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REPORT

Simulated Impacts of Climate Change on Current Farming Locations of Striped Catfish (*Pangasianodon hypophthalmus*; Sauvage) in the Mekong Delta, Vietnam

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Abstract In Vietnam, culturing striped catfish makes an important contribution to the Mekong Delta's economy. Water level rise during rainy season and salt intrusion during dry season affect the water exchange and quality for this culture. Sea level rise as a consequence of climate change will worsen these influences. In this study, water level rise and salt water intrusion for three sea level rise (SLR) scenarios (i.e., +30, +50, and +75 cm) were simulated. The results showed that at SLR +50, the 3-m-flood level would spread downstream and threaten farms located in AnGiang, DongThap and CanTho provinces. Rising salinity levels for SLR +75 would reduce the window appropriate for the culture in SocTrang and BenTre provinces, and in TienGiang's coastal districts. Next to increasing dikes to reduce the impacts, the most tenable and least disruptive option to the farming community would be to shift to a salinity tolerant strain of catfish.

Keywords Climate change · Salinity intrusion · Water level rise · Striped catfish aquaculture · Mekong Delta

INTRODUCTION

Striped catfish (*Pangasianodon hypophthalmus* Sauvage) farming in the Mekong Delta (Fig. 1) accounts for approximately 60 % of Vietnam's overall aquaculture production (Anonymus 2011). Processed catfish, mainly in the form of filet, was exported to over 100 countries and was valued at 1.4 billion US$ in 2010 (De Silva and Nguyen 2011). The sector provides employment for more than 170 000 workers (De Silva et al. 2010) and includes both small-scale farmer managed holdings that deliver their produce to processing companies, and fully integrated companies which own feed-mills, ponds, and processing facilities.

Farming of catfish started with *Pangasius bocourti* in cages in the two main branches of the Mekong, Tien and Hau, or its tributaries. The culture gradually moved to ponds after artificial propagation of striped catfish was developed (Phan et al. 2009; Bui et al. 2013). These ponds are deep, enabling yields of 200–400 t ha^{-1} crop^{-1} (Phan et al. 2009), and cover approximately 6200 ha in total (Bosma et al. 2009). To obtain the desired white filet color catfish farming requires regular water exchange. To meet the large volume of water that is required to be exchanged on a very regular basis (Phan et al. 2009) and to reduce costs associated with this exchange (i.e., pumping), most catfish farms are located along the Tien and Hau river branches (c.f. Fig. 1).

These rivers have a relatively high tidal range, though their hydrological regime is affected by tidal and river discharge, depending on the season (Wassmann et al. 2004). The floods from the rainy season (May–November), and the salt intrusion from the dry season (March–April) are important criteria of suitable locations for striped catfish farming. In particular, salinity concentrations higher than 4 ‰ are deemed unsuitable for striped catfish farming (Department of Aquaculture 2008; De Silva and Nguyen 2011). Besides the seasonal impact on hydrological regimes, the projected impacts of climate change should be considered. The projected sea level rise of about 1 cm year^{-1} until 2100 (Grinsted et al. 2009) and the simultaneous reduction in river flow cause an upstream increase in saline water intrusion during the dry season and flooding during the wet season (DFID 2007).

Considering all sea level rise impact indicators, Vietnam has been ranked among the top five countries most affected by rising sea levels (Dasgupta et al. 2007). Vietnam's Ministry of Natural Resources and Environment (MONRE

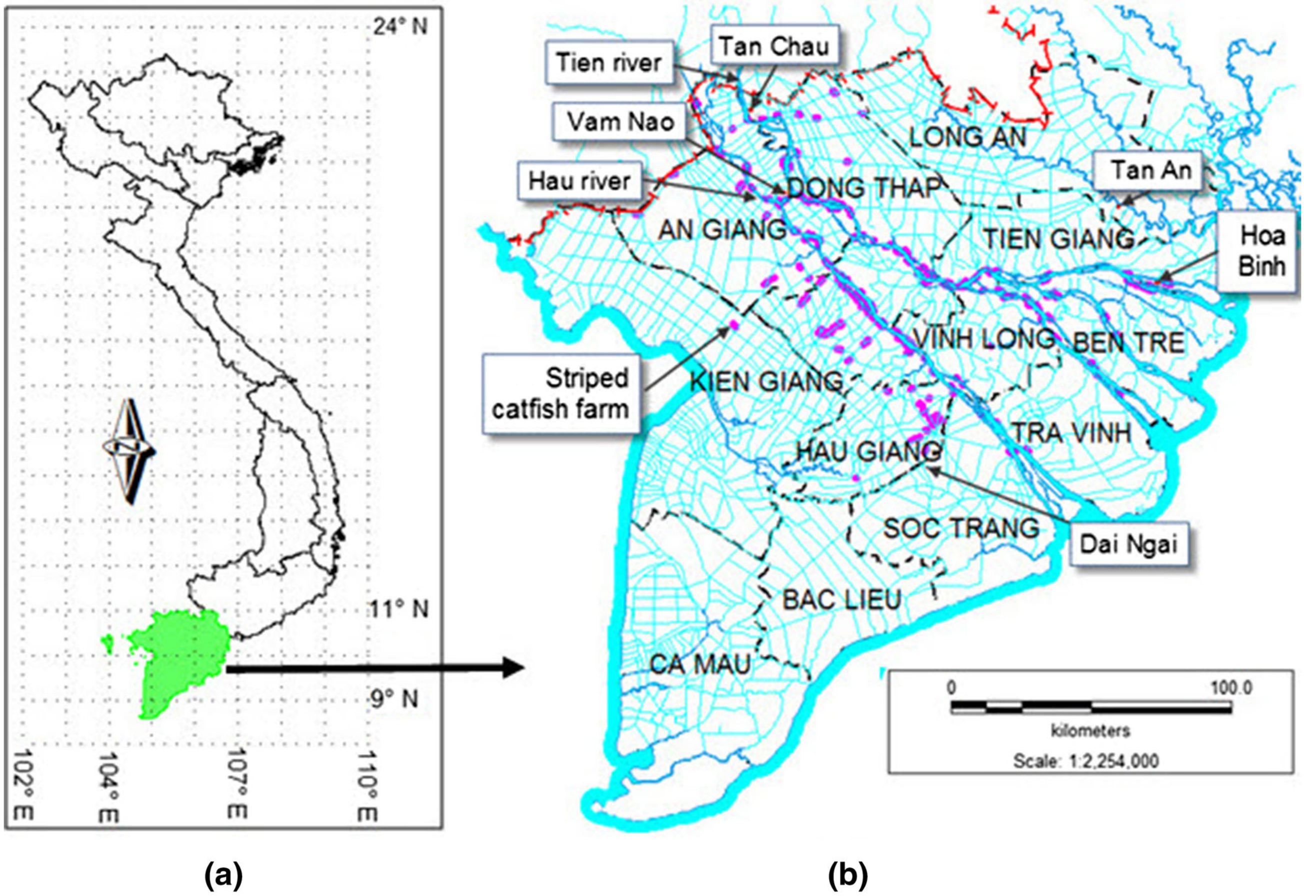

Fig. 1 **a** Mekong delta part of Vietnam. **b** Administrative map of the Mekong delta with the rivers and canals system, locations of the striped catfish farms in 2009 and stations for model calibration

2009) computed the country's sea level rise scenarios by using the IPCC SRES projections (Nakicenovic et al. 2000). MONRE (2009) argued that the lowest B1 scenario is very unlikely, since conflicting views on climate change mitigation between various countries will hamper the stabilization of greenhouse gas concentrations. On the other hand, with the world's campaign in "combatting climate change," MONRE expects that the highest scenario (A2) will not happen either. They expect a sea level rise of 30 cm in 2050, 46 cm in 2070, and 75 cm in 2100, using scenario B2.

Prior to MONRE's sea level rise projections, researchers have already worked on climate change-related studies. To assess sea level rise and salinity intrusion in the Mekong Delta, researchers have begun using hydrological models and GIS data since the start of this century. Specifically, the VRSAP model was used by Wassmann et al. (2004) to map the vulnerable rice production areas and by Nguyen and Savenije (2006) to predict the salinity distribution in the Mekong river branches using topography, tide, and river discharge data. Hoa et al. (2007, 2008) used an integrated hydraulic model, HydroGis, in tracking the impact of sea level rise and flooding in general. Khang et al. (2008) simulated changes in water flow and salinity intrusion for two sea level rise scenarios (+20 and +45 cm) by using the MIKE11 model and a GIS.

However, no studies have yet examined the impact of sea level rise on the striped catfish farming areas in the Mekong Delta (Fig. 1). The vulnerability of *Pangasius* farming has two aspects: (1) the exposure to and sensitivity for climate change impacts and (2) the perception of risk and possibilities for its mitigation. A later paper will focus on the second aspect. The present study focuses mainly on the exposure and sensitivity. Thereto salinity intrusion predictions and water levels are combined with the current locations of striped catfish farming in the Mekong Delta, to estimate the potential impact of different sea level rises (i.e., +30, +50, and +75 cm) on these striped catfish farming areas.

MATERIALS AND METHODS

This study mapped the catfish farms in the Mekong delta for 2009. We assessed the impacts of water level and salinity intrusion along the Tien and Hau branches of the Mekong river in time and space by applying model-based scenarios for sea level rise and reduced river flow (e.g., Alcamo et al. 1998; Wassmann et al. 2004; Hoa et al. 2007, 2008; Khang et al. 2008).

The Model Setup

The river flow and salinity intrusion in the two branches of Mekong river were simulated by using the MIKE 11 model, which was developed by the Danish Hydraulic Institute (DHI 2003). Two modules of MIKE 11 were applied: (a) the hydrodynamic module for flow simulation, and (b) the advection–dispersion module for salt expansion. The model used data on water level, rainfall, and salinity from 24 hydro-meteorological stations (i.e., Kratie, PhnomPenh, Tonle Sap, Tan Chau, Chau Doc, Long Xuyen, Ha Tien, Rach Gia, Ca Mau, Ganh Hao, Bac Lieu, Soc Trang, Can Tho, Tra Vinh, My Tho, Vinh Long, Cao Lanh, Sa Dec, My Thuan, Ben Tre, Tan An, Moc Hoa, and Tan Son Nhat) and considered boundaries for 68 downstream-end data of tidal water level and salinity, and seven upstream discharge boundaries with updated data of water discharge.

The input data for the model comprised the boundaries, as well as databases on hydrological and meteorological conditions. The hydraulic data included the hydrology of the Mekong river downstream from the Kratie boundary, including the land levels above sea and the hydraulic elements of rivers and canals system in 2005. The model also included irrigation and water control sluice systems.

Model Calibration

To calibrate the two modules of the original MIKE 11 model, we compared the projected change and the actual water level and salinity intrusion for the year 2005 (see "Comparison of Maps" section). The data on tidal boundaries for calibration were provided by the Southern Center for Hydro-meteorological Forecasting. The flood data at the Kratie main discharge station were obtained from the Mekong River Commission. The data on water levels, water discharge, and salinity of 2005 were obtained from the Hydro-meteorological Survey Mission for the Mekong delta. Subsequently, the best fit values between simulated and observed parameters were used for scenario predictions.

The calibration process of the hydrodynamic module was performed by adjusting model parameters such as the initial water level in rivers and canals together with Manning coefficients of canal and river segments (Wassmann et al. 2004; Khang et al. 2008). Figure 2 shows the comparison between the computed and observed water level and water discharge at Tan Chau and Vam Nao (in upstream part of the delta) and Tan An (in the coastal part) (c.f. Fig. 1). The model accurately simulated the observed data both for water level and water discharge.

The calibration process for the advection–dispersion module was carried out by adjusting the initial salinity concentration and dispersion coefficient for several segments of rivers and canals. This process was more complicated compared to the calibration of the hydrodynamic module, because the saline water spreads under influence of the density of the water network with its dams and sluices, and of the dispersion coefficient which depends on flow velocity and also on wind conditions (Khang et al. 2008). Table 1 and Fig. 3 illustrate the results of model calibration for salinity intrusion compared with observed data at some stations in the coastal part of the Mekong delta. The result

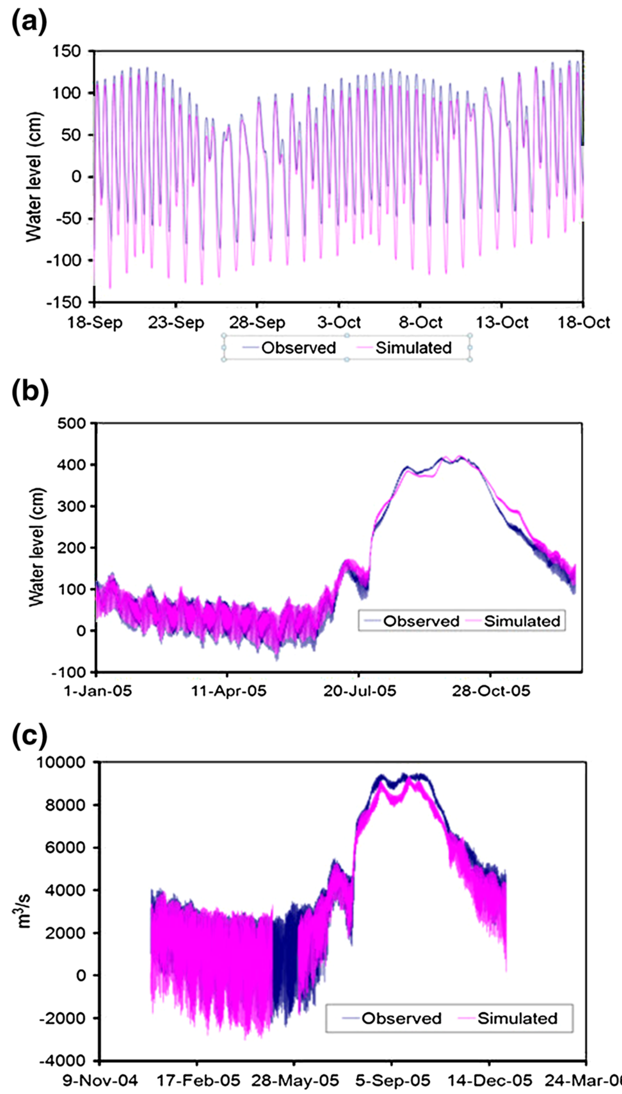

Fig. 2 Comparison of observed and simulated value of: **a** hourly water level at Tan An station from September to October; **b** daily water level at Tan Chau station; and **c** daily water discharge at Vam Nao station in 2005

Table 1 Comparison between observed and simulated salinity concentration values at Tra Vinh, Song Doc, My Tho, and Tan An station in the coastal part of Mekong delta

Station	Max. of salinity concentration (‰)			Average of salinity concentration (‰)		
	Simulated	Observed	Diff.	Simulated	Observed	Diff.
Tra Vinh						
10/2–13/2/2005	5.8	6.2	0.4	3.5	3.7	0.2
18/2–21/2/2005	9.5	8.3	−1.2	5.5	6.2	0.7
26/2–01/3/2005	7	6.8	−0.2	3.9	5	1.1
11/3–14/3/2005	10	9	−1	5.75	6.5	0.75
29/3–01/4/2005	9	10	1	8	7.75	0.25
Song Doc						
10/2–13/2/2005	11	10	−1	6	8	2
23/2–26/2/2005	11	10	−1	7.5	8.5	1
11/3–14/3/2005	13	16	3	12	12	0
29/3–01/4/2005	14	16	2	13.5	13	−0.5
My Tho						
10/2–13/2/2005	1.2	0.7	−0.5	0.35	0.6	0.25
26/2–01/3/2005	1.1	1.1	0	0.6	0.75	0.15
03/3–08/3/2005	2.6	2.2	−0.4	1.2	1.6	0.4
17/3–21/3/2005	3.5	3.1	−0.4	1.95	2.2	0.25
Tan An						
10/2–13/2/2005	5	4.5	−0.5	3	3.25	0.25
26/2–01/3/2005	6.5	6.5	0	4.8	5	0.2
11/3–14/3/2005	6.8	6.5	−0.3	5.25	5	0.25
19/3–21/3/2005	9	8	−1	6	6.5	0.5

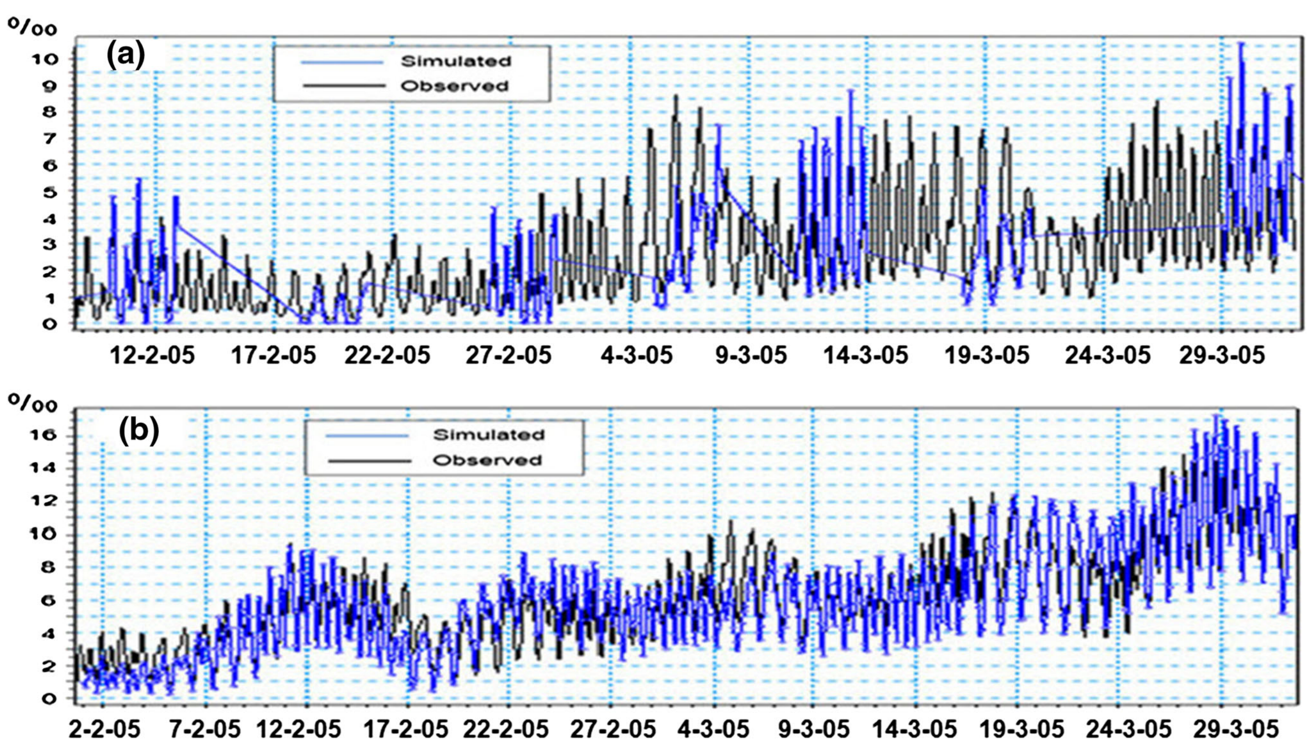

Fig. 3 Comparison of observed and simulated value of salinity concentration at **a** Dai Ngai and **b** Hoa Binh stations (c.f. Fig. 1) in February and March, 2005

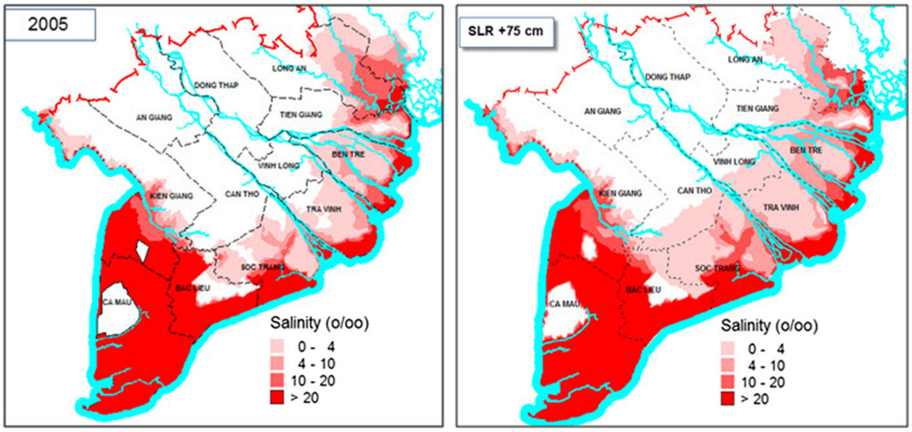

Fig. 4 The areas affected by salinity intrusion according in ‰ concentrations for the 2005 baseline and the SLR +75 cm scenarios

Table 2 The total area (km^2) of the Mekong Delta affected by the salinity intrusion for the baseline and three SLR scenarios

Salinity (‰)	2005	Sea level rise scenarios					
	0 cm	+30 cm	%	+50 cm	%	+75 cm	%
<4	4780	6430	+35	7450	+56	8090	+69
4–10	2360	2515	+7	2745	+16	3240	+37
10–20	2280	2610	+14	2530	+11	2570	+13
>20	9380	9240	−1	9170	−2	9130	−3
Total area >4	14020	14 365	+2	14 445	+3	14 940	+7

predicts the trend of salinity variation with an acceptable accuracy. Thus, the parameters computed after the calibration could be used for the scenarios modeling.

Comparison of Maps

Water level and salinity intrusion were projected based on separated baseline maps. We chose the data of serious events of flood and drought in recent year as baseline data according to the highlights of the Mekong River Commission (MRC 2012) in order to map the maximum potential impact of sea level rise scenarios. Thus, water level was projected based on the water level map of the year 2000, as this was characterized by extreme flooding, both in duration and depth, across the Cambodian lowlands and the Mekong Delta (MRC 2012). The salinity intrusion was projected based on the salinity map of 2005 when the drought was severe in all four riparian countries, especially in the Mekong Delta, where low stream flows allowed ocean salinity to penetrate further upstream then normal (MRC 2012). The salinity levels were mapped by using four categories: <slightly saline 4 ‰, slightly to moderately saline 4–10 ‰, moderately to highly saline 10–20 ‰, and highly saline >20 ‰.

The maps of water level and salinity intrusion resulting from the different sea level rise (SLR) scenarios (SLR +30 cm, SLR +50 cm, and SLR +75 cm) were compared with those of the baseline map to estimate the impacted area. The current striped catfish farming map was overlaid by the contour line of increased water level and salinity by the GIS software MAPinfo® to determine the striped catfish farming locations at risk in the future.

RESULTS

Saltwater Intrusion According to the SLR Scenarios

The area affected by intrusion of low level salinity (i.e., <4 ‰) is currently 4780 km^2 and expands to 1660, 2670, and 3310 km^2 for SLR +30 cm, SLR +50 cm, and SLR +75 cm, respectively (Fig. 4). The saltwater intrudes into the non-coastal provinces starting with the SLR +30 cm scenario. However, the expansion of the area affected by salinity levels above 4 ‰ is smaller: 345 km^2 for the scenario SLR +30; 425 km^2 for SLR +50 cm, and 920 km^2 for SLR +75 cm (Table 2). Thus, the 4 ‰ level expands less, while sea level rises from SLR +30 cm to SLR +50 cm.

In some upstream areas, at a specific SLR, the fresh water from the river pushed by sea water is transferred to low-lying areas located inland such as Quan Lo-Phung Hiep. In such areas, the salinity levels will be decreasing instead of increasing (Table 2, 10–20 and >20 ‰).

Due to seasonal variation in river discharge, the effect on salinity levels is lower during the SW monsoon, which is the flood season, running from May to October. Salinity levels rise from January to April (Fig. 5). At present, the saline front of 4 ‰ shifts inward 29 and 32 km in Hau river by end of March and April, respectively. For the SLR +50 cm scenario, the saline front of 4 ‰ in Hau river will reach 10 km inland from the sea in January then extend up to 24 km in February, 35 km in March, and 38 km in April.

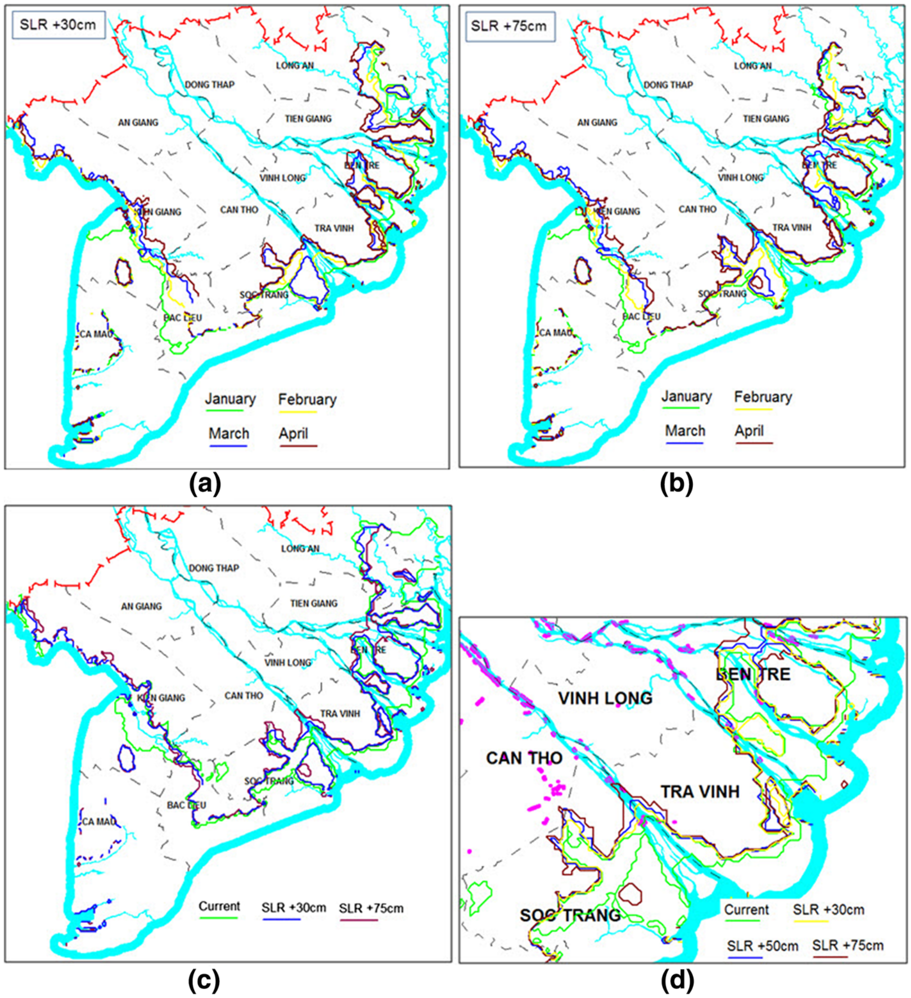

Fig. 5 Coastal areas affected by salinity intrusion (4 ‰) from January to April for **a** SLR +30 scenario, **b** SLR +75 scenario; and in April for **c** two scenarios and the baseline, and **d** affect the striped catfish farm locations in Ben Tre, Tra Vinh, and Soc Trang provinces

For the SLR +30 cm scenario, the central part of Soc Trang and the coast lines of Ben Tre will be affected by the intrusion of salinity concentration of 4 ‰.

Water Level According to the SLR Scenarios

The water level in the Mekong delta will be affected by changes in tides and floods as a consequence of climate change. The simulated peak water levels at various stations will increase when sea level rises (Table 3).

In the coastal provinces, floods are projected to arrive earlier and persist longer than at present. This early high flood may reduce the window for risk-free farming of striped catfish in Soc Trang, Tra Vinh, Ben Tre, and coastal districts of Tien Giang. Inundation areas will also increase in the SLR +30 cm and SLR +75 cm scenarios (Fig. 6). As SLR increases from +50 to +75 cm, the higher flood level will cause flooding in a much larger area of the Mekong Delta for the upstream provinces of An Giang, Dong Thap, and Can Tho.

Table 3 The peak water levels at 4 stations in 2000 and according to the SLR scenarios

Stations	Baseline	Sea level rise scenarios		
	Year 2000	+30 cm	+50 cm	+75 cm
Tan Chau	5.10	5.16	5.24	5.33
Vam Nao	3.87	3.96	4.01	4.10
Dai Ngai	1.78	2.07	2.26	2.50
Tan An	1.60	1.89	2.09	2.32

Area of Striped Catfish Farming at Risk

When the salinity map is overlaid on the map of striped catfish farm locations of 2009 for Ben Tre, Tra Vinh, and Soc Trang provinces, it is shown that the effect on the farms is local (Fig. 5). In Tra Vinh, the location in the southwestern area is projected to suffer, while the conditions for farms in the northeast will not change significantly. In Ben Tre, most farms deal already with 4 ‰

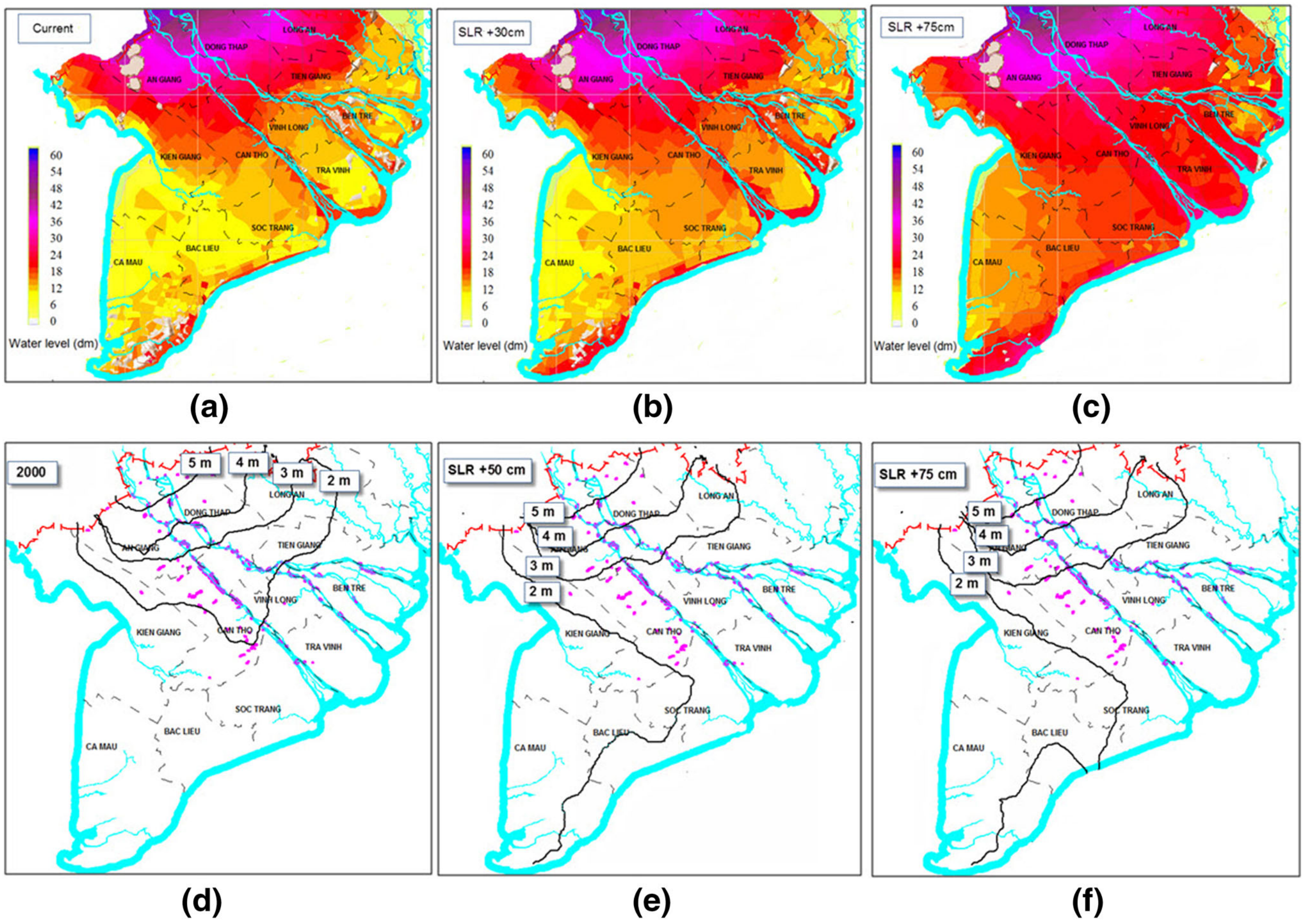

Fig. 6 The maximal water levels in October for **a** the baseline, **b** SLR +30 scenario and **c** SLR +75 scenario of sea level rise; and the map of the Mekong delta' striped catfish farm locations and the risk of water level in October for **d** the year 2000, **e** SLR +50 cm scenario and **f** SLR +75 cm scenario

salinity levels but periods subjected to this salinity may become longer and farms located further upstream (i.e., to the west) may also have to deal with it. In Soc Trang, all farms already have to deal with these prolonged periods.

Overlay of the contour map of water level on the map of 2009 striped catfish farm locations shows that all striped catfish farms have to deal with a 2-m-flood level for the SLR +50 cm scenario (Fig. 6). Added to these already affected farms at present are those located downstream in the province Can Tho, Tien Giang, and Vinh Long, and all farms in Ben Tre, Soc Trang, and Tra Vinh. The number of extra farms to be affected in SLR +75 cm, however, is not large.

DISCUSSION

One of the limitations of our study is the use of current topographical data for projecting the salinity intrusion due to sea level rise scenarios. Nguyen and Savenije (2006) pointed that the high sediment transport capacity of the Mekong river and the lack of updated topographical data will affect the results of salinity models like ours. In addition, topographical changes are very difficult to predict given that future infrastructure changes are likely to influence water discharge and drainage. Hoa et al. (2007) predicted that "The future flood control works planned to be completed by 2010 will cause an increase in runoff peaks and prolong the duration of the flood recession."

In general, the present study confirms that three sea level rise scenarios will lead to an increase of the water level in the rainy season and to an expanded salinity intrusion in the dry season both at spatial and temporal scales in the Mekong Delta, Vietnam, thus increasing the vulnerability of the delta area to climate changes (Wassmann et al. 2004; Khang et al. 2008; Hoa et al. 2008). Syvitski et al. (2009) presented an assessment of 33 densely populated and heavily farmed deltas globally and estimated the delta areas vulnerable to flooding could increase by 50 % by sea level rise in the twenty-first century. The Mekong Delta is particularly at risk because of its large surface area below mean sea level, its limited coastal barrier protection(s), and because the rates of global sea level rise are enforced by reduced sediment depositions (due to upstream dams and downstream flood protection dykes) plus an accelerated soil subsidence (Syvitski et al. 2009). However, a direct comparison of the present findings with others is not an easy task. We used 4 ‰ as the threshold value to accept the impact of salinity intrusion to striped catfish farming, whereas earlier research (Khang et al. 2008) predicted this impact on rice production with a threshold of 2.5 ‰. Wassmann et al. (2004) predicted an average water level rise at the peak of flood season (October) of 11.9 cm (SLR +20) and 27.4 cm (SLR +45) which compares reasonable to our results of 17 cm (SLR +30) and 28.3 cm (SLR +50), respectively.

The main stream of the lower Mekong River (running through Cambodia, Lao PDR, Thailand and Vietnam) has currently no dams. Plans to do so in the future have provoked controversy and public debate (see Kummu and Sarkkula 2008; Dugan et al. 2010; Keskinen et al. 2012, among others). Li and He (2008) stated that "the downstream effects of the present dams on water levels are very limited at the annual mean and wet season mean levels." Delgado et al. (2010) and MRC (2012) concluded that dam construction had little impact on downstream flood levels in the last two decades of twentieth century. Wassmann et al. (2004) pointed out that the effect of hydro-dams or reservoirs was insignificant due to the regulation of the Tonle Sap lake in Cambodia and the strong tidal effect from the seas. However, the construction of additional dams will likely affect the water level and the drainage behavior of Tonle Sap, and will increase the possibility of dam ruptures causing floods (MRC 2012). Thus, the hydrological regime of the lower reaches of the Mekong river will rely on the regulatory capacity of Tonle Sap.

De Silva and Soto (2009) predicted that aquaculture activities occurring in deltaic areas of major rivers in Asia, South America, and the Caribbean will encounter saline water intrusion caused by climate change. In the Mekong Delta, striped catfish farms of coastal provinces (Tien Giang, Ben Tre, Tra Vinh, and Soc Trang) cover approximate 864 ha with a production of 190 000 tonnes, which accounts for 26 % of the total catfish farming area in the Delta and contributed 20 % to the striped catfish production in 2013 (Directorate of Fisheries 2013). These farms experience currently minor salinity variations depending on tidal amplitude (De Silva and Nguyen 2011). Farmers do not stock fingerlings in months with high salinity, and thus their window for farming is reduced. Pham et al. (2009) demonstrated that the annual yield from catfish farms located in the lower reaches of the Mekong River branches is significantly lower, and suggested that the lowered yields could be a result of the diurnal fluctuations in the salinity. Yet, already in 2011, the increased salt water intrusion in Ben Tre province, resulting in salinities up to 15 ‰, has resulted in increased mortality and in reduced growth rates, compared to those in 2010 (Ben Tre DARD, 2012). For the worst case SLR +75 cm scenario, this area will expand further and affect also Soc Trang province and Tien Giang province's coastal districts.

The above analysis shows that the risk from saltwater intrusion reduces the suitable area for catfish farming in the coastal provinces of the Mekong delta, from January to April. Therefore, to produce two crops in a year, farmers must either invest in water recirculation technologies to raise fingerling and reduce grow-out in ponds to three months, or raise other species. A shift to farming other species will need capacity building among rural farming communities, and even changes in infrastructure, in particular that of ponds. In catfish farming a water depth of 4.0–4.5 m is preferred, but such deep ponds are unsuitable for other commonly farmed, salinity tolerant species such as Asian sea bass or even shrimp. Altering the pond structure is likely to be very costly.

De Silva and Soto (2009) suggested that an alternative solution to the problem may lie in the development of a salinity tolerant strain of striped catfish. This strategy was further elaborated by De Silva and Nguyen (2011) suggesting that the use of genomic selection technology would help to speed up the process by improving accuracies of selection (Meuwissen et al. 2001). This technology, widely applied in livestock and crop selection (Goddard and Hayes 2009), was recently attempted in aquatic species, such as for salmon. Furthermore, De Silva and Nguyen (2011) pointed out the advantages of such a strategy being that it will bring about minimal changes to farming practices and related infrastructure, and will avoid the need to develop fresh market chains. Whether or not it will be cost effective in the long term has to be studied.

Many experimental studies on the salinity tolerance of a number of freshwater fish species have been conducted and comprehensive reviewing this vast literature is challenging because approaches strongly differ. Among catfish species such studies were conducted by Bringolf et al. (2005), for example, showed that juvenile flathead catfish (*Pylodictis olivaris*), which could tolerate exposure to brackish water. Its dispersal may not be limited by estuarine salinities. Capps et al. (2011) studied the salinity tolerance of suckermouth armored catfish (*Pterygoplichthys Siluriformes Loricariidae*) a strictly freshwater fish, of south-eastern Mexico. Their individuals normally maintained in a salinity of 0.2 ‰ were able to survive salinities up to 10 ‰ with little mortality over 10 days. However, few individuals survived salinities up to 11 or 12 ‰ for 20 h, but none survived after few hours in salinities of 16 ‰ and higher.

With respect to striped catfish, several studies have been carried out to test the impact of salinity. Nguyen et al. (2011) studied the effect of salinities of 0, 3, 6, 9, 12, and 15 ‰ on the physiological changes and growth in fish of an average weight of 25 g. The results indicated that culture of striped catfish in salinity of 9 ‰ is possible but the growth was significantly reduced. Do et al. (2012) studied the salinity tolerance of egg and larvae of striped catfish. After being artificially fertilized, the eggs were incubated in salinities of 0, 1, 3, 5, 7, 9, 11, 13, 15, 17, and 19 ‰. The results showed that the embryos of striped catfish can develop and hatch in brackish water up to 11 ‰. These above results can be seen as an initial success encouraging further studies on mitigating measures to adapt to the impact of salinity intrusion caused by climate change, and also indirectly indicate the potential of developing a salinity resistant strain of catfish without sacrificing its growth and overall yield.

In the rainy season, the increased water levels from August to October may affect the farm infrastructures. In all scenarios, the coastal provinces will have to deal with higher water levels. In the SLR +50 cm scenarios, the water level of 3 m will spread downstream and not only threaten the striped catfish farms located in An Giang and Dong Thap provinces, but also the farms in Can Tho province. Wassmann et al. (2004) predicted that floods will arrive earlier and persist longer than at present and that the inundation area will also increase. To deal with the rising water level, farmers will need to invest more in the pond (or farm protection) dyke to increase its height and to maintain its protected function, and in increased operational cost of water exchange.

CONCLUSION

This study predicted potential impacts of climate change to striped catfish farming, which is the most important aquaculture sector in the Mekong Delta, Vietnam, using scenarios with a sea level rise of, respectively, +30, +50, and +75 cm.

Salinity levels increase from January to April in all scenarios but the affected areas extend most in the +50 and +75 cm scenarios. The low level of salinity (<4 ‰) expands faster than levels above 4 ‰, which is harmful for grow-out of striped catfish. The number of affected farms in the coastal provinces of Soc Trang, Ben Tre, and Tra Vinh increases not only because of increased salinity intrusion, but also because the period with higher salinity levels will last longer.

Sea level rise will also impede the rivers to discharge their water to the sea. This will lead to longer flood periods and larger inundation areas. The catfish farmers have to increase the height of their pond dykes and invest more in water exchange.

Investment in new striped catfish farms in the coastal provinces of the Mekong delta is not advisable because of these apparent threats. However, our analysis does not specify when the impacts are likely to occur. A more sustainable approach that would minimize dislocation of farmers and ensure the continued usage of the existing facilities might be to breed a strain of catfish that is salinity tolerant, up to about 17–20 ‰. Such an approach will minimize the changes needed in the value chain of this major food production sector, as compared to investing in water recirculation technologies or shifting to euryhaline species.

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REFERENCES

Alcamo, J., R. Leemans, and G.J.J. Kreileman. 1998. *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*. Pergamon & Elseviers Science, London.

Anonymus. 2011. Nine major events of Tra and Basa in 2010. Tra & Basa in Vietnam, *Vietnam Fisheries Society*, 20–21. Ministry of Agriculture & Rural Development, Tra Vinh Provincial Government, Tra Vinh, Vietnam (in Vietnamese).

Ben Tre Department of Agriculture and Rural Development (DARD). 2012. Report of striped catfish aquaculture of the year 2011 and plan for 2012. Ben Tre Provincial Government, Ben Tre, Vietnam (in Vietnamese).

Bosma, R.H., C.T.T. Hanh, and J. Potting. 2009. Cradle-to-gate environmental impacts of *Pangasius* farming in the Mekong Delta. *Aquaculture Europe* 34: 13–17.

Bringolf, R.B., T.J. Kwak, W.G. Cope, and M.S. Larimore. 2005. Salinity tolerance of flathead catfish: Implications for dispersal of introduced populations. *Transaction of the American Fisheries Society* 134: 927–936.

Bui, T.M., P.T. Nguyen, H.G. Nguyen, and S.S. De Silva. 2013. Fry and fingerling transportation in the striped catfish, *Pangasianodon hypophthalmus* farming sector, Mekong Delta, Vietnam: A pivotal link in the production chain. *Aquaculture* 388–391: 75–88.

Capps, K.A., L.G. Nico, M. Mendoza-Carranza, W. Arevalo-Frias, A.J. Ropicki, S.A. Heilpern, and R.R. Rodiles-Hernandez. 2011. Salinity tolerance of non-native suckermouth armoured catfish (*Loricariidae:* Pterygoplichthys) in south-eastern Mexico: Implications for invasion and dispersal. *Aquatic Conservation: Marine and Freshwater Ecosystems* 21: 528–540.

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan. 2007. The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. World Bank Policy Research Working Paper 4136, Washington, DC.

De Silva, S.S., and P.T. Nguyen. 2011. Striped catfish farming in the Mekong Delta: A tumultuous path to a global success. *Reviews in Aquaculture* 3: 45–73.

De Silva, S.S., and D. Soto. 2009. Climate change and aquaculture: Potential impacts, adaptation and mitigation. *FAO Fisheries and Aquaculture Technical Paper* 530: 151–210.

De Silva, S.S., B.A. Ingram, P.T. Nguyen, T.M. Bui, G.J. Gooley, and G.M. Turchini. 2010. Estimation of nitrogen and phosphorus in effluent from the striped catfish farming sector in the Mekong Delta, Vietnam. *AMBIO* 39: 504–514.

Delgado, J.M., H. Apel, and B. Merz. 2010. Flood trends and variability in the Mekong River. *Hydrology and Earth system*

Sciences, 14: 407–418. Retrieved May 11, 2010, from http://www.hydrol-earth-syst-sci.net/14/407/2010/.
Department of Aquaculture. 2008. Tra catfish culturing and marketing development plan to 2010 and strategy to 2020 (in Vietnamese).
DFID. 2007. The effects of climate change on global aquaculture, a global perspective. Retrieved Feb 7, 2009, from http://www.aquaculture.stir.ac.uk/GISAP/pdfs/Climate_full.pdf.
DHI. 2003. MIKE 11—A modelling system for Rivers and Channels. Reference Manual.
Directorate of Fisheries. 2013. The striped catfish production in 11 months of 2013's crop (in Vietnamese) http://www.fistenet.gov.vn/c-thuy-san-viet-nam/b-nuoi-trong/tinh-hinh-nuoi-va-tieu-thu-ca-nuoc-ngot-ca-bien-cua-viet-nam-10-thang-111au-nam-2013/.
Do, T.T.H., and N.T.Q. Tran. 2012. The effect of salinity on the embryonic development and osmoregulatory of the striped catfish (*Pangasianodon hypophthalmus*) larvae and fingerling stages. *Journal of Science* 21b: 29–37. Can Tho University, Vietnam (in Vietnamese, English summary).
Dugan, P.J., C. Barlow, A.A. Agostinho, E. Baran, G.F. Cada, D. Chen, I.G. Cowx, et al. 2010. Fish Migration, Dams and Loss of Ecosystem Services in the Mekong Basin. *AMBIO* 39: 344–348.
Goddard, M.E., and B.J. Hayes. 2009. Mapping genes for complex traits in domestic animals and their use in breeding programmes. *Nature Reviews Genetics* 10: 381–391.
Grinsted, A., J. Moore, and S. Jevrejeva. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics.* doi:10.1007/s00382-008-0507-2.
Hoa, L.T.V., N.H. Nhan, E. Wolanski, T.T. Cong, and H. Shigekoa. 2007. The combined impact on the flooding in Vietnam's Mekong River delta of local man-made structures, sea level rise, and dams upstream in the river catchment. *Estuarine, Coastal and Shelf Science* 71, 110–116.
Hoa, L.T.V., H. Shigeko, N.H. Nhan, and T.T. Cong. 2008. Infrastructure effects on floods in the Mekong River Delta in Vietnam. *Hydrological Processes* 22: 1359–1372.
IPCC. 2007. Climate Change 2007: Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
Keskinen, M., M. Kummu, M. Käkönen, and O. Varis. 2012. Mekong at the Crossroads: Next Steps for Impact Assessment of Large Dams. *AMBIO* 41: 319–324.
Khang, N.D., A. Kotera, T. Sakamoto, and M. Yokozawa. 2008. Sensitivity of salinity intrusion to sea level rise and river flow change in Vietnamese Mekong Delta—Impacts on availability of irrigation water for rice cropping. *Journal of Agricultural Meteorology* 64: 167–176.
Kummu, M., and J. Sarkkula. 2008. Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse. *AMBIO* 37: 185–192.
Li, S., and D. He. 2008. Water Level Response to Hydropower Development in the Upper Mekong River. *AMBIO* 37: 170–177.
Meuwissen, T.H., B.J. Hayes, and M.E. Goddard. 2001. Prediction of total genetic value using genome-wide dense marker maps. *Genetics* 157: 1819–1829.
MRC (Mekong River Commission). 2012. Flood Management and Mitigation Programme: The Impact & Management of Floods & Droughts in the Lower Mekong Basin & the Implications of Possible Climate Change. Working Paper (2011–2015). http://www.mrcmekong.org/assets/Publications/basin-reports/FMMP-working-paper-110820.pdf.
MONRE (Ministry of Natural Resources and Environment). 2009. Climate change, sea level rise scenarios for Vietnam. Publisher Ha Noi.
Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, et al. 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. 599 pp.
Nguyen, A.D., and H.H.G. Savenije. 2006. Salt intrusion in multi-channel estuaries: a case study in the Mekong Delta, Vietnam. *Hydrology and Earth System Sciences* 10: 743–754.
Nguyen, C.L., D.T.T. Huong, V.N. Son, and N.T. Phuong. 2011. Physiological changes and growth of the striped catfish (*Pangasianodon hypophthalmus*) exposed to different salinities. *Journal of Science* 17a: 60–69. Can Tho University, Vietnam (in Vietnamese, English summary).
Phan, L.T., T.M. Bui, T.T.T. Nguyen, G.J. Gooley, B.A. Ingram, H.V. Nguyen, P.T. Nguyen, and S.S. De Silva. 2009. Current status of farming practices of striped catfish, *Pangasianodon hypophthalmus*, in the Mekong Delta, Vietnam. *Aquaculture* 296: 227–236.
Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vorosmarty, et al. 2009. Sinking deltas due to human activities. *Nature Geoscience* 2. Retrieved Nov 26, 2013, from www.nature.com/naturegeoscience.
Wassmann, R., N.X. Hien, C.T. Hoanh, and T.P. Tuong. 2004. Sea level rise affecting the Vietnamese Mekong Delta: Water elevation in the flood season and implications for rice production. *Climatic Change* 66: 89–107.

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