansion of triple rice, (b) RCP 4.5 and shift back to double rice, (c) RCP 8.5 and expansion of triple rice, (d) RCP 8.5 and shift back to double rice

First, we focus on the inequality that results from external developments without adaptation policies (Baseline column in Figure 4a-d). Large upstream dam development (lower left maps in Figure 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 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 4a with Figure 4c (RCP 4.5 vs RCP 8.5 with triple rice expansion) and by comparing Figure 4b with Figure 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 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 Supplementary Information S1 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 & 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).

To assess the impacts of societal preference and land-use demand on inequality patterns, we compare Figure 4a with Figure 4b (different societal preferences under RCP 4.5), and Figure 4c with Figure 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 large dam development and RCP 4.5 river discharge, the relative profitability of these districts decreases when a shift back to double-rice happens (lower left maps in Figure 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 possibilities also hardly affect the inequality patterns, as the flood regime in both discharge possibilities is quite similar.

What about the impacts of alternative adaptation policies to the inequality patterns? To this end, 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 4a). 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. 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. between the two branches of the river). The low dike policy exposes the autumn-winter crop to more frequent flooding. The fertilizer subsidy policy, as expected, raises the relative profitability of districts located far from the river, turning districts between the river branches relatively less profitable.

The simulation results suggest that the impacts of external developments and adaptation policies cannot be simply analyzed separately as the model shows non-linear responses in terms of inequality patterns. For example, the high dikes policy under the RCP 4.5 and triple-rice expansion scenario (Figure 4a) yields relatively equal profitability across districts under small dam development, while, in contrast, districts along the river benefit when a larger number of upstream dams is constructed. 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 4b, high dikes – large dam development). The inequalities from other adaptation policies are less sensitive to differences in external developments. For example, the societal preference scenarios do not alter the inequality patterns resulting from the fertilizer subsidy policy under the medium dam development and RCP8.5 scenario (see Figure 4c and d).

4.2 Aggregated performance: efficiency and equity

We use total rice production as an indicator for efficiency and the inter-district Gini coefficient as an indicator for equity (Figure 5). We find neither a large correspondence nor a clear trade-off between these two indicators, as the effectiveness of the policies depends on the scenarios. Some scenarios of external developments result in bad efficiency but good equity performance, such as in case of the outcomes of the low dikes policy in the top-left part of the figure. Other scenarios lead to synergies of good efficiency and equity performance, such as those on the top-right part of the figure. The figure 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 efficiency axis.

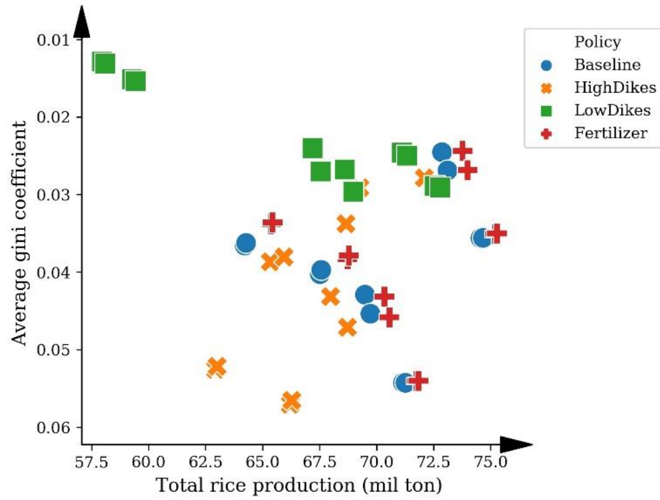

Figure 5. Equity (expressed by the Gini coefficient) and efficiency (expressed by the total rice production) of the agricultural sector under different scenarios. The arrows on the axes represent the direction of desirability (low Gini implies good equity performance and high total production implies good efficiency performance)

We summarize the efficiency and equity performance of the alternative policies in **Table *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 efficiency and equity. Most scenarios involving large upstream dam development have relatively low efficiency and equity performance, while most scenarios involving small upstream dam development score better on both efficiency 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.

Table 4. Summary of aggregated efficiency and equity indicators by 2050 across all scenarios. Scoring is presented on a relative scale where '--' implies the worst while '++' implies the best performance

		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	-	-	+	--	--	--	-

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 efficiency 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 efficiency 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 (good equity performance) but at the expense of a very low total rice production (bad efficiency 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 better efficiency performance 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 good equity performance in all scenarios, although it yields relatively worse efficiency especially in the large dam scenario. 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.

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). 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 efficiency 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.

5 Discussion

5.1 Computational tool to support equitable adaptation planning

In adaptation planning, future inequality is affected both by how uncertain factors play out in the future and what adaptation measures are taken. Various uncertain factors affect different parts of the system (e.g., climate change affects the biophysical system, societal value change affects the socioeconomic system), and so do the adaptation measures (e.g., dike construction affects the hydrological system, fertilizer subsidy affects the socioeconomic system). Therefore, it is essential for a decision support tool to capture the relevant multisectoral dynamics shaping future inequality patterns (Holman et al., 2016; Little et al., 2019). Overlooking the relevant multisectoral dynamics can result in misleading policy advice (Harrison et al., 2016; Jafino et al., 2019). In the case of adaptation planning for the VMD, previous computational tools mainly focus on only one sector or system (e.g., the impact on livelihoods of floods (Radhakrishnan et al., 2017; Triet et al., 2020; Triet et al., 2018), subsidence (e.g., Nhung et al., 2018), or droughts (e.g., Kontgis et al., 2019)). The few studies that did consider multiple sectors either disregard the temporal dynamics of the multisectoral interactions (e.g., Braese et al., 2020; Tran et al., 2019), focus only on the implications of the dynamics at a household level (e.g., Chapman & Darby, 2016), or put little to no emphasis on inequality implications of climate change and adaptation to it (e.g., Smajgl et al., 2015).

Including multisectoral dynamics requires one to enlarge the conceptual scope of the model. This often comes at the cost of reducing the details and resolution of some of the systems through simplifications (Audsley et al., 2008; Davis & 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. 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 & 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 very 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. The fact that we simplify some parts of the system and include multiple sectors in the model implies that we cannot simply follow the traditional statistical validation approach. Rather, we suggest the use of the fit for purpose approach. This approach has been promoted as an appropriate model validation approach under three conditions (Haasnoot et al., 2014; 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 plausible 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.

We have demonstrated the fitness of the model we developed for the purpose of exploring plausible inequality patterns under various scenarios. Specifically, we use several guiding evaluative questions to assess the realism and the structural adequacy of the model, identify the weak points of the model, explain the mechanisms that give rise to the weak points, and reason why the model is still fit for purpose despite its weaknesses. By answering the evaluative questions, we show that the model results comply reasonably well to past studies and observations (i.e., model realism), and that applying shocks to the model produces reasonable outcomes (i.e., structural adequacy).

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 & Bigelow, 1998; Davis & Tolk, 2007; Hong & 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.

5.2 Insights for the Vietnam Mekong Delta

This study provides two important insights for agricultural adaptation 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 affecting the VMD's agricultural sector, both in terms of equity and efficiency. As expected, 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, however, 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, instead, 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 and exogenous in this study, in reality it can be a subject of negotiation with the Cambodian government. The importance of this driver makes pursuing a catchment-wide approach to delta planning through coordination with upstream countries a critical step for the Vietnamese government in order to secure the future of the delta.

6 Conclusion

In this study, we argue why multisectoral dynamics need to be considered when we want to account for equity in any quantitative analysis supporting adaptation planning. We show how this can be done by developing a spatially-explicit decision support tool to explore plausible inequality patterns due to the interplay of adaptation measures and uncertain futures. We also discuss 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 decision support tool. The 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 efficiency and equity performance. While previous studies mostly focus on either the aggregate efficiency of the agricultural sector in the entire region, or equity issues at an individual farmer level, in this study we assess both disaggregate equity and aggregate efficiency at a regional level.

We recognize three broader insights for model-based support for equitable adaptation planning in deltas. First, the relationships between uncertainties and adaptation policies with equity and efficiency are complicated and non-linear. Different combinations of uncertain future developments and adaptation policies may lead to quite different inequality patterns. We also present how small changes in an uncertain factor, when compounded with different adaptation policies, can lead to very different inequality patterns with different 'winners' and 'losers'. This implies that when offering model-based support for 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 computational tools, one needs to incorporate relevant multisectoral dynamics as well as interactions between the different systems that give rise to distinctive inequality patterns.

Second, equitable adaptation planning should involve the consideration of not only efficiency indicators 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. 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. It can also help planners navigate multi-actor trade-offs and avoid policy deadlock and contestation during the planning process.

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., 2013). 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.

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Marjolijn Haasnoot: Conceptualization, Methodology, Writing – Review & Editing.
Edwin Sutanudjaja: Software, Methodology, Writing – review & editing.

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