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Responding to rising sea levels in the Mekong Delta

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Vietnamese communities in the Mekong Delta are faced with the substantial impacts of rising sea levels and salinity intrusion. The construction of embankments and dykes has historically been the principal strategy of the Vietnamese government to mitigate the effects of salinity intrusion on agricultural production. A predicted sea-level rise of 30 cm by the year 2050 is expected to accelerate salinity intrusion. This study combines hydrologic, agronomic and behavioural assessments to identify effective adaptation strategies reliant on land-use change (soft options) and investments in water infrastructure (hard options). As these strategies are managed within different policy portfolios, the political discussion has polarized between choices of either soft or hard options. This paper argues that an ensemble of hard and soft policies is likely to provide the most effective results for people's livelihoods in the Mekong Delta. The consequences of policy deliberations are likely to be felt beyond the Mekong Delta as levels of rice cultivation there also affect national and global food security.

As global temperatures are expected to increase further, accelerated melting of ice sheets and glaciers is a likely consequence that would lead to further sea-level rise[1,2]. This phenomenon is not expected to have a consistent global consequence for all coastal areas, as sea levels are predicted to increase much more for some areas than for others[2]. Based on the IPCC Fourth Assessment Report[3], a sea-level rise of 30 cm by 2050 (ref. 4) is predicted for the coast of southern Vietnam. More recent predictions based on the Fifth Assessment Report by the IPCC have confirmed this prediction, with a 5–95% uncertainty range of approximately 20–40 cm for IPCC's Representative Concentration Pathway 8.5 (ref. 5). Rising sea levels are likely to infiltrate groundwater aquifers and increase salinity gradients in large parts of the Mekong Delta, in particular during the dry-season months of October through May. Approximately 1.8 million ha of delta land is subject to increased dry-season salinity, of which approximately 1.3 million ha is affected by saline water above 5 g l^{-1} (refs 6,7). Increased Mekong River flows during the monsoon partially reverse salinity dynamics, seasonally reducing upstream salinity concentrations.

The Mekong Delta is the most important rice production region contributing to Vietnamese national food security. Central government plans have dedicated approximately 1.8 million ha of agricultural land in the Mekong Delta to rice production, with an annual target production of 23 million tons of rice for domestic consumption and export[8]. Since the Doi Moi reform in 1986, Vietnamese rice exports have become increasingly relevant for global food security, with a share in the global rice trade of 19.3% in 2011 (ref. 9). However, increasing salinity levels in the Mekong Delta have substantially reduced agricultural productivity and caused declining rice production[4,10,11], in particular for crops and varieties with a low tolerance to salt. Remedial and management initiatives by the Vietnamese government are influenced by the conditions, investments and potentially antagonistic decisions occurring in independent sovereign nations. These uncertainties include upstream developments (such as mainstream and tributary dams, water diversion for irrigation schemes), basin-wide changes in precipitation and temperature, and the capacity for household adaptation in the Mekong Delta.

Eleven tributary dams are in operation in Laos, a further nine are under construction and another 71 are planned. There are also nine mainstream dams being considered for the Mekong River reaches in Laos (ref. 12). Cambodia has one tributary dam in operation, another 11 are planned in addition to two planned mainstream dams[12]. Seven tributary dams are in operation in Thailand and Vietnam, while developers in Vietnam are proposing to construct another five, with plans for a further three tributary dams[12]. Chinese agencies operate, are constructing or planning to construct 17–19 dams in the upper Mekong Basin[13]. Increased dry-season flows from upstream hydropower dam releases could limit salinity intrusion in the Mekong Delta during the dry season, but reduced flows may limit salt flushing during the wet season[14]. Generally, concessions to construct and operate dams are negotiated independently, and are not subject to a coordinated basin-wide operational strategy.

Principal adaptation options

The Vietnamese government has the option of investing in large-scale sea-dykes and sluice gates to manage salinity levels, referred to as hard policy options. Alternatively, agricultural production strategies and land use could be adjusted by introducing salinity-tolerant rice varieties and crops, referred to as soft policy options. These are not novel options as salinity intrusion has been a recurring and enduring problem, although the increasing threat of sea-level rise and the estimated alterations to the hydrologic regime have accelerated the imperative to initiate mitigating actions. Many small-scale embankments and sluice gates are in operation and householders in many coastal communities have turned to farming shrimp and other types of aquaculture as adaptation strategies at the household level[15,16]. The vast majority of the debate has been polarized, advocating either only hard or only soft options for reasons that are explained below. As a consequence, several competing Mekong Delta Development plans have evolved geared to either hard or soft policy options and large magnitude changes are likely to be introduced. Independently commissioned plans lack

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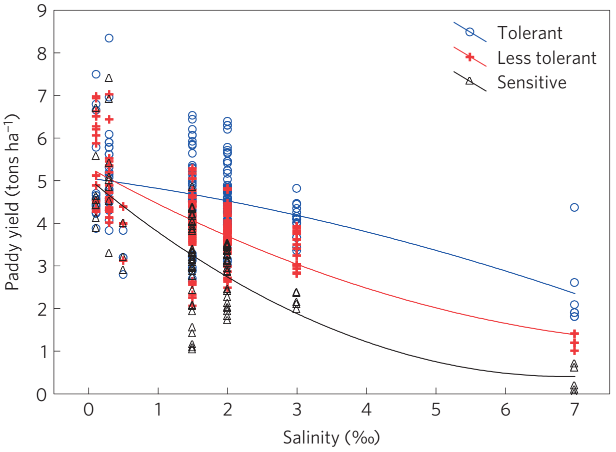

Figure 1 | Relationship between soil salinity and yields of rice varieties of variable salinity tolerances based on multiple field trials in 2005–2010. Soil salinity measured between 10 and 30 days after seeding (see Methods for more details).

coordination, and include the Dutch–Vietnamese-funded Mekong Delta Plan[17], which links to Vietnam's Ministry of Natural Resources and the Environment, the JICA-funded Climate Change Adaptation Master Plan[18], which links to Vietnam's Ministry of Agriculture and Rural Development, the Mekong Delta Water Resources Plan[19], and the National Program on Responding to Climate Change[20]. The first three plans advocate hard solutions and argue that proposed investments in infrastructure are the most efficient way to reduce risks from salinity intrusion and to maintain rice production for reasons of national food security. The fourth plan advocates soft solutions and argues that these would come at lower costs, with opportunities to increase household income.

This study has evaluated and compared the effectiveness of existing and proposed hard and soft policies potential. First, the salinity reduction effects of sea-dykes were modelled, in addition to 30 cm sea-level rise, the realization of all planned hydropower dams listed above, and an extension of the irrigation area in Thailand, Laos and Cambodia from 3.4 million ha to 6.62 million ha (ref. 21). Two large-scale estuary sluice gates were considered, the Cai Lon and Cai Be rivers in the western provinces (Hau Giang, Kien Giang and Ca Mau) and Ham Luong and Co Chien in the eastern provinces (Ben Tre and Tra Vinh), as well as a substantial upgrade of the existing sea-dyke. Based on the MIKE 11 model, parameterized and validated by the Southern Institute of Water Resource Research[22], the western dykes could convert an additional area of 155,000 ha subject to brackish water into permanent freshwater conditions. The eastern dykes would convert an additional 174,000 ha into freshwater; Table 1 provides the disaggregated projection.

Cost estimates for an upgrade of sea-dykes and the construction of new large-scale estuary sluice gates vary between US$5,329 million[23] and US$8,176 million[24]. In addition to the high costs of hard measures, policy makers need to consider the introduced risk of infrastructure investments: the Mekong Delta is geologically relatively young, having expanded rapidly over the past 3,000 years as a consequence of an annual mean sediment deposition of 144 million tonnes[19].

Substantial economic losses are estimated to occur for farmers in the Mekong Delta as a consequence of a 55–100% reduction of the 160–200 × 10^6 t yr^{-1} sediment load, attributed to the number of constructed dams. Reductions in associated nutrient loads are estimated at 20–65%, requiring substantial investments to replace fertilizer inputs to maintain present production levels[14,25]. The substantial reduction in sediment loads combined with sea-level rise and increasing storm surge is likely to limit the long-term efficacy of sea-dykes[26,27]. These questions regarding operational efficiency of sea-dykes have lead to the opposing view favouring soft policies, emphasizing land-use change and altered cropping systems. Land use at present is dominated by rice cultivation. Large areas cultivate two or three crops a year. Production levels and total area devoted to rice production are dictated by the central Ministry of Agriculture and Rural Development and driven by national food security targets. The testing of a range of available rice varieties has shown that rice production could be maintained if salinity-sensitive rice varieties were replaced by salinity-tolerant varieties subject to soil salinity levels up to 3‰ (Fig. 1).

If the soil salinity level exceeds 3‰ in more than two weeks, additional land-use options include amending farming systems through the introduction of either shrimp, salinity-tolerant sugar cane, pineapple and yam, or vegetables, which have a short-duration production cycle. The latter are referred to as upland crops. The occurrence of highly acidic soils in the Mekong Delta is a constraining factor, particularly limiting the extent of vegetable production. Shrimp production and aquaculture are key livelihoods widely adopted by coastal communities in response to increasing salinity levels. Responses from 1,265 randomly sampled households (see Methods for survey details) indicated an approximately 50% increase of annual household income using the shrimp–rice rotation system (US$1,735) as compared to a two-rice-crop system (US$1,019). However, shrimp farming is associated with high production risks due to the outbreak of disease; since 1994 many households reliant on shrimp production have experienced a total or substantial loss of income[28,29]. Thus, more reliable shrimp farming requires alignment with aquaculture diversification, improved pond management, improved protection of mangrove habitats, and an accessible micro-insurance system.

Adding climate change

In response to the combined effect of sea-level rise, the construction and operation of upstream dams and upstream irrigation, the costs associated with hard policies (US$5,329 million[23] and US$8,176 million[24], see above) are estimated to be 83 times the start-up costs of the soft policy approach (based on the land-use change recommendation of 180,000 ha in the following section and available 2013-adjusted dollar per ha cost estimates (ref. 30)), which is fairly effective in maintaining rice cultivation and increasing household income. Contingent on these changes, the assumed number of reservoirs and river impoundments may create a phenomenon that could be critical to the Mekong Delta. As a corollary of climate variability, most reservoirs would be likely to operate at a higher refill rate at the onset of the wet season following a dry year with low wet-season rainfall. Our modelling shows that this could delay the onset of the flood pulse in the Mekong Delta by up to two weeks, with two main effects. First, the critical volume of water during the April rice planting would not be available, diminishing or even eliminating the major rice crop[31,32]. Second, salinity would probably intrude further inland than under any other scenario, as shown in Fig. 2. Although the effects of drought-induced low flows are likely to occur every four years, flood frequency is also likely to increase, with 100-year flood events predicted to occur every ten years[33].

Land-use change recommendations

The task to prepare the Mekong Delta for an uncertain future is complex, as upstream development and climate change introduce substantial interacting changes. We identified land-use change strategies that maximize household income by considering the two principal modelled future states of the Mekong Basin. First, the all-driver scenario (Fig. 3) represents a sea-level rise of 30 cm combined with the development of all planned reservoirs and irrigation schemes and prolonged periods of low flows in the Mekong Delta.

Table 1 | Projected change in area at different levels of salinity due to construction of sea-dykes.

	Fresh	<2 g l^{-1}	2–4 g l^{-1}	4–10 g l^{-1}	10–20 g l^{-1}	>20 g l^{-1}
Cai Lon and Cai Be	155	−74	6	36	63	−186
Ham Luong and Co Chien	174	100	−88	−115	−71	0
Both	329	26	−82	−79	−8	−186

Columns 2–7 quantify in 1,000 hectares the change in area under freshwater conditions, with salinity levels of 0–2 g l^{-1}, 2–4 g l^{-1}, and so on. The sum across the salinity gradient should equal zero, as the total area does not change.

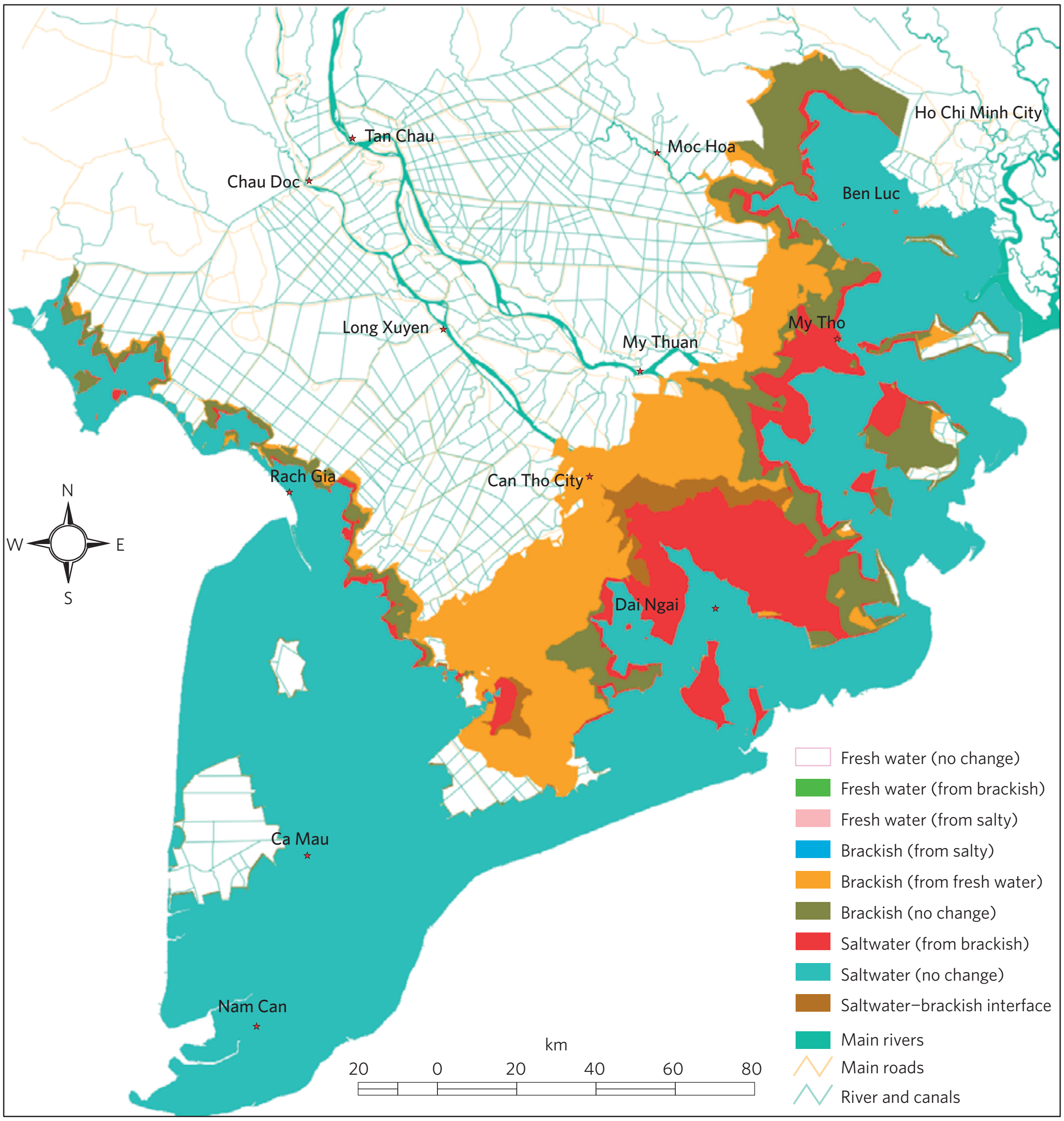

Figure 2 | Salinity intrusion (indicated by an increasing red colouration) for the all-driver scenario, including 30 cm of sea-level rise, development of all planned upstream reservoirs and irrigation schemes, and an increase in dry years. Red stars indicate cities.

Second, the hard adaptation scenario (Fig. 4) combines the first scenario with an upgrade of existing sea-dykes and the construction of major estuary sluice gates in Cai Lon and Cai Be rivers on the west coast, and Ham Luong and Co Chien rivers on the east coast. The maximization of household income accounts for projected spatial and temporal salinity changes, and the prevalence and distribution of soil acidity (preventing many upland crops) and the cropping system.

For the all-driver scenario this work recommends changes to agricultural production systems for approximately 180,000 ha in nine mid-stream and downstream provinces. Amended agricultural systems rely primarily on changing from two or three crops of rice to a mixed regime of rice and aquaculture or upland crops. For the hard adaptation scenario, most of the present rice land could be maintained to contribute to national food security objectives and only a minor area of 13,000 ha would need to undergo land-use

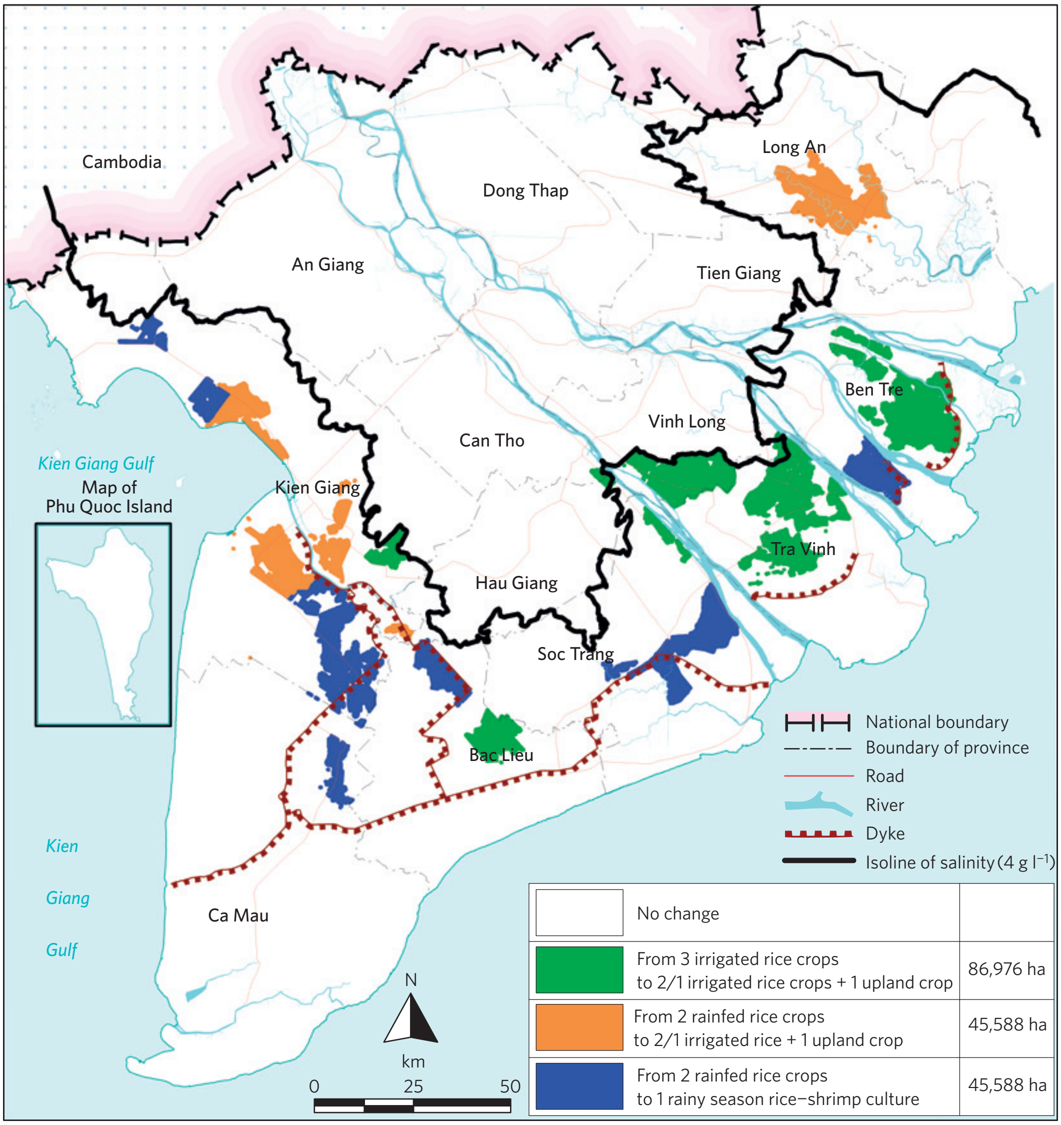

Figure 3 | Recommended land-use change for the all-driver scenario, which includes 30 cm of sea-level rise, development of all proposed upstream reservoirs and irrigation streams, and an increasing number of dry years.

change. Recommended changes in farming systems are expected to improve farm income but reduce rice production. If implemented, many of the recommended changes and investments benefit communities under all scenario characteristics and circumstances; that is, the recommendations represent no-regrets strategies. This raises the question what impediments prevent change. The central government explicitly prioritizes national food security and national rice exports earning[34], but does not specify stabilized farm incomes. The national goal of maintaining surplus rice for export introduces a substantial institutional impediment to change and creates path dependencies and lock-in effects for households. However, equally relevant are behavioural impediments elicited from surveyed households across the Mekong Delta.

The relevance of household behaviour

The above outlines some clear advantages in employing soft adaptation measures in response to sea-level rise and investing in selected sea-dykes to manage drought-related risks. However, policy initiatives that are antagonistic to household-level motivations can reduce implementation effectiveness and render such top-down investments redundant[35]. For instance, if initiatives implemented to promote changes in agricultural practices from rice to combined shrimp–rice farming are rejected by the majority of households, the on-the-ground adaptation is unlikely to become effective. Similarly, if sea-dykes are constructed and households adapted to increased water salinity by cultivating shrimp, farmers might invest in localized strategies to increase saltwater volumes, countering the objective of sea-dykes.

Household livelihoods and adaptation behaviour were based on a survey of 1,265 randomly sampled households across three representative provinces in the Mekong Delta (Tra Vinh, Can Tho, An Giang). Survey responses elicited households' composition, attributes, present livelihood status, their livelihood motivations and possible adaptation intentions in response to a hypothetical economic crisis and changes to livelihood circumstances related to climate change. Respondents could select one option from four future livelihood strategies: either remain in their village and continue present livelihood activities (no intention to adapt); stay and adjust activities; migrate and continue with present activities; or move and replace present activities. We found that 65% of households would not change their present livelihood activities and would not migrate out of their present village even if their

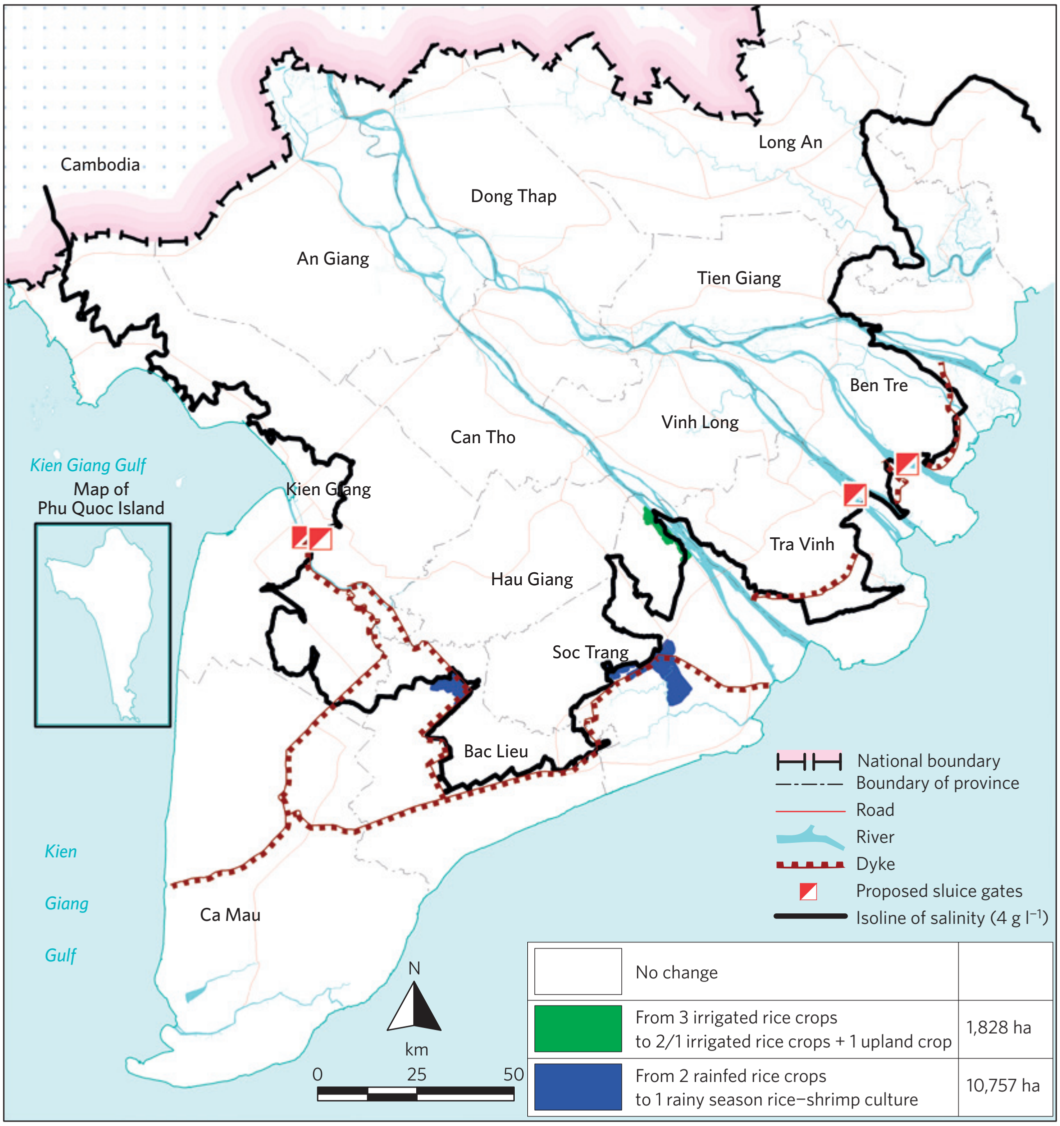

Figure 4 | Recommended land-use change for the hard adaptation scenario, which includes the upgrade of existing sea-dykes and the construction of major estuary sluice gates in Cai Lon, Cai Be, Ham Luong and Co Chien.

production was hypothetically reduced by 50% or more for five years or more. A series of subsidiary questions elicited constraining and enabling factors that influenced a respondent's capacity to adapt.

The main behavioural impediment for adapting present livelihoods (62% reported rice cultivation as the primary livelihood activity) were: insufficient education and skills (33%), a desire to continue with present livelihoods (20%), lack of assistance to facilitate change (15%), and the need for food for living (15%). The main reason for not considering outmigration in spite of an economic crisis was the importance of remaining in their ancestors' village (48%). 6.5% of the respondents were less than 35 years old. Compared to the older respondents, the younger cohort indicated an increased, but not significant ($p < 0.05$) willingness to adapt, including migration to large urban centres consistent with existing literature[36,37]. Present behavioural impediments to adapt may become less relevant if the present attitudes of the younger cohort prevail.

Our dialogue with central government representatives revealed the expectation that migration would be households' main adaptation strategy. In contrast, the survey results indicate that a gradual and linear outmigration process in response to sea-level rise is unlikely, and households are more likely to persist with present activities and resist migration imperatives as long as possible. From a macro-economic perspective, the revealed behavioural reality is likely to lead to high-amplitude, short-duration outmigration in fifteen to twenty years time. The predicted migration pattern introduces substantial short time-frame pressures on peri-urban areas, with attendant higher costs of adaptation investment (largely in urban infrastructure) compared to the more evenly spaced costs associated with the widely expected incremental outmigration.

To improve the understanding of household-level vulnerabilities we simulated crop production and household income in an agent-based model, imputing household intentions, spatial land-use distributions, crop growth and market prices; for model details see Methods. Estimates of households' ability to replace expected income loss were derived from survey responses and deployed as an indicator of economic vulnerability. If the majority of households are unwilling or unable to adopt new livelihood activities this indicator will be close to zero. If all households are willing and able to adopt alternative livelihoods the indicator will be close to 100%. The results illustrated in Fig. 5 represent the mean percentage of income loss households are able to replace derived from 200 Monte Carlo model iterations of the simulation model.

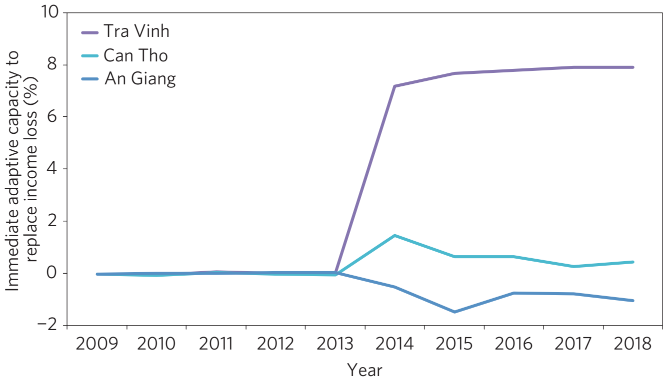

Figure 5 | Ability of households to replace income losses in Tra Vinh, Can Tho and An Giang based on an integrated simulation model.

These simulation results indicate high levels of economic vulnerability for the three study provinces (Tra Vinh, Can Tho, An Giang). Coastal communities in Tra Vinh score the highest adaptive capacity (or lowest vulnerability), indicating an ability to replace 7.9% (±0.07) of potential income losses by employing alternative adaptive strategies, but still considered as vulnerable. Respondents from mid-stream areas in and around Can Tho have an adaptive capacity approaching zero (0.4% ± 0.06) and are identified as highly vulnerable. The modelling indicates lowest adaptive capacity for An Giang (−1.1% ± 0.03), characterized by alluvial soils and year-round available fresh water for rice production and the most upstream province of the study. Adaptation strategies elicited from survey respondents in An Giang are likely to worsen the household's economic situation, emphasizing the lack of understanding of adaptation options and their consequences among households.

Discussion

Mekong Delta communities are located in one of the most globally vulnerable deltas, exposed to the combined effects of rising sea levels, salinity intrusion, exposure to an increased frequency of extreme climate effects and reduced sediment/nutrient loads. The combination of factors threatens the present livelihoods of 282,000 farming households and Vietnamese national food security imperatives. The changes in biophysical factors also coincide with strong behavioural impediments to adapt amongst surveyed Mekong Delta farming communities. Historically, household-level adaptation has been strongly guided by central government policies. The complexity of contemporary stressors and polarized institutional strategies to either invest in soft adaptation or hard adaptation options, has created an inertia of central government indecision. Attendant with the adaptation options are substantial changes to the distribution of central budgets between the two relevant ministries; the Ministry of Natural Resources and Environment and the Ministry of Agricultural and Rural Development. Our strategy proposes that the most effective adaptation strategy is a mixture of both, as such a combined approach is likely to improve livelihoods and mitigate risks better than implementing only the soft or the hard option. Soft adaptation measures, including crop and land-use change, have the potential to substantially mitigate livelihood threats. Realizing the potential of soft options requires coordinated agricultural extension efforts to address identified adaptation impediments. Selected investments in sea-dykes along the eastern coastline would further reduce the risk of increasing drought frequency and duration. Sea-dykes in the western parts of the Mekong Delta are likely to reduce the income of thousands of households that have already adapted to increasing salinity levels by cultivating shrimp. In essence, our strategy favours soft options for the western areas of the Mekong Delta and hard options for the eastern coastline.

As a complementary strategy to ameliorate drought impacts, coordinated management of upstream reservoir releases would provide an effective instrument to manage salinity intrusion, critical in very dry years. Endeavours by the Vietnamese government to promote the coordination of dam operations would serve as a cost-effective risk management strategy. Avoiding the high costs of sea-dykes may be a sufficient incentive to explore and eventually ratify a bilateral agreement with the Laotian government to ensure reservoir management is not only contributing to power-generation objectives and Laotian export revenues, but also regional food security goals[38]. The substantial dividends accruing to negotiating countries warrant investigation into the feasibility of alternative economic and regulatory instruments and potential externalities.

Household-level motivations emphasize the need to implement top-down mitigating strategies capable of preparing farmers for alternative livelihoods. The low levels of present adaptive capacity revealed from the surveyed provinces amplifies the vulnerability of Mekong Delta communities. Thus it is promising that the Vietnamese government intends to take action. However, adaptation in this complex context needs to be implemented as a multilevel strategy that considers the local requirements and constraints to trigger a sustainable transformation and avoid maladaptive outcomes[39]. Mekong Delta communities are not prepared for the necessary adaptations to climate-change-related risks, demanding a well-coordinated portfolio of instruments and investments. However, central government imperatives of sovereign food security, and subsequent decrees dictating rice production, need to be re-evaluated to address prevailing institutional barriers that perpetuate the cultivation of rice as communities' primary and obligatory livelihood pursuit. Amended institutional arrangements are required to introduce the necessary flexibility for households to adjust land use to changing environmental conditions.

Methods

This study modelled the hydrologic and floodplain dynamics of the Mekong Delta in MIKE 11 (ref. 22), yielding estimates of amended hydrologic regimes as a function of hydropower dam impoundments and operation, and modified monthly fluctuations of Mekong Delta salinity levels. The calibration of the MIKE 11 model was based on data from 2000 and validated with flood data for 1999, 2001 and 2011. Salinity levels were calibrated with data from 1998 and validated with data from 2005 and 2010. The model application approximated a semi-two-dimensional model, as more than 5,000 spills were included to represent the condition of overland flood flows. The model was initially developed with the software developer DHI (funded by DANIDA) and has since been applied to flood and salinity intrusion forecasting by SIWRR. For this study a total of nine scenarios were simulated for salinity intrusion in the Mekong Delta. Scenarios took into account changes to upstream development (dams and irrigation expansion), delta development (expansion of irrigation areas), sea-level rise, climate change (precipitation), and proposed structural measures to mitigate the consequences in the Mekong Delta of sea-level rise.

Crop yield and production responses of alternate rice varieties to variable salinity levels were derived from the results of eight randomized experimental plots in different agricultural zones in the Mekong Delta[40]. These experiments on rice varietal selection included freshwater and different saline ecologies. Field-water salinity was measured using a portable salinity refractometer. Experiments were conducted at provincial seed testing stations of Soc Trang, Kien Giang, Ben Tre (salinity-affected provinces), Can Tho and Vinh Long (freshwater provinces). Experiments were replicated three to four times in plots between 20 and 25 m^2. In total, 158 rice varieties were tested and productivity changes in response to changes in salinity levels were recorded. The experiments commenced in 2005.

Household characteristics and adaptive responses were derived from a randomized household survey of 1,265 rural households, conducted by face-to-face interviews in the Tra Vinh, Can Tho and An Giang provinces of the Vietnam Delta. Responses from a single household member elicited socio-demographic characteristics, household assets, self-assessed well-being, the present suite of household, farm and off-farm livelihood activities, costs and revenues from agricultural production, and intentional adaptation responses to prescribed, hypothetical changes to livelihood circumstances. Changed livelihood circumstances were comprised of a five-year economic crisis, access to increased industrial employment, increased salinity intrusion and changes to seasonal floods. The survey was carried out in April 2011 (the questionnaire can be found in Appendix 1 of ref. 41).

The three research strands of hydrologic data, agricultural data (including crop response functions) and behavioural data informed an integrated agent-based simulation model. In daily time-steps, modelled rainfall occurs according to historic data, triggering surface water flow and changes in soil moisture. Based on land-use and population data, survey responses were mapped into the model landscape and thereby livelihood activities spatially referenced and distributed. Agent households conduct activities according to specific livelihood activities (such as planting and harvesting) and accrue income based on historic commodity prices. Most parameter values (such as rainfall and commodity prices) are assigned range values, which introduce high levels of stochasticity. Two hundred model runs were conducted to account for stochasticity: mean and variance remained stable in subsequent model runs. The results were most sensitive to variance in household responses. However, model results were mainly validated through stakeholder consultation as part of a participatory process[42,43]. Model assumptions are detailed in ref. 41.

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References

1. Grinsted, A., Moore, J. C. & Jevrejeva, S. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Clim. Dynam.* **34,** 461–472 (2010).
2. Church, J. A., Gregory, J. M., White, N. J., Platten, S. M. & Mitrovica, J. X. Understanding and projecting sea level change. *Oceanography* **24,** 130–143 (2011).
3. IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
4. Wassmann, R., Hien, N. X., Hoanh, C. T. & Tuong, T. P. Sea level rise affecting the Vietnamese Mekong Delta: Water elevation in the flood season and implications for the rice production. *Climatic Change* **66,** 89–107 (2004).
5. Church, J. A., Monselesan, D., White, N., Zhang, X. & Platten, S. in *High-Resolution Climate Projections for Vietnam: Technical Report* (eds Katzfey, J., McGregor, J. & Ramasamy, S.) Ch. 8, 159–173 (CSIRO, 2014).
6. Carew-Reid, J. *Rapid Assessment of the Extent and Impact of Sea Level Rise in Vietnam, Climate Change* (ICEM–International Centre for Environmental Management, 2008).
7. *Impacts of Changes in Salinity Intrusion. Assessment of Basin-Wide Development—Technical Note 8* (Mekong River Commission, 2010).
8. Dang, K. N., Vu, A. P., Tran, H. P. & Nguyen, H. T. *Rice Production Response and Technological Measures to Adapt to Salinity Intrusion in the Coastal Mekong Delta* (Can Tho University, 2012).
9. *FAOSTAT* (FAO, 2013); http://faostat3.fao.org
10. Hoang, H. N., Huynh, H. X. & Nguyen, T. H. *Computing and Communication Technologies, Research, Innovation, and Vision for the Future (RIVF)* 1–4 (IEEE, 2012).
11. Le Dang, H., Li, E., Bruwer, J. & Nuberg, I. Farmers' perceptions of climate variability and barriers to adaptation: Lessons learned from an exploratory study in Vietnam. *Mitig. Adapt. Strategies Glob. Change* 1–18 (2013).
12. *Planning Atlas of the Lower Mekong River Basin* (Mekong River Commission, 2011).
13. Grumbine, R. E., Dore, J. & Xu, J. Mekong hydropower: Drivers of change and governance challenges. *Front. Ecol. Environ.* **10,** 91–98 (2012).
14. ICEM *Strategic Environmental Assessment of Hydropower on the Mekong Mainstream—Final Report* (Mekong River Commission, 2010).
15. Hoanh, C. T. *et al.* Livelihood impacts of water policy changes: Evidence from a coastal area of the Mekong river delta. *Water Policy* **5,** 475–488 (2003).
16. Joffre, O. M. & Schmitt, K. Community livelihood and patterns of natural resources uses in the shrimp-farm impacted Mekong Delta. *Aquacult. Res.* **41,** 1855–1866 (2010).
17. *Mekong Delta Plan: Long-term Vision and Strategy for a Safe, Prosperous and Sustainable Delta* (Government of Vietnam, 2013).
18. *JICA Helps the Coastal Mekong Delta Adapt to Climate Change* (JICA, 2011); http://www.jica.go.jp/vietnam/office/information/press/pdf/press2011/2011104_02e.pdf
19. Xue, Z., Liu, J. P., DeMaster, D., Nguyen, L. V. & Ta, T. K. O. Late Holocene evolution of the Mekong Subaqueous Delta, Southern Vietnam. *Mar. Geol.* **269,** 46–60 (2010).
20. *The National Strategy on Climate Change in the Period of 2011–2020* (Government of Vietnam, 2011); http://chinhphu.vn/portal/page/portal/English/strategies/strategiesdetails%3FcategoryId%3D30%26articleId%3D10051283
21. Blackmore, D., Perry, C. & Stein, R. *Modelled Observations on Development Scenarios in the Lower Mekong Basin* 146 (World Bank, 2004).
22. Dung, N. V., Merz, B., Bárdossy, A., Thang, T. D. & Apel, H. Multi-objective automatic calibration of hydrodynamic models utilizing inundation maps and gauge data. *Hydrol. Earth Syst. Sci.* **15,** 1339–1354 (2011).
23. *Mekong Delta Water Resources Master Plan to Response to Climate Change and Sea Level Rise. Internal Report* (in Vietnamese) (Southern Institute for Water Resources Planning, 2011).
24. *Mekong Delta Water Resources Planning in the Period of 2012–2020 and a Vision to 2050 Under the Projected Climate Change and Sea Level Rise* (in Vietnamese) (Government of Vietnam, 2012).
25. Thorne, C. *et al. Review of Sediment Transport, Morphology, and Nutrient Balance. Report to the Mekong River Commission Secretariat prepared as part of the Xayaburi MRCS Prior Consultation Project Review Report* (Nottingham University, 2011).
26. Kummu, M. & Varis, O. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* **85,** 275–293 (2007).
27. Hein, H., Hein, B. & Pohlmann, T. Recent sediment dynamics in the region of Mekong water influence. *Glob. Planet. Change* **110,** 183–194 (2010).
28. Ha, T. T. P., van Dijk, H., Bosma, R. & Sinh, L. X. Livelihood capabilities and pathways of shrimp farmers in the Mekong Delta, Vietnam. *Aquacult. Econ. Manag.* **17,** 1–30 (2013).
29. Son, V., Phuong, N., Hai, T. & Yakupitiyage, A. Production and economic efficiencies of intensive black tiger prawn (*Penaeus monodon*) culture during different cropping seasons in the Mekong Delta, Vietnam. *Aquacult. Int.* **19,** 555–566 (2011).
30. Joffre, O. M. & Bosma, R. H. Typology of shrimp farming in Bac Lieu Province, Mekong Delta, using multivariate statistics. *Agricult. Ecosys. Environ.* **132,** 153–159 (2009).
31. Kim, N. Q., Toan, T. Q. & Thang, T. D. *An Investigation on the Efficient Use of Water Related to the Upstream Development Scenarios to Prevent Drought and Salinity Intrusion in the Mekong Delta* (Hanoi Water Resources University, 2010).
32. Mainuddin, M., Kirby, M. & Hoanh, C. Impact of climate change on rainfed rice and options for adaptation in the lower Mekong Basin. *Nature Hazards* **66,** 905–938 (2013).
33. Hirabayashi, Y. *et al.* Global flood risk under climate change. *Nature Clim. Change* **3,** 816–821 (2013).
34. *The Resolution on Ensured National Food Security* (in Vietnamese) (Government of Vietnam, 2009).
35. Bohensky, E., Smajgl, A. & Brewer, T. Patterns in household-level engagement with climate change in Indonesia. *Nature Clim. Change* **2,** 348–351 (2013).
36. Huy, H. T. *Rural to Urban Migration as a Household Decision: Experimental Evidences from the Mekong Delta, Vietnam* (DEPOCEN Working Paper Series 2009/20, Development Policies Research Center, 2009).
37. Tacoli, C. & Mabala, R. Exploring mobility and migration in the context of rural–urban linkages: Why gender and generation matter. *Environ. Urban.* **22,** 389–395 (2010).
38. Smajgl, A. & Ward, J. (eds) in *The Water–Food–Energy Nexus in the Mekong Region. Assessing Development Strategies Considering Cross-Sectoral and Transboundary Impacts* 215–234 (Springer, 2013).
39. Conway, D. & Mustelin, J. Strategies for improving adaptation practice in developing countries. *Nature Clim. Change* **4,** 339–342 (2014).
40. Nhan, D. K., Phap, V. A., Phuc, T. H. & Trung, N. H. *Rice Production Response and Technological Measures to Adapt to Salinity Intrusion in the Coastal Mekong Delta* (Can Tho University, 2012).
41. Smajgl, A. *et al. The Mekong Region Simulation (Mersim) Model - Design Document* (CSIRO Climate Adaptation Flagship, 2013).
42. Smajgl, A., House, A. & Butler, J. Implications of ecological data constraints for integrated policy and livelihoods modelling: An example from East Kalimantan, Indonesia. *Ecol. Model.* **222,** 888–896 (2011).
43. Smajgl, A. & Ward, J. A framework for bridging science and decision making. *Futures* **52,** 52–58 (2013).

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Author contributions

A.S. was lead author of this paper, designed the study and the simulation model, co-designed the survey instrument and the hydrologic scenarios, and analysed the results. J.W. contributed extensively to the writing of this manuscript, designed the study and the survey instrument, and analysed the survey results. T.Q.T. contributed to the writing, designed the hydrologic scenarios, and conducted their implementation and the hydrologic analysis. N.H.T. contributed to the writing, designed the hydrologic scenarios, conducted their implementation and the hydrologic analysis, analysed land-use suitability, and designed the overall study. D.K.N. contributed to the writing, designed the survey instrument, implemented the households survey, analysed land-use suitability, conducted the agronomic analysis, and designed the overall study. L.Q.T. contributed to the writing and to the assessment of land-use suitability. V.P.D.T. contributed to the writing and to the hydrologic simulations. P.T.V. contributed to the writing, to the assessment of land-use suitability, and developed the maps.

Additional information

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Competing financial interests

The authors declare no competing financial interests.