Implications of Climate Change and Other Environmental Issues for the Sustained Food Production in the Mekong Delta[1]

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Abstract

This review first points out the importance of the Mekong Delta in food production and biodiversity. We then summarize the current knowledge about the major threats to agricultural and aquacultural production in the Mekong Delta by climatic and other environmental factors. The topics cover climate and river flow change, mangrove loss, plastic litter, water pollution, and food safety. The data are collected from literature surveys, analyzed and discussed. We subsequently discuss the possible use of emerging approaches to maintain the food production, such as selective breeding of salt-tolerant strains of agricultural and aquacultural species, use of recirculating aquaculture systems, life cycle assessment, and increased use of market incentive measures. An experience of the City of Kitakyushu, Japan is introduced as an example to prove that environmental restoration is indeed possible. We emphasize the crucial importance of coordinated collaboration between the public, government, private sectors and academia for the sustainable development of food production in the healthy environment of the Mekong Delta.

Keywords: agriculture, aquaculture, climate change, environment, Mekong Delta, sustainable development

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[1] A preliminary, shorter version of this paper written in Japanese has been uploaded as an information material at the JICA CTU Project website [https://www.jica.go.jp/Resource/project/vietnam/060/materials/cr73nr0000005ydv-att/Mekong_Delta_01.pdf]

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1. MEKONG DELTA AS A HOT SPOT

1.1. A hot spot of food production

The Mekong Delta is a hotspot of food production, yielding significant amounts of both agricultural (Table 1) and aquacultural products (Table 2). Vietnam exports rice with annual export revenue of 3.29 billion USD in 2021 (General Statistics Office, 2021), and the Mekong Delta contributes to about 90% of national rice exports (Dao et al., 2020). Among aquaculture fishes, the striped catfish (*Pangasianodon hypophthalmus*) has the highest commercial value, and this commodity is exported to about 130 countries including the US, China-Hong Kong, and the member countries of the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP) such as Japan, Canada and Australia, with annual export revenue of 1.6 billion USD in 2021 (Vietnam Association of Seafood Exporters and Producers, 2022). Commercially even more important are shrimps. There are two major aquaculture shrimp species in Vietnam, black tiger shrimp (*Penaeus monodon*) and white-leg shrimp (*Litopenaeus vanamei*). Collectively, these shrimps are exported to about 100 countries including the US, Japan, China-Hong Kong and Korea, with the export value of 3.9 billion USD in 2021 (Vietnam Association of Seafood Exporters and Producers, 2022). Thus, the Mekong Delta plays a crucial role in food production, not only for Vietnam but also for other countries of the world.

Table 1. Importance of the Mekong Delta in Vietnamese agricultural production

Region	Rice[1] (2020)	Vegetables[2] (2009)	Fruits[3] (2014)	Cattle[1] (2020)	Poultry[1] (2020)
		1000 tons		1000 ind.	
Vietnam	42,765	11,885	7,000	6,326	512,675
Mekong Delta	23,828	3,564	3,080	948	86,985
%Mekong Delta	56	30	44	15	17

Data source:[1] General Statistics Office (2021), [2] Ly et al. (2013), [3] Uiterwijk and Linh (2017)

Table 2. Importance of the Mekong Delta in Vietnamese aquacultural production (1000 tons, 2020)

Region	Fish	Shrimp	Others*	Total
Vietnam	3,264	945	530	4,739
Mekong Delta	2,318	790	213	3,321
% Mekong Delta	71	84	40	70

*Data source: General Statistics Office (2021), *calculated as total minus fish and shrimp.*

1.2. A hotspot of biodiversity

The Mekong Delta is also a hotspot of biodiversity. According to the Institute of Tropical Biology, Vietnam Academy of Science and Technology, 1068 new species were discovered in the Mekong Delta in 13 years between 1997 and 2009 (Vietnam Tourism Environment, 2022). This is about 36% of the number of new species found from 1997 to 2020 in the Greater Mekong (3007 new species) including Cambodia, Laos, Thailand Myanmar and Vietnam (WWF, 2022). Twenty-two new species of land snails were discovered in the hills of the Mekong Delta near the border between Cambodia and Vietnam in 2019, pointing to the probable occurrence of many more undescribed species (Vermeulen et al., 2019).

Particularly rich is the fish fauna. In the entire Mekong River, 850 freshwater species have been identified and the number increases to 1100 species if coastal and brackish-water species are included (Hortle, 2009). The number of freshwater fishes given by Kang and Huang (2022) is 899, presumably indicating the continuing discovery of new fish species from the Mekong River in recent years. Tran et al. (2013) described 322 species of freshwater and brackish-water fishes from the Mekong Delta. The number of freshwater fishes in the Mekong River is nearly 70% of the number of freshwater fishes reported from the Amazon River, which is renowned for the world's highest freshwater-fish diversity of about 1200 species (Baran et al., 2012). One unusual fact about the fish fauna of the Mekong River is a high proportion of fishes that breathe air in addition to water. Air-breathing fishes are commercially important in the region, constituting a large percentage of aquaculture production from the Mekong Delta. The commercially most important species is the striped catfish, followed by species of Clariidae, Channidae, and Synbranchidae. These are all air-breathing fishes. It is noteworthy that the global aquaculture production of air-breathing fishes surpasses the global fresh- and saltwater culture of Salmonidae by as much as 60% (Bayley et al., 2020). In addition, air-breathing fishes are exceptionally important from the viewpoint of evolutionary biology (Ishimatsu, 2012; Ahlberg, 2019; Mai et al., 2019).

The bird fauna is also rich in the Mekong Delta, including 20 threatened or nearly threatened species. Neither amphibians nor reptiles nor invertebrates have been investigated as much (Campbell, 2012). The flora of the Mekong Delta has been extensively modified from the original natural vegetation (Rundel, 2009).

2. CURRENT AND PROJECTED FUTURE THREATS TO THE MEKONG DELTA

Despite the remarkable significance of the Mekong Delta in food production and biodiversity, there are threats that potentially deteriorate its value and function. The following lists the major threats that should be given priority in planning and implementing conservation and restoration activities of the Mekong Delta.

2.1. Climate and river flow changes

The Mekong Delta is one of the three mega deltas that are regarded as the most vulnerable to climate change impacts because it is flat and low-lying (Ericson et al., 2006). The area below 2 m above mean sea level reaches 20,900 km^2 in the Mekong Delta, which far exceeds 9,440 km^2 of the Nile (the world's longest river), 7,140 km^2 of the Mississippi, and only 1,960 km^2 of the Amazon (Syvitski et al., 2009).

Because of its low topography, tide-induced flood and saltwater intrusion are the most concerning threats to the Mekong Delta by climate change. Sea level along the Vietnamese coast is projected to rise 20-37 cm by 2050 and 51-106 cm by the end of the century under the worst scenario of climate change projection (Table 3). Figure 1 shows the areas of inundation risk (black) with a sea level rise of 100 cm. Under this condition, 47% of the surface area of the Mekong Delta would be inundated. The western provinces are particularly vulnerable; about 61% of Hau Giang province, 76% of Kien Giang and 80% of Ca Mau would be inundated. Under the sea level rise of 70 cm, the values are 28% for the whole Mekong Delta, 39% (HG), 76% (sic, KG) and 57% (CM)(the values reported in the latest report, MONRE, 2021).

Table 3. Projected climate change in the Mekong Delta

	2050	2100
Temperature (℃)	+1.7−2.3	+3.2−4.2
Sea level rise (cm)*	+20−37	+51−106
Annual rainfall (%)	+10−15	+10−25

*Data Source: MONRE 2021. Projections based on RCP8.5 (IPCC 5th Assessment Report). *Sea level rise for the entire East Sea Region.*

Saltwater intrusion into the Mekong Delta is intensified in the dry season when the river discharge is low and the coastal water level is high. In addition, recent studies indicated that the decrease in flows and sediment supply from the Mekong River by upstream

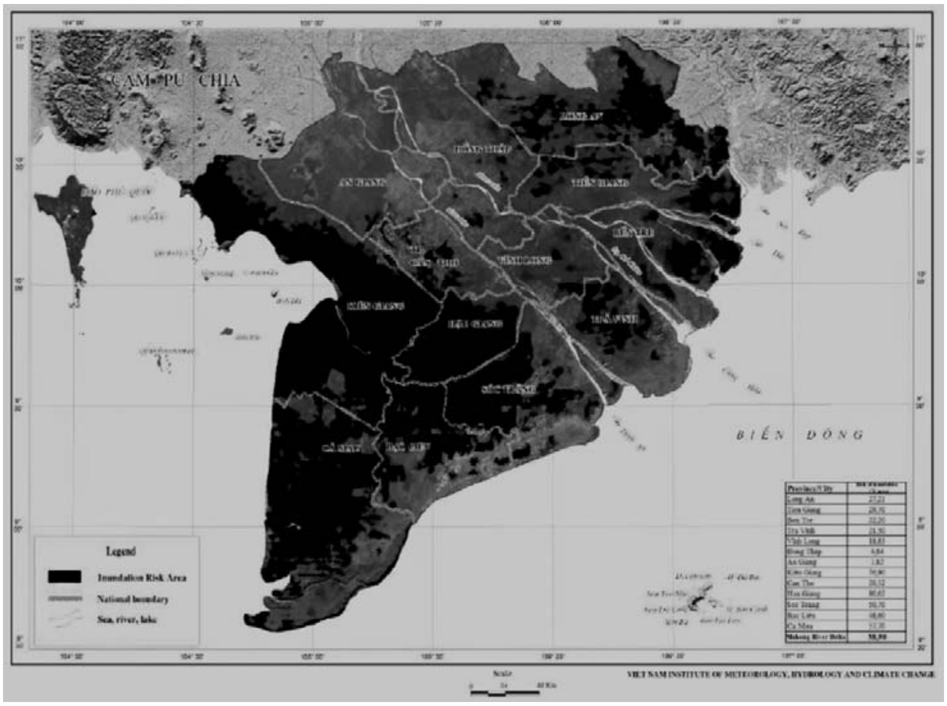

Figure 1 . The inundation risk map with a sea-level rise of 100 cm（MONRE, 2016).

dam construction has by far the strongest impact on saltwater intrusion than other causes such as riverbed mining, sea level rise, and land subsidence（Pokhrel et al., 2018). Ho et al.（2021）also found that the upstream dams are the largest cause for saltwater intrusion, followed subsequently by riverbed mining, sea level rise and land subsidence in the magnitude of impact. Eslami et al.（2021）estimated that land subsidence and river bed incision due to upstream sediment trapping and downstream sand mining, when combined, can increase the salinity-affected areas by 10-27%, while sea level rise adds 6-19% increase.

During the 2015/2016 El Niño period, the Mekong Delta experienced a historical saltwater intrusion（FAO, 2016). During the flood season in 2015, the water level measured at Tan Chau station（10 km downstream from the Cambodia-Vietnam border along the Mekong River, also known as the Tien River in Vietnam）was 2-3 m lower than the level recorded in the same months（September-October）in 2000 and 2011（high-flood years). Consequently, saltwater intruded 45-65 km upstream along the Mekong River and 55-60 km along the Bassac River（the Mekong's largest distributary, also known as the Hau River in Vietnam）during the drought event. Salinity showed a peak of 8 g L^{-1} in March 2016, measured at An Lac Tay station（50 km upstream from the coastline along the Bassac River）, which is 6 g L^{-1} higher than in 2005 and 2007（Kantoush et al., 2017）.

Extreme drought re-occurred in the dry season from late 2019 to early 2020. The low river discharge and high tide resulted in saltwater intrusion 2.5-3.5 months earlier than the annual average（10-20 days earlier than in 2015-2016）and lasted approximately 30 days longer. Figure 2 shows that the saltwater（4 g L^{-1}）intruded 65-75 km into the main waterways in 2020, 10-15 km deeper than in 2016（see also United Nations, 2020）.

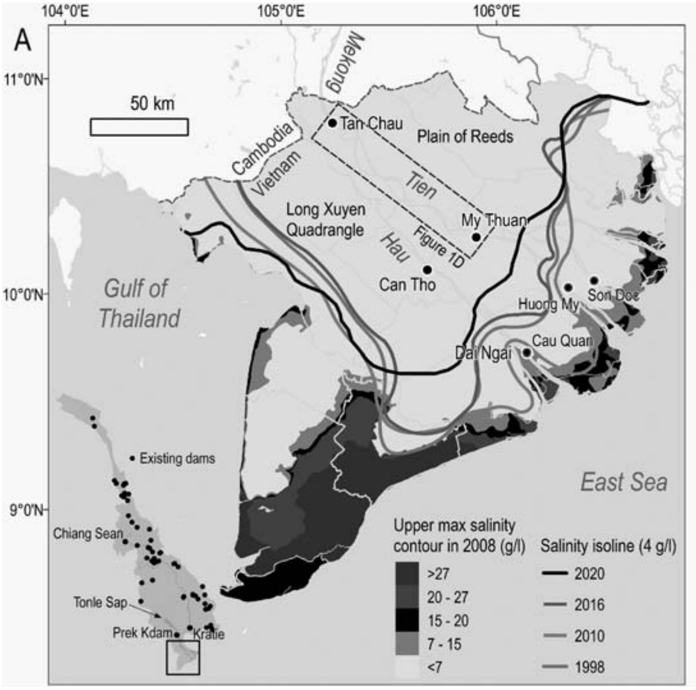

Figure 2. Saltwater intrusion in four drought years（1998, 2010, 2016 and 2020, Ho et al., 2021）. Also shown are the spatial patterns of saltwater in a normal year（2008）. Reproduced from Ho et al（2021）with permission. The color version of this figure is available at: https://www.sciencedirect.com/science/article/pii/S0048969720374507#f0005

Rice is sensitive to salinity, with 50% yield loss recorded at 7.2 dS m^{-1}（4 ppt at 25℃）（Thorat et al., 2018; Schneider & Asch, 2020）. The 2016 saltwater intrusion resulted in the loss of 800,000 tons of rice（Ho et al., 2021）. In the 2019-2020 saltwater intrusion event, at least 30,000 ha of paddy rice and 20,000 ha of fruit trees were likely to have been damaged（Park et al., 2022）. Vu et al.（2018）had projected that saltwater intrusion up to 50-60 km into the river would affect about 30,000 ha of the agricultural area.

Mandal et al.（2020）demonstrated that the growth of fingerlings of striped catfish was significantly reduced above 6 ppt while survival significantly decreased above 14 ppt after

60 days of rearing. Hossain et al. (2021) found significantly lower embryonic survival, hatching, larval survival and growth (48 h) of striped catfish at salinities higher than 8 ppt. Nguyen et al. (2021) found that the survival of larval striped catfish (24-36 h post hatch) was significantly reduced at 12 ppt after 60-day exposure, while the growth was unaffected. The optimal salinity of black tiger shrimp and white-leg shrimp was reported to be 20-25 ppt for both species (Li et al., 2017; Rahi et al., 2021). Hence salinization itself may not be a significant threat to shrimp aquaculture. However, shrimp farming did incur severe damage during the droughts due to insufficient water supply to culture ponds (SeafoodSource, 2022).

There has been no large fluvial flood entering the Delta since 2011, but threats of unexpected fluvial floods still exist due to climate change and upstream activities (Bussi et al., 2021). Using a flood propagation model, Nguyen et al. (2020) projected that the annual maximum water levels in the central and coastal regions of the Mekong Delta would be approximately 40 cm higher than the values under the baseline scenario as a result of the combination of climate change, sea-level rise, upstream hydropower development, land subsidence, and changes in flood control infrastructure. These authors also indicated potential damage of up to 223.0 million USD to rice production. Unfortunately, the paper lacks supplementary tables to confirm details. Nguyen et al. (2014) pointed out that 3-m floods under the sea level rise scenario of +50 cm would threaten striped catfish farms in An Giang and Dong Thap provinces and Can Tho City. Increased salinity would also affect catfish farms in Ben Tre and Tra Vinh provinces, but the effects would be local and relatively minor.

Climate change also increases the temperature and affects rainfall patterns and intensity, all of which significantly impact ecosystem structure, function and services. Even though temperature rise is projected to be smaller in the tropics than at higher latitudes (IPCC, 2021), tropical terrestrial and aquatic ectotherms (cold-blooded species) are nonetheless more susceptible to mild temperature increases than higher-latitude species (Tewksbury et al., 2008), and may therefore incur substantial negative impacts by warming. Coral bleaching is known to occur at only 1-2℃ above the historical mean summer maximum sea temperature (Baird et al., 2009).

Elevated temperature (27-33℃) and CO_2 (7-21 mmHg), when applied alone or combined, had no significant effect on the physiology and growth of striped catfish (Do et al., 2021). Growth of juvenile black tiger shrimp showed the highest rate at 32℃ and a slightly lower rate at higher (34℃) and lower (20-30℃) temperatures (Deering & Fielder, 1995). The growth of white-leg shrimp was also strongly affected by temperature, but the effect varied among size classes. The optimum temperature for the shrimp weighing > 10 g body weight is about 27℃ (Wyban et al., 1995). Even though there is huge literature on the effect of ocean acidification, i.e., a decrease of seawater pH by increasing CO_2 concentration, on marine organisms (Doney et al., 2020), this has been little investigated for aquaculture species of Vietnam.

2.2. Mangrove loss

Mangrove forests play an important role in protecting the coasts from erosion and extreme weather, creating nursing grounds and habitats for coastal animals, and providing timber, fuel wood, and salt. Furthermore, mangrove forests play a vital role in carbon storage (Veettil et al., 2019). Mangroves in Vietnam protect 8 million people from flooding, and the value of property protected by mangroves ranked fifth in a global list (Losada et al., 2018). Although Vietnam has conducted extensive mangrove reforestation since 1975 (Veettil et al., 2019), mangrove-forest conservation and restoration remain crucial to the country.

The mangrove forests along the coasts of the Mekong Delta have suffered significant areal reductions during the last several decades. A recent remote sensing study estimated that the mangrove area in the Mekong Delta decreased from 185,800 ha in 1973 to 89,650 ha in 2010, but then increased to 102,160 ha in 2020 (Figure 3; Phan & Stive, 2022). They concluded that shrimp farming was the major driver of the reduction, with a lesser contribution by rice production and coastal erosion. Other studies also identified aquacul-

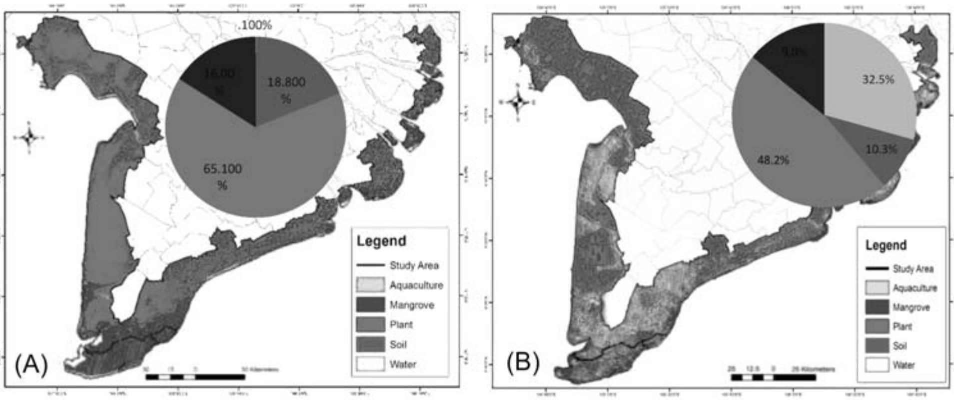

Figure 3. Changes in mangrove areas (dark gray) in the Mekong Delta in 1973 (A) and 2020 (B). Reproduced from Phan and Stive (2022) with permission. The pie graphs show relative coverage. The color version of this figure is available at: https://www.sciencedirect.com/science/article/pii/S0964569121004968#fig5

ture as a principal threat to mangrove systems in Vietnam（e.g., Binh et al., 2005; Orchard et al., 2015）. Phan & Stive（2022）pointed out that reforestation decisions for protection, improvement of forest areas, and the creation of 5 million ha of forests along the country have contributed to the recent increase in mangrove area. Among coastal provinces of the Mekong Delta, Ca Mau province has had the largest area of mangroves throughout the study period（129,660 ha in 1973; 68,110 ha in 2020, Phan & Stive, 2022）. Son et al.（2015）demonstrated that the mangrove forests in the southern Ca Mau Peninsula declined from 112,035 ha in 1979 to 43,810 ha in 2013.

The Ministry of Agriculture and Rural Development listed five major causes of mangrove loss in Vietnam:（1）conversion of land from mangrove to aquaculture production;（2）storms, waves, and natural disasters;（3）over-extraction of timber, fuel-wood, and natural resources;（4）environmental pollution caused by chemical residues from agricultural production and wastes; and（5）weak regulatory mechanisms that cannot mobilize local communities and households to protect and sustainably develop mangrove areas（Hawkins et al., 2010）.

2.3. Plastic litter

Plastic litter has rapidly become a global concern, which poses another significant threat to the environment and human health. Reflecting such recognition, the number of publications on this issue has exponentially increased during the last decade（Li et al., 2021）. Lebreton et al.（2017）estimated that the Mekong River discharges a range of 18,800 to 37,600 tons of plastic into the ocean each year. Jambeck et al.（2015）estimated the mass of plastic waste entering the ocean from the coastal populations of whole Vietnam as 280,000 to 730,000 tons/year, ranked fourth in the global list. In addition, Salhofer et al.（2021）reported on plastic recycling practices in Vietnam, and stressed an urgent need to improve recycling technologies and processes to reduce risks to human health and the environment.

A recent study demonstrated that macroplastic debris from the bottom of both the Hau and Tien Rivers amounts to 10-20 g 100m^{-2} in the majority of sampling sites, but the value as high as 923 g 100 m^{-2} was recorded from the samples collected in Can Tho and Vinh Long during a low-water period（Figure 4, Karpova et al., 2022）. During the monsoon floods, the values lowered, suggesting partial flushing of the bottom plastic debris into the ocean. Karpova et al.（2022）attempted to correlate fish and decapod abundance with the amount of bottom plastic debris, but no clear picture emerged.

Mangrove forests act as traps for marine litter, particularly pneumatophores, special-

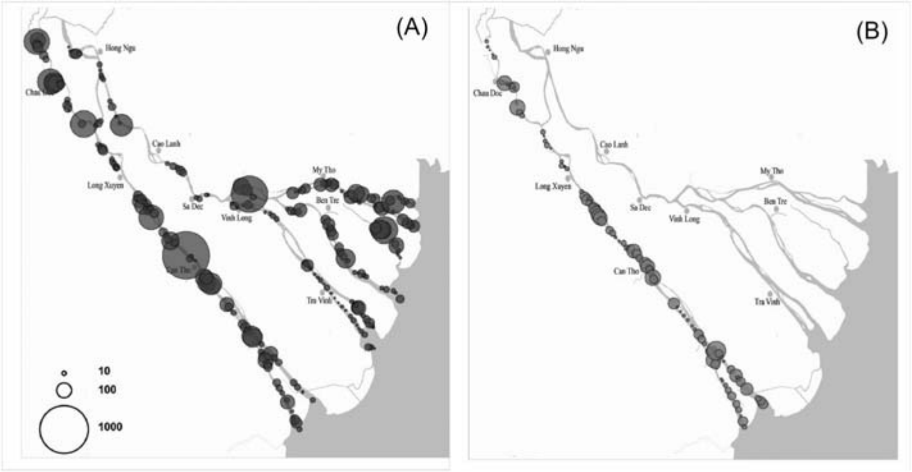

Figure 4 . Plastic litters collected from the bottom of the Hau and Tien Rivers (g 100 m^{-1}) during low-water (A) and flood (B) periods. The Hau River is one of the two major distributaries of the Mekong River, running to the west of the Tien River. The Tien River further divides into four distributaries before flowing into the South China Sea (or East Sea, see also Fig. 2). Reproduced from Karpova et al. (2022) with permission.

ized aerial respiratory roots sticking up out of the soil, retaining large plastic objects (Martin et al., 2019). Larger plastic objects are degraded through weathering and other physical, chemical and biological actions to the formation of smaller particles, referred to as microplastics (diameter/size < 5 mm). Microplastics will settle down and accumulate in sediments (Deng et al., 2020). Utsunomiya et al. have conducted a preliminary survey on the plastic debris in the mangrove forests near the river mouth of the Hau River and found that 70% of coastal litter consisted of plastic bags and their fragments. The weight of plastic wastes collected from the mudflat surface in those areas amounted to 300 kg km^{-2} (Utsunomiya et al., unpublished data).

Microplastics will be ingested by marine benthos such as bivalves, gastropods and crustaceans (Hasbudin et al., 2022) and also by fish (Wootton et al., 2021). There is increasing evidence that the ingestion of microplastics has adverse effects on the health of aquatic animals (Vázquez-Rowe et al., 2021). Microplastics are prone to adsorb other chemicals like heavy metals and trace micropollutants, possibly serving as carriers of these chemicals (Deng et al., 2020).

2.4. Water pollution

The Mekong Delta is also suffering from a huge load of waste from agriculture, aquaculture, and domestic and industrial activities, causing serious problems, especially of the water and soil quality. Wilbers et al.（2014）pointed out that major sources of water pollution in the Mekong Delta are（1）acid soil, which increases the mobility of toxic metals, potentially affecting crop production, aquatic organisms and drinking water sources,（2）aquaculture, which causes high levels of chemical and biochemical oxygen demand and nutrients as a result of the applied fish feed, and（3）urbanization. Impacts of urbanization on the water quality have been reported in other countries like the US and China, but not much data are available for the Mekong Delta. Wilbers et al.（2014）found concentrations higher than the Vietnamese drinking water guidelines in As in 11％ and 14％ of water samples collected from the secondary canals of Can Tho City and Hau Giang province, and Soc Trang province, respectively; Hg in 67％ and 72％, Mn in 49％ and 72％, Al in 99％ and 96％, and Fe in 100％ and 100％. Of these, 11-14％（CT-HG）and 96-100％（ST）of samples were higher than the As and Fe levels defined in the Vietnamese domestic water quality guidelines. Even more striking were the high cell counts of *Escherichia coli* and other coliforms, which were detected in all water samples from the sampling sites of Can Tho（18 locations）and Hau Giang（9）province, and 80-100％ of the samples from Soc Trang sampling sites（5）. The high cell counts are likely caused by untreated sewage water discharged directly to rivers and canals, and by livestock farms. River water generally showed lower concentrations, yet Hg, Al and Fe levels, microbial indicators（*E. coli* and other coliforms）and turbidity were higher than the values in the drinking and domestic water guidelines.

2.5. Food safety

Even though the Mekong Delta is a significant food production region, the products from the region have faced several issues that affect its reputation and the economic gain. One of the most concerning problems is the safety of aquaculture products exported from Vietnam. The main reasons for the rejection of Vietnamese foods in importing countries include bacterial contamination and veterinary drug residues. The rejection rate is relatively high for fish and fishery products and fruit and vegetables（UNIDO, 2015）.

Vietnam is ranked one of the top users of antibiotics in aquaculture in the world（Lulijwa et al., 2020）, and striped catfish and shrimp from Vietnam have been rejected repeatedly by importing countries such as the US, the EU, and Japan（Nguyen et al., 2017）. Antibiotics have been detected in the culture environment, sediments and farmed animal tissues, which would potentially affect human, wildlife and environmental health（Lulijwa et al., 2020）.

A recent study demonstrated that the consumption of striped catfish available on the

European market does not pose any concern for the health of consumers（Murk et al., 2018), but the banned substances, including antibiotics, are not permitted as residues in seafood at any level. Even though the quality of striped-catfish fillets exported to developed countries is under strict monitoring, there is a concern about the level of antibiotics and other chemicals in the flesh of striped catfish consumed in Vietnam, which needs to be investigated.

The same concern applies to microbial contamination of domestically sold fish. Luu et al.（2016） found that 42 and 39% of samples from fishing ports and fish markets, respectively, in Khanh Hoa province（south central coastal region of Vietnam), Ba Ria Vung Tau province（southeast region）and Ben Tre province（Mekong Delta), were unacceptable from the microbial standards of Vietnam, mainly due to high levels of coliforms.

3. EMERGING STRATEGIES FOR THE SUSTAINABLE FOOD PRODUCTION OF THE MEKONG DELTA

3.1. Climate and river flow changes

3.1.1 Agriculture

The response strategy in safeguarding agricultural production from climatic hazards needs transformative adaptation measures. Transformative adaptation is fundamental systems' changes that address root causes of vulnerability. These measures are characterized as being restructuring, innovative, path-shifting, multi-scale, system-wide, and persistent（Fedele et al. 2019). Accordingly, the first or lowest level of adaptation is the genetic approach, selecting of climatic stress-tolerant strains species. Further adaptation measures would be developed with increasing salinity impacts, including farming technology improvement, farming system shifts（farm level), and capacity development of farmers and communities（household, community, and value chain levels). For the Mekong Delta, salinity adaptation is considered to be most crucial in agricultural production.

Numerous papers have been published on salinity adaptation, reflecting the already visible serious damage to rice production during the recent events of saltwater intrusion（see 2.1 Climate and river flow change). Intensive breeding programs yield new rice varieties with enhanced salinity tolerance that are suitable for the conditions in the Mekong Delta（Emerick et al., 2016). Applying genome sequencing and screening, Nguyen et al.,（2022） found a promising salinity-tolerant accession among rice landraces. Better use of wild-relative-derived rice lines and appropriate application to participatory varietal evaluation and selection are necessary to expand the genetic base of varieties well-tolerant to climatic stresses and fully meet the goals of farmers (Huynh et al., 2021).

The varietal breeding and selection approach is only at the crop and farm level. Extensive adaptation approaches at the farm and community scale are of great importance (Emerick et al., 2016). Adaptive cropping technologies and alternative farm-economic activities can help farmers better deal with unfavorable climatic and non-climatic conditions (Emerick et al., 2016; Nhan et al., 2020; Paik et al., 2020). Furthermore, at larger and higher levels, building the adaptive capacity of farmer communities, upgrading and/or developing value chains, markets and large-scale infrastructure for increasing resilience of rice commodity and farmer livelihoods are vital long-run strategies (Smajgl et al., 2015; Dang et al., 2020; Tran et al., 2020; Mills et al., 2022).

3.1.2 Aquaculture

Probably due to the less compelling concern over the influence of saltwater intrusion on aquaculture, there have been fewer papers published on potential adaptation measures. De Silva and Nguyen (2011) already pointed out the selective breeding of salt-tolerant strains of striped catfish as a potentially effective countermeasure to saltwater intrusion.

A recent study demonstrated that selective breeding of striped catfish for salinity tolerance could indeed be effective (Dao Minh et al., 2022). The eggs obtained from the second-generation (G2) fish of size-selected, larger individuals that were pre-adapted to 5-10 ppt for three years showed a higher hatching rate and lower embryonic deformity than control under elevated salinities. Larvae and fry of this group showed a higher survival and growth rates in high salinity. Adults of both G1 and G2 size-selected groups kept in 10 ppt to the age of 11 months were larger than the freshwater group of the same age. The fish in the non-selected group showed similar but less pronounced performance at higher salinities than the size-selected fish. This line of study could have great practical importance for sustainable aquaculture production in the Mekong Delta, and should be pursued. Nguyen et al. (2016) reported on the potential candidate genes involved in the salinity adaptation of striped catfish on the basis of transcripts differentially expressed in fish reared in 0 and 15 ppt.

As in the case of rice production, adaptive strategies for aquaculture are necessary at farm and larger scales. The adoption of a recirculating aquaculture system (RAS) can ensure fish production in unfavorable environmental conditions under climate change, and is not associated with adverse environmental impacts such as habitat destruction, water pollution and disease outbreaks（Ahmed & Turchini, 2021）. In contrast, Bohnes et al.（2019）indicated that RAS is related to increased climate change impact（CO_2 emission）and energy demand, based on 65 life cycle analysis studies of aquaculture systems（see 3.4）. The high initial investment is shown to be the major obstacle to adopting RAS（Ngoc et al., 2016）. The choice of suitable RAS type should depend on the type of a farm（hatchery, nursery or grow-out）and its size, and the locality. Fish larvae are in general more vulnerable to environmental perturbations（Pankhurst & Mundy, 2011）and rearing of larvae and juveniles requires a smaller volume of water than that necessary for adults. RAS may therefore be more acceptable in hatchery and nursery farms. For grow-out sectors, the in-pond RAS design equipped with a nitrification reactor and additional devices for sludge separation as described by Ngoc et al.（2016）may be considered. The high initial investment cost might be affordable if farmers form cooperatives.

Farming management strategies can improve technical efficiency through appropriate stocking densities and water exchange rates, and rational input costs（Nguyen et al., 2017）. For coastal shrimp production in Bangladesh, Islam et al.（2019）found that farmers adapt to climatic stresses through better farming management, including increasing pond depths, exchanging tidal water, providing shade using aquatic plants, and strengthening the earthen dike. The authors suggested that polyculture shrimp farming is necessary to improve climate change adaptation and to promote farming. The contrary was found in the coast shrimp production in some cases. Intensive shrimp farming systems appear to be less vulnerable to expected climate change effects relative to less intensive ones with mixed production or lower density rates（Quach et. al., 2017）. Moreover, building the capacity of small-scale farmers and strengthening linkages among actors of shrimp value chains are of great importance under climate change（Kais & Islam, 2018）.

3.2. Mangrove loss

Aquaculture is the most significant driver for the reduction of mangrove forest. The aquaculture sector, however, greatly contributed to the economic growth and poverty alleviation of Vietnam. Thus, we must consider how we can reconcile the benefits that the society receives from aquacultural production, and economic and ecological services of mangrove forests. For example, in Ca Mau province, which has the largest（66.7%）mangrove area in the Mekong Delta（Phan & Stive, 2022）, the mangrove area is divided into three zones with respect to mangrove protection and use: the full protection zone, the buffer zone of mixed mangrove/farming, and the economic zone. In the buffer zone, integrated mangrove-shrimp farming is permitted in which 60% of the land is allocated to mangrove and 40% to shrimp aquaculture (Nair, 2015). Nguyen et al. (2022) reported that the People's Committee of Ca Mau Province recently promulgated a decision No 111/QD-UBND, under which farmers adopting the mangrove-shrimp farming system can receive economic benefits from a higher shrimp price for 'organic shrimps', a premium by using a certificated organic brand, and payment for forest ecosystem services. The mangrove-shrimp farming system has a considerable advantage in protecting mangroves, whereas its inherent low productivity would probably not replace the large shrimp production by intensive and super-intensive systems targeting the international market. Thus, to minimize the footprint of shrimp farming on mangroves, a suitable farming system should be selected in respective farming sites, based on the capital and land available to farmers, surrounding environmental conditions, and social settings. Both traditional extensive shrimp farming and industrialized intensive shrimp farming also occur in Ca Mau province (Nguyen et al., 2022). It also probably benefits farmers, particularly small-scale ones, to form cooperatives in case they choose intensive or super-intensive systems (Nguyen et al., 2019).

Vietnam has undertaken a variety of mangrove restoration initiatives. However, it is often challenging to evaluate the survival rates of planted trees, which vary from 30 to 50% for the majority of observed programs (Hai et al., 2020). This low success rate stems from insufficient understanding of the factors hindering natural regeneration opportunities, inappropriate selection of restoration sites and species, a lack of incentives to encourage local communities for management. Thorough planning and long-term monitoring are critical for the success of mangrove restoration (Bosire et al., 2008; Hai et al., 2020).

Mudskippers, amphibious gobies of the subfamily Oxudercinae, have been used as indicator species of the health of mangrove areas (Polidoro, 2017). Studies of mudskipper biology may contribute to diagnosing the health of mangrove ecosystems in the Mekong Delta.

3.3. Plastic litter

A multi-faceted, comprehensive approach is indispensable to tackle the problem of plastic pollution, as in other environmental issues. Yet, the legal framework on the plastic waste issue has not been adequately formulated (Nguyen & Chu, 2019; Nguyen, 2020). The amount of newly discarded plastic debris both on the land and in the sea must be reduced. Furthermore, already existing plastic materials in the environment must also be collected and properly treated.

To the best of our knowledge about the plastic contamination of aquatic animals in Vietnam, there is only one paper dealing with the microplastic content of marine animals（Phuong et al., 2019）. They detected microplastic particles（2.6 ± 1.1 particles per individual）in the green mussel（*Perca viridis*）sampled from the northern coast of Vietnam（Thanh Hoa province）. No data are available on the plastic content of any aquatic animals from the Mekong Delta coast. Since the Mekong River ranks among the top 20 rivers of plastic discharge into the oceans（Lebreton et al., 2017）, freshwater and coastal animals probably contain plastic materials in their tissues. The two main aquaculture products of the Mekong Delta are produced either along the freshwater reaches of the Hau and Tien Rivers（striped catfish, Phan et al., 2009）or along the provinces on the coast of the Mekong Delta that are strongly affected by river discharge（shrimp, General Statistics Office, 2021）. Thus, both of them, together with products of capture fisheries from the region, need to be investigated for their plastic contents. Ma et al.（2020）reported high levels of microplastics in aquaculture ponds in China. Ingestion of microplastics has been shown to have negative effects on aquaculture animals from larval to adult stages（Vázquez-Rowe et al., 2021）, yet the effect of microplastics on human health remains unclear（Wu et al., 2022）.

3.4. Water pollution

To assess environmental impacts of a product, process or activity throughout its lifetime, a technique called life cycle assessment（LCA）has been used in a wide range of industries and sectors（ISO 2006a,b）, including agriculture（e.g., Roy et al., 2009）and aquaculture（e.g., Bohnes et al., 2019）worldwide. LCA has been applied to the two major aquaculture production systems in the Mekong Delta, i.e., striped catfish（Bosma et al., 2011; Kluts et al., 2012; Nhu et al., 2016）and shrimp（Jonell and Henriksson, 2015; Järviö et al., 2018）farming. Impact categories commonly assessed in LCA for aquaculture include those related to water pollution（water eutrophication and acidification）and factors related to climate change（CO_2 emission and energy demand）.

With regard to reducing pollution by aquaculture activities, Cassou et al.（2017）stated "Market incentives have seemingly done more to motivate farmers, and those seeking certification under the Good Agriculture Practices in Vietnam（VietGAP, see also 3.5 Food safety）, GLOBALG.A.P., Aquaculture Stewardship Council（ASC）, and eco-labels seem to demonstrate better environmental management". LCA provides a scientific basis for analyzing system improvement and the development of certification and eco-labelling criteria.

3.5. Food safety

Nguyen-Viet et al. (2017) pointed out that two key issues of food safety in Vietnam are the lack of ethics of stakeholders and the lack of motivating factors to reduce unethical behaviors. These authors also stressed that approaches with empowering and encouraging stakeholders to self-regulation are more effective than those with inspection and punishment, as having them to realize that the self-regulation is more profitable in the long run.

One strategy to deal with food safety issues is the application of aquaculture guidelines under certification systems such as VietGAP, aiming at farming of safe and hygienic products; reducing disease and pollution; and promoting animal health, social responsibilities, and as the traceability of products (Nguyen et al., 2020). However, based on the survey data by Nguyen et al. (2020), only 33% of investigated farmers, who engaged in intensive farming of white-leg shrimp in Soc Trang and Ben Tre provinces and applied for the certification, have been awarded officially, because of the high cost of the application and the absence of specific premium of GAP products. Meanwhile, 19,000 ha shrimp farms in Ca Mau province (of a total of 280,000 ha, from intensive to mangrove-shrimp farms) have been granted international and national standard certificates such as GlobalGAP and Global ASC for increasing shrimp export as well as VietGAP. The province is also tightening regulations on the use of Ca Mau geographical indication for black tiger shrimp to protect shrimp breeders and consumers (Viet Nam News, 2022).

Binh et al. (2018) stressed the importance of antibiotic resistance issues and pointed out the lack of a good system of wastewater treatment as the main driver to increase the risk. Because of the cost involved in installing such systems around the country, they recommended building better wastewater treatment systems for main point sources such as hospitals and pharmaceutical manufacturing factories. On the other hand, Luu et al. (2021) indicated the importance of information dissemination by the government for the proper use of antibiotics and the monitoring and managing of the quality of veterinary medicine in the market.

4. LESSONS LEARNED FROM EXPERIENCES IN THE CITY OF KITAKYUSHU, JAPAN

The City of Kitakyushu, located in the northern part of the Kyushu Island, Japan, used to suffer severe environmental pollution due to heavy industry. In the 1960's, the air in the city ranked as the worst in Japan, recording the average monthly amount of fall dust of 80 tons km^{-2} month^{-1} (max. 108 tons km^{-2} month^{-1}, Figure 5A: note that Figure 5A does not include those extremely high values in the earlier years of 1960's). In 1960, the City issued a smog warning, for the very first time in Japanese history. The Dokai Bay located in the center of the city was heavily polluted by wastewater discharge from factories and households. The 1969 survey reported a dissolved oxygen concentration of 0.6 mg L^{-1}, and chemical oxygen demand (COD) of 48.4 mg L^{-1} (Figure 5B: note that this extremely high COD value was recorded in a sampling site not covered in Figure 5B). The Dokai Bay was called the "Sea of Death", where even *Escherichia coli* bacteria were unable to survive.

It was the mothers who worried about the health of their children and took initiative to call for mitigation measures against pollution. Citizen's campaign and press reports then helped enhance social awareness about the pollution ("Kogai" in Japanese, literally means public hazard), and triggered the enforcement of mitigation measures against pol-

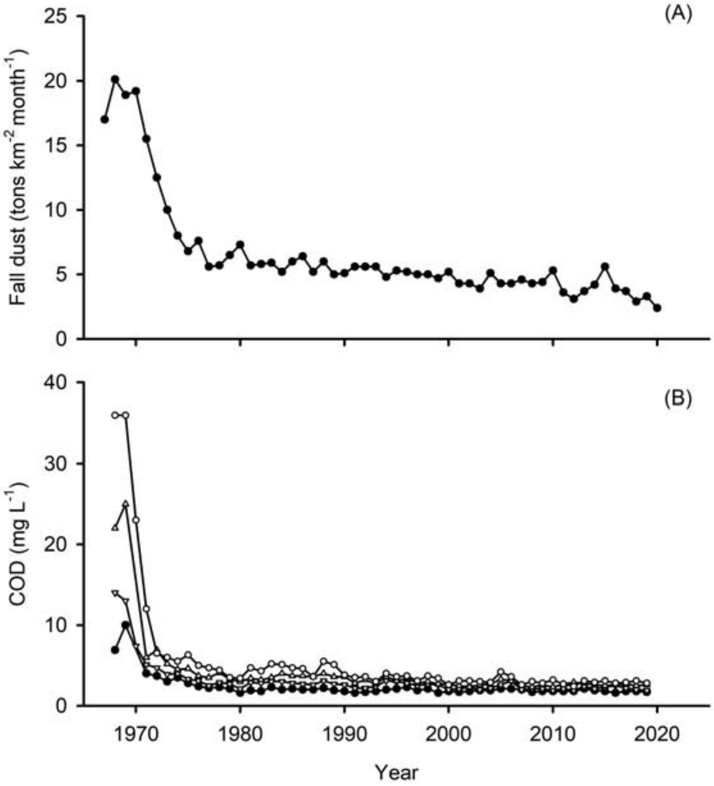

Figure 5. Yearly changes in aerial fall dust (A) and chemical oxygen demand (COD) of the water in the Dokai Bay (B) in the City of Kitakyushu, Japan. Plots with different symbols in (B) indicate data from different sampling sites. This figure is produced using original data offered by the City of Kitakyushu.

lution by the central and local governments and industries.

Technological development not only reduced environmental impacts but also enhanced productivity. Factories actively improved production procedures, installed facilities for treating wastes and removing pollutants, assessing and selecting feedstock, performing thorough control of maintenance and operation, and planted trees for green development. The City of Kitakyushu, on the other hand, implemented a wide range of environmental measures, such as setting up environmental monitoring centers, establishing financial measures and regulatory systems necessary to promote pollution control, concluding “pollution control agreements” with industry to supplement legislative constraints, improving sewers and green spaces, building waste incinerators and disposal sites, and effecting relief of victims by “Kogai”. The City conducted large-scale dredging of the Dokai Bay to remove sediment contaminated by mercury and other pollutants.

As the result of these environmental countermeasures, enforced through the collaboration of industries and local government, the environment of the City of Kitakyushu has been dramatically ameliorated. In fact, it is impressive to see how rapidly the levels of contaminants both in the air（Figure 5A）and sea（Figure 5B）declined once the countermeasures were taken in a full-scale operation. The City was selected as one of the cities with starry sky by the Ministry of Environment, Japan in 1987. The Dokai Bay now nurtures over 100 species of fish and other organisms, and has become a wintering site of many migrating birds（this section has been translated from Japanese in the website of the City of Kitakyushu, https://www.city.kitakyushu.lg.jp/kurashi/menu01_0448.html by AI）.

5. CONCLUSIONS

The threats that the Mekong Delta is facing with are complex and ramified: if the land over the Mekong Delta is going to be inundated as projected by even less severe scenarios, there would be huge, detrimental impacts on the society, industry and nature, which will require extensive collaboration between the public, government, private sectors, and academia. We must make coordinating use of emerging and traditional countermeasures in technical, socioeconomical and legitimate fields, and adopt different measures for different localities to optimize outcomes. Biodiversity, a phenomenal yet fragile wealth of the Mekong Dela, must be conserved for its own value and as a genetic resource for food production. The example of the City of Kitakyushu proves that pollution and other environment deteriorations can be rapidly and remarkably ameliorated through concerted efforts by the government, private sectors, and academia.

In March 2021, Can Tho University launched the comprehensive forum, the Sustainable Development of the Mekong Delta 2045 (SDMD 2045), creating a platform where relevant stakeholders to address, propose solutions and act regarding various issues of the sustainable development of the Mekong Delta. The forum also offers opportunities for continued education for those who are willing to attain respective goals in relevant fields. Such a forum will hopefully contribute to harmonizing the environmental protection and economic development of the Mekong Delta.

ACKNOWLEDGMENTS

We thank Dr. Dang Kieu Nhan, Mekong Delta Development Institute, Can Tho University and Dr. Van Pham Dang Tri, Institute of Climate Change Research, Can Tho University, and Dr. Vo Quoc Tuan, College of Environment and Natural Resources, Can Tho University, for their comments to an earlier version of the manuscript. We also thank the Ministry of Natural Resources and Environment of the Social Republic of Vietnam for the use of Figure 1. We are grateful to the City of Kitakyushu, Japan for providing us the original data used for Figure 5.

This study was funded in part by the Technical Cooperation Project "Science-based Integrated Collaboration towards Sustainable Development of the Mekong Delta Region under Climate Change" of the Japan International Cooperation Agency (JICA). We are also partly supported by the JSPS Grants-in-Aid for Scientific Research (No. 21K01653).

REFERENCES

Ahlberg, P. E. (2019). Follow the footprints and mind the gaps: A new look at the origin of tetrapods. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, *109* (1-2), 115-137. doi.org/10.1017/S1755691018000695

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production*, *297*, 126604. doi.org/10.1016/j.jclepro.2021.126604

Baird, A. H., Bhagooli, R., Ralph, P. J., & Takahashi, S. (2009). Coral bleaching: The role of the host. *Trends in Ecology & Evolution*, *24* (1), 16-20. doi.org/10.1016/j.tree.2008.09.005

Baran, E., Chum, N., Fukushima, M., Hand, T., Hortle, K. G., Jutagate, T., & Kang, B. (2012). Fish biodiversity research in the Mekong Basin. In S.-i. Nakano (Ed.), *The biodiversity observation network in the Asia-Pacific Region: Toward further development of monitoring* (pp. 149-164) : Springer. doi.org/10.1007/978-4-431-54032-8_11

Bayley, M., Damsgaard, C., Nguyen, V. C., Nguyen, T. P., & Do, T. T. H. (2020). Aquaculture of air-breathing fishes. In A. P. Farrell, C. J. Brauner, & T. J. Benfey (Eds.) *Fish physiology, Vol. 38 Aquaculture* (pp. 315-353). Academic Press. doi.org/10.1016/bs.fp.2020.09.005

Binh, V. N., Dang, N., Anh, N. T. K. A., & Thai, P. K. (2018). Antibiotics in the aquatic environment of Vietnam: Sources, concentrations, risk and control strategy. *Chemosphere*, *197*, 438-450. doi.org/10.1016/j.chemosphere.2018.01.061

Binh, T., Vromant, N., Hung, N. T., Hens, L., & Boon, E. (2005). Land cover changes between 1968 and 2003 in Cai Nuoc, Ca Mau peninsula, Vietnam. *Environment, Development and Sustainability*, *7* (4), 519-536. doi.org/10.1007/s10668-004-6001-z

Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2019). Life cycle assessments of aquaculture systems: A critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture*, *11*, 1061-1079. doi.org/ 10.1111/raq.12280

Bosire, J. O., Dahdouh-Guebas, F., Walton, M., Crona, B. I., Lewis III, R. R., Field, C., Kairo, J. G., & Koedam, N. (2008). Functionality of restored mangroves: A review. *Aquatic Botany*, *89*, 251-259. doi.org/10.1016/j.aquabot.2008.03.010

Bosma, R., Pham, T. A., & Potting, J. (2011). Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. *International Journal of Life Cycle Assessment*, *16*, 903-915. doi.org/10.1007/s11367-011-0324-4

Bussi, G., Darby, S. E., Whitehead, P. G., Jin, L., Dadson, S. J., Voepel, H. E., Vasilopoulos, G., Hackney, C. R., Hutton, C., Berchoux, T., Parsons, D. R., & Nicholas, A. (2021). Impact of dams and climate change on suspended sediment flux to the Mekong Delta. *Science of the Total Environment*, *755*, 142468. doi.org/10.1016/j.scitotenv.2020.142468

Campbell, I. (2012). Biodiversity of the Mekong Delta. In F. Renaud & C. Kuenzer (Eds.), *The Mekong Delta system: Interdisciplinary analyses of a river delta* (pp. 293-313). Springer Science + Business Media. doi.org/10.1007/978-94-007-3962-8_11

Cassou, E., Tran, D., Nguyen, T., Dinh, T., Nguyen, C., Cao, B., Jaffee, S., & Ru, J. (2017). *An overview of agricultural pollution in Vietnam: Summary report*. Prepared for the World Bank.

Dang, K. K., Do, T. H., Le, T. H., L., Le, T. T. H., & Pham, T. D. (2020). Impacts of farmers' adaptation to drought and salinity intrusion on rice yield in Vietnam's Mekong Delta. *Journal of Agribusiness in Developing and Emerging Economies*, *11* (1), 27-41. doi.org/10.1108/JADEE-08-2019-0132

Dao, T. A., Thai, V. T., & Nguyen, N. V. (2020). The domestic rice value chain in the Mekong Delta. In C. Cramb (Ed.), *White gold: The commercialisation of rice farming in the Lower Mekong Basin* (pp. 375-395). Palgrave Macmillan. doi.org/10.1007/978-981-15-0998-8_18

Dao Minh, H., Duong, T. Y., Pham, T. L., Bui, M. T., Vo, N. S., Do, T. T. H., Bui, T. B. H., Nguyen, T. N. T., Dang, Q. H., Kestemont, P., Nguyen, P. T., & Farnir, F. (2022). Selective breeding of saline-tolerant striped catfish (*Pangasianodon hypophthalmus*) for sustainable catfish farming in climate vulnerable Mekong Delta, Vietnam. *Aquaculture Reports*, *25*, 101263. doi.org/10.1016/j.aqrep.2022.101263

De Silva, S. S., & Nguyen, T. P. (2011). Striped catfish farming in the Mekong Delta, Vietnam: A tumultuous path to a global success. *Reviews in Aquaculture*, *3*, 45-73. doi.org/10.1111/j.1753-5131.2011.01046.x

Deering, M. J., & Fielder, D. R. (1995). Effects of temperature on growth and protein assimilation in juvenile leader prawn *Penaeus monodon. Journal of the World Aquaculture Society*, *26* (4), 465-468.

Deng, H., He, J., Feng, D., Zhao, Y., Sun, W., Yu, H., & Ge, C. (2020). Microplastics pollution in mangrove ecosystems: A critical review of current knowledge and future directions. *Science of the Total Environment*, *753*, 142041. doi.org/10.1016/j.scitotenv.2020.142041

Do, T. T. H., Chau, H. T. T., Nguyen, T. K. H., Le, T. H. G., Ishimatsu, A. & Nguyen, T. P. (2021). Effects of carbon dioxide (CO2) at different temperatures on physiological parameters and growth in striped catfish (*Pangasianodon hypophthalmus*) juveniles. *Aquaculture*, *534*, 736279. doi.org/10.1016/j.aquaculture.2020.736279

Doney, S. C., Busch, D. S., Cooley, S. R., & Kroeker, K. J. (2020). The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annual Review of Environment and Resources*, *45* (1), 11.1-11.30. doi.org/10.1146/annurev-environ-012320-083019

Emerick, K., de Janvry, A., Sadoulet, E., & Dar, M. H. (2016). Technological innovations, downside risk, and the modernization of agriculture. *American Economic Review*, *106* (6), 1537-1561. doi.org/10.1257/aer.20150474

Ericson, J. P., Vörösmarty, C. J., Dingman, S. L., Ward, L. G., & Meybeck, M. (2006). Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change*, *50* (1-2), 63-82. doi.org/10.1016/j.gloplacha.2005.07.004

Eslami, S., Hoekstra, P., Minderhoud, P. S., Trung, N. N., Hoch, J. M., Sutanudjaja, E. H., Dung, D. D., Tho, T. Q., Voepel, H. E., Woillez, M.-N., & Woillez, M.-N. (2021). Projections of salt intrusion in a mega-delta under climatic and anthropogenic stressors. *Communications Earth & Environment*, *2* (1), 1-11. doi.org/10.1038/s43247-021-00208-5

FAO (2016). *"El Niño" event in Viet Nam－agriculture, food security and livelihood needs assessment in response to drought and salt water intrusion.* Food and Agriculture Organization of the United Nations, Ha Noi.

Fedele, G., Donatti, C. I., Harvey, C. A., Hannah, L., & Hole, D. G. (2019). Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy*, *101*, 116-125. doi.org/10.1016/j.envsci.2019.07.001

General Statistics Office. (2021). *Statistical Yearbook of Viet Nam.*

Hai, N. T., Dell, B., Phuong, V. T., & Harper, R. J. (2020). Towards a more robust approach for the restoration of mangroves in Vietnam. *Annals of Forest Science*, *77*, 18. doi.org/10.1007/s13595-020-0921-0

Hasbudin, H., Harith, M. N., & Idrus, F. A. (2022). A review on microplastic ingestion in marine vertebrates from Southeast Asia. *Songklanakarin Journal of Science and Technology*, *44* (3), 609-618.

Hawkins, S., Phuc, X., Pham, X., Pham, T., Nguyen, D., Chu, V., Brown, S., Dart, P., Robertson, S., Nguyen, V., & McNally, R. (2010). *Roots in the water: Legal frameworks for mangrove PES in Vietnam*. Katoomba Group's Legal Initiative Country Study Series. Forest Trends.

Ho, H. L., Doan, V. B., Park, E., Shrestha, S., Tran, D. D., Vu, H. S., Nguyen, H. T. T., Nguyen, P. M., & Seijger, C. (2021). Intensifying saline water intrusion and drought in the Mekong Delta: From physical evidence to policy outlooks. *Science of the Total Environment*, *757*, 143919. doi.org/10.1016/j.scitotenv.2020.143919

Hortle, K. G. (2009). Fishes of the Mekong－how many species are there? *Catch and Culture*, *15* (2), 4-12.

Hossain, F., Islam, S. M. M., Ashalf-Ud-Doulah, M., Ali, M. S., Islam, M. S., Brown, C., & Shahjahan, M. (2021). Influences of salinity on embryonic and larval development of striped catfish *Pangasianodon hypophthalmus*. *Frontiers in Marine Science*, *8*, 781951. doi.org/ 10.3389/fmars.2021.781951

Huynh, Q. T., Nguyen, H. L., Bjornstad, Å, & Kilian, B. (2021). Participatory selection of CWR-derived salt-tolerant rice lines adapted to the coastal zone of the Mekong Delta. *Crop Science*, *61*, 277-288. doi.org/ 10.1002/csc2.20405

IPCC (2021). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfab, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3-32). Cambridge University Press. doi.org/10.1017/ 9781009157896.001

Ishimatsu, A. (2012). Evolution of cardiorespiratory system in air-breathing fishes. *Aqua-BioScience Monographs*, *5*, 1-28. doi.org/10.5047/absm.2012.00501.0001

Islam, Md. A., Akber, Md. A., Ahmed, M., Rahman, Md. M., & Rahman, M. R. (2019). Climate change adaptations of shrimp farmers: A case study from southwest coastal Bangladesh. *Climate and Development*, *11* (6), 459-468. doi.org/10.1080/17565529.2018.1442807

ISO (2006a). ISO 14040:2006—environmental management—life cycle assessment—principles and framework.

ISO (2006b). ISO 14044:2006—environmental management—life cycle assessment—requirements and guidelines.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, *347* (6223), 768-771. doi.org/10.1126/science.1260352

Järviö, N., Henriksson, P. J. G., & Guinée, J. B. (2018). Including GHG emissions from mangrove forests LULUC in LCA: A case study on shrimp farming in the Mekong Delta, Vietnam. *International Journal of Life Cycle Assessment*, *23*, 1078-1090. doi.org/10.1007/s11367-017-1332-9

Jonell, M., & Henriksson, P. J. G. (2015). Mangrove-shrimp farms in Vietnam-comparing organic and conventional systems using life cycle assessment. *Aquaculture*, *447*, 66-75. doi.org/10.1016/j.aquaculture. 2014.11.001

Kais, S. M., & Islam, Md. S. (2018). Impacts of and resilience to climate change at the bottom of the shrimp commodity chain in Bangladesh: A preliminary investigation. *Aquaculture*, *493*, 406-415. doi.org/10. 1016/j.aquaculture.2017.05.024

Kang, B., & Huang, X. (2022). Mekong fishes: Biogeography, migration, resources, threats, and conservation. *Reviews in Fisheries Science and Aquaculture*, *30* (2), 170-194. doi.org/10.1080/23308249.2021. 1906843

Kantoush, S., Binh, D. V., D., Sumi, T., & Trung, L. V. (2017). Impact of upstream hydropower dams and climate change on hydrodynamics of Vietnamese Mekong Delta. *Journal of Japan Society of Civil Engineering, Ser. B1*, *73* (4), I_109-I_114.

Karpova, E., Abliazov, E., Statkevich, S., & Cu, N. D. (2022). Features of the accumulation of microplastic on the river bottom in the Mekong delta and the impact on fish and decapods. *Environmental Pollution*, *297*, 118747. doi.org/10.1016/j.envpol.2021.118747

Kluts, I. N., Potting, J., Bosma, R. H., Phong, L. T., & Udo, H. M. J. (2012). Environmental comparison of intensive and integrated agriculture-aquaculture systems for striped catfish production in the Mekong Delta, Vietnam, based on two existing case studies using life cycle assessment. *Reviews in Aquaculture*, *4*, 195-208. doi.org/ 10.1111/j.1753-5131.2012.01072.x

Lebreton, L. C., Van Der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, *8*, 15611. doi.org/10.1038/ncomms15611

Li, E., Wang, X., Chen, K., Xu, C., Qin, J. G., & Chen, L. (2017). Physiological change and nutritional requirement of Pacific white shrimp *Litopenaeus vannamei* at low salinity. *Reviews in Aquaculture*, *9* (1), 57-75. doi.org/ 10.1111/raq.12104

Li, L., Zuo, J., Duan, X., Wang, S., Hu, K., & Chang, R. (2021). Impacts and mitigation measures of plastic waste: A critical review. *Environmental Impact Assessment Review*, *90*, 106642. doi.org/10.1016/j.eiar.2021.106642

Losada, I., Menéndez, P., Espejo, A., Torres, S., Díaz-Simal, P., Abad, S., Beck, M. W., Narayan, S., Trespalacios, D., Pfliegner, P., & Kirch, L. (2018). *The global value of mangroves for risk reduction. Technical Report*. The Nature Conservancy, Berlin. doi.org/10.7291/V9DV1H2S

Lulijwa, R., Rupia, E. J., & Alfaro, A. C. (2020). Antibiotic use in aquaculture, policies and regulation, health and environmental risks: A review of the top 15 major producers. *Reviews in Aquaculture*, *12* (2), 640-663. doi.org/ 10.1111/raq.12344

Luu, P. H., Dunne, M. P., Pearce, W., & Davies, B. (2016). Seafood safety compliance with hygiene regulations within Vietnamese domestic distribution chains. *British Food Journal*, *118* (4), 777-794. doi.org/10.1108/BFJ-07-2015-0234

Luu, Q. H., Nguyen, T. B. T., Nguyen, T. L. A., Do, T. T. T., Dao, T. H. T., & Padungtod, P. (2021). Antibiotics use in fish and shrimp farms in Vietnam. *Aquaculture Reports*, *20*, 100711. doi.org/10.1016/j.aqrep.2021.100711

Ly, N. B., Le, N. D. D., Ngo, T. P. D., Duong, T. P. L., Nguyen, N. M., & Doan, D. C. P. (2013). *MACBETH project report－overview and situation of vegetable production in Vietnam－case study of sweet potato & purple onion*. Can Tho University.

Ma, J., Niu, X., Zhang, D., Lu, L., Ye, X., Deong, W., Li, Y., & Lin, Z. (2020). High levels of microplastic pollution in aquaculture water of fish ponds in the Pearl River Estuary of Guangzhou, China. *Science of the Total Environment*, *744*, 140679. doi.org/10.1016/j.scitotenv.2020.140679

Mai, V. H., Tran, L. X., Dinh, Q. M., Tran, D. D., Murata, M., Sagara, H., Yamada, A., Shirai, K., & Ishimatsu, A. (2019). Land invasion by the mudskipper, *Periophthalmodon septemradiatus*, in fresh and saline waters of the Mekong River. *Scientific Reports*, *9* (1), 14227. doi.org/10.1038/s41598-019-50799-5

Mandal, S. C., Kadir, S., & Hossain, A. (2020). Effects of salinity on the growth, survival and proximate composition of pangas, *Pangasius hypophthalmus*. *Bangladesh Journal of Zoology*, *48* (1), 141-149. doi.org/10.3329/bjz.v48i1.47883

Martin, C., Almahasheer, H., & Duarte, C. M. (2019). Mangrove forests as traps for marine litter. *Environmental Pollution*, *247*, 499-508. doi.org/10.1016/j.envpol.2019.01.067

Mills, B., Le, D. P., Ta, D. P., Nhu, L., Vo, D. T., & Labarta, R. (2022). Intensive and extensive rice farm adaptations in salinity-prone areas of the Mekong Delta. *Climate and Development*, *15* (2), 162-176. doi.org/10.1080/17565529.2022.2072800

MONRE (2016). *Climate change and sea level rise scenarios for Viet Nam*. Ministry of Natural Resources and Environment, Vietnam.

MONRE (2021). *Kịch bản biến đổi khí hậu (Bản tóm tắt)*. Ministry of Natural Resources and Environment, Vietnam.

Murk, A. J., Rietjens, I. M., & Bush, S. R. (2018). Perceived versus real toxicological safety of striped catfish: A review modifying market perspectives. *Reviews in Aquaculture*, *10* (1), 123-134. doi.org/10.1111/raq.12151

Nair, S. (2015). Shrimp aquaculture in Ca Mau, Vietnam. In S. J. Scherr, K. Mankad, S. Jaffee, & C. Negra (Eds.), *Steps toward green: Policy responses to the environmental footprint of commodity agriculture in East and Southeast Asia* (pp. 123-142). EcoAgriculture Partners and the World Bank.

Ngoc, P. T. A., Meuwissen, M. P. M., Le, T. C., Bosma, R. H., Verreth, J., & Lansink, A. O. (2016). Adoption of recirculating aquaculture systems in large pangasius farms: A choice experiment. *Aquaculture*, *460*, 90-97. doi.org/10.1016/j.aquaculture.2016.03.055

Nguyen, T. X. S. (2020). Policy on marine plastic waste in ASEAN and Viet Nam. *Environmental Claims Journal*, *33* (1), 41-53. doi.org/10.1080/10406026.2020.1775347

Nguyen, V. T., & Chu, B. (2019). Plastic marine debris: Sources, impacts and management. *International Journal of Environmental Studies*, *76* (6), 953-973.

Nguyen, A. L., Dang, V. H., Bosma, R., Verreth, J. A. J., Leemans, R., & De Silva, S. S. (2014). Simulated impacts of climate change on current farming locations of striped catfish (*Pangasianodon hypophthalmus*; Sauvage) in the Mekong Delta, Vietnam. *Ambio*, *43*, 1059-1068. doi.org/10.1007/s13280-014-0519-6

Nguyen, T. V., Jung, H., Nguyen, T. M., Hurwood, D., & Mather, P. (2016). Evaluation of potential candidate genes involved in salinity tolerance in striped catfish (*Pangasianodon hypophthalmus*) using an RNA-Seq approach. *Marine Genomics*, *25*, 75-88. doi.org/10.1016/j.margen.2015.11.010

Nguyen, H. T. K., Phan, T. T. H., Tran, T. N. T., & Lebailly, P. (2017). Vietnam's fisheries and aquaculture development's policy: Are exports performance targets sustainable? *Oceanography and Fisheries Open Access Journal*, *5* (4), 555667. doi.org/10.19080/OFOAJ.2017.05.555667

Nguyen, L. A., Pham, T. B. V., Bosma, R., Verreth, J., Leemans, De Silva, S., & Lansink, A. O. (2017). Impact of climate change on the technical efficiency of striped catfish, *Pangasianodon hypophthalmus*, farming in the Mekong Delta, Vietnam. *Journal of the World Aquaculture Society*, *49* (3), 570-581. doi.org/10.1111/jwas.12488

Nguyen, T. A. T., Nguyen, K. A. T., & Jolly, C. (2019). Is super-intensification the solution to shrimp production and export sustainability? *Sustainability*, *11*, 5277. doi.org/10.3390/su11195277

Nguyen, T. K. Q., Huynh, V. H., Le, N. G. K., Yagi, N., & Riple, A. K. L. (2020). Quality management practices of intensive whiteleg shrimp (*Litopenaeus vannamei*) farming: A study of the Mekong Delta, Vietnam. *Sustainability*, *12*, 4520. doi.org/10.3390/su12114520

Nguyen, V. K. Y., Nguyen, V. D., Long, P. H., Nguyen, L. D., Dung, D. T., Tran, T. A., Kummu, M., Merz, B., & Apel, H. (2020). Future projections of flood dynamics in the Vietnamese Mekong Delta. *Science of the Total Environment*, *742*, 140596. doi.org/10.1016/j.scitotenv.2020.140596

Nguyen, T. K. H., Nguyen, T. E., Nguyen, M. N., Takagi, Y., Nguyen, T. P., & Do, T. T. H. (2021). Effects of salinity on growth performance, survival rate, digestive enzyme activities and physiological parameters of striped catfish (*Pangasianodon hypophthalmus*) at larval stage. *Can Tho University Journal of Science*, *13* (*Special issue on Aquaculture and Fisheries*), 1-9. doi.org/10.22144/ctu.jen.2021.011

Nguyen, H., Chu, L., Harper, R. J., Dell, B., & Hoang, H. (2022). Mangrove-shrimp farming: A triple-win approach for communities in the Mekong River Delta. *Ocean and Coastal Management*, *221*, 106082. doi.org/10.1016/j.ocecoaman.2022.106082

Nguyen, T. T., Dwiyanti, M. S., Sakaguchi, S., Koide, Y., Le, D. V., Watanabe, T., & Kishima, Y. (2022). Identification of a *Saltol*-independent salinity tolerance polymorphism in rice Mekong Delta landraces and characterization of a promising line, Doc Phung. *Rice 15*, 65. doi.org/10.1186/s12284-022-00613-0

Nguyen-Viet, H., Tuyet-Hanh, T. T., Unger, F., Dang-Xuan, S., & Grace, D. (2017). Food safety in Vietnam: Where we are at and what we can learn from international experiences. *Infectious Diseases of Poverty*, *6*, 39. doi.org/ 10.1186/s40249-017-0249-7

Nhan, D. K., Tran, H. P., Tran, V. D., Dang, D. N., & Heng, L. K. (2020). Soil salinity management for rice production in the Mekong River Delta, Vietnam. In: *Landscape salinity and water management for improving agricultural productivity* (IAEA-TECDOC-1916, pp. 166 -177). Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

Nhu, T. T., Schaubroeck, T., Henriksson, P. J. G., Bosma, R., Sorgeloos, P., & Dewulf, J. (2016). Environmental impact of non-certified versus certified (ASC) intensive Pangasius aquaculture in Vietnam, a comparison based on a statistically supported LCA. *Environmental Pollution*, *219*, 156-165. doi.org/10.1016/j.envpol.2016.10.006

Orchard, S. E., Stringer, L. C., & Quinn, C. H. (2015). Impacts of aquaculture on social networks in the mangrove systems of northern Vietnam. *Ocean & Coastal Management*, *114*, 1-10. doi.org/10.1016/j.ocecoaman.2015.05.019

Paik, S. Y., Le, D. T. P., Nhu, L. T., & Mills, B. F. (2020) Salt-tolerant rice variety adoption in the Mekong River Delta: Farmer adaptation to sea-level rise. *PLoS ONE 15* (3), e0229464. doi.org/10.1371/journal.pone.0229464

Pankhurst, N. W., & Mundy, P. L. (2011). Effects of climate change on fish reproduction and early history stages. *Marine and Freshwater Research*, *62*, 1015-1026. doi.org/10.1071/MF10269

Park, E., Ho, H. L., Doan, V. B., & Kantoush, S. (2022). The worst 2020 saline water intrusion disaster of the past century in the Mekong Delta: Impacts, causes, and management implications. *Ambio*, *51*, 691-699. doi.org/10.1007/s13280-021-01577-z

Phan, M. H., & Stive, M. J. (2022). Managing mangroves and coastal land cover in the Mekong Delta. *Ocean & Coastal Management*, *219*, 106013. doi.org/10.1016/j.ocecoaman.2021.106013

Phan, L. T., Bui, T. M., Nguyen, T. T. T., Gooley, G. J., Ingram, B. A., Nguyen, H. V., Nguyen, P. T., & De

Silva, S. S. (2009). Current status of farming practices of striped catfish, *Pangasianodon hypophthalmus* in the Mekong Delta, Vietnam. *Aquaculture*, *296*, 227-236. doi.org/10.1016/j.aquaculture.2009.08.017

Phuong, N. N., Pham, Q. T., Duong, T. T., Le, T. P. Q., & Amiard, F. (2019). Contamination of microplastic in bivalve: First evaluation in Vietnam. *Vietnam Journal of Earth Science*, *41* (3), 252-258. doi.org/10.15625/0866-7187/41/3/13925

Pokhrel, Y., Shin, S., Lin, Z., Yamazaki, D., & Qi, J. (2018). Potential disruption of flood dynamics in the Lower Mekong River basin due to upstream flow regulation. *Scientific Reports*, *8* (1), 1-13. doi.org/10.1038/s41598-018-35823-4

Polido, B. (2017). Taxa and habitat conservation. In Z. Jaafar & E. O. Murdy (Eds.), *Fishes out of water: Biology and ecology of mudskippers* (pp. 349-367). CRC Press.

Quach, A. V., Murray, F., & Morrison-Saunders, A. (2017). The vulnerability of shrimp farming income to climate change events: A case study in Ca Mau, Vietnam. *International Journal of Climate Change Strategies and Management*, *9* (2), 261-280. doi.org/10.1108/IJCCSM-05-2015-0062

Rahi, M. L., Azad, K. N., Tabassum, M., Irin, H. H., Hossain, K. S., Aziz, D., Moshtaghi, A., & Hurwood, D. A. (2021). Effects of salinity on physiological, biochemical and gene expression parameters of black tiger shrimp (*Penaeus monodon*): Potential for farming in low-salinity environments. *Biology*, *10* (12), 1220. doi.org/10.3390/biology10121220

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., & Shiina, T. (2009). A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering*, *90*, 1-10. doi.org/10.1016/j.jfoodeng.2008.06.016

Rundel, P. (2009). Vegetation in the Mekong Basin. In I. Campbell (Ed.), *The Mekong: Biophysical environment of an international river basin* (pp. 143-160). Academic Press.

Salhofer, S., Jandric, A., Soudachanh, S., Le Xuan, T., & Tran, T. D. (2021). Plastic recycling practices in Vietnam and related hazards for health and the environment. *International Journal of Environmental Research and Public Health*, *18* (8), 4203.

Schneider, P., & Asch, F. (2020). Rice production and food security in Asian mega deltas—a review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change. *Journal of Agronomy and Crop Science*, *206* (4), 491-503. doi.org/10.3390/ijerph18084203

SeafoodSource. (2022, 22 August). *Drought wreaking havoc on Vietnam's pangasius and shrimp farms.* https://www.seafoodsource.com/features/drought-wreaking-havoc-on-vietnam-s-pangasius-and-shrimp-farmers

Smajgl, A., Toan, T.Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., Tri, V. P. D, & Vu, P. T. (2015). Responding to rising sea-levels in the Mekong Delta. *Nature Climate Change* *5*, 167-174. doi.org/10.1038/nclimate2469

Son, N.-T., Chen, C.-F., Chang, N.-B., Chen, C.-R., Chang, L.-Y., & Thanh, B.-X. (2015). Mangrove mapping and change detection in Ca Mau Peninsula, Vietnam, using Landsat data and object-based image analysis. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *8* (2), 503-510. doi.org/10.1109/JSTARS.2014.2360691

Syvitski, J. P., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., & Nicholls, R. (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2* (10), 681-686. doi.org/10.1038/ngeo629

Tewksbury, J. J., Huey, R. B., & Deutsch, C. A. (2008). Putting the heat on tropical animals. *Science*, *320*, 1296-1297. doi.org/ 10.1126/science.1159328

Thorat, B., Bagkar, T., & Raut, S. (2018). Responses of rice under salinity stress: A review. *International Journal of Chemical Studies*, *6* (4), 1441-1447.

Tran, D. D., Shibukawa, K., Nguyen, T. P., Ha, P. H., Tran, X. L., Mai, V. H., & Utsugi, K. (2013). *Fishes of the Mekong Delta, Vietnam*. Can Tho University Publishing House.

Tran, T. A., James, H., & Nhan, D. K. (2020). Effects of social learning on rural farmers' adaptive capacity: Empirical insights from the Vietnamese Mekong Delta. *Society & Natural Resources*, *33* (9), 1053-1072. doi.org/10.1080/08941920.2019.1693677

Uiterwijk, W., & Linh, V. (2017). *Opportunities for Vietnamese fruits and vegetables exports to Europe*. European Trade Policy and Investment Support Project.

UNIDO (2015). Meeting standards, winning markets: Trade standards compliance 2015. United Nations Industrial Development Organization.

United Nations (2020). *Joint Assessment Report, Vietnam: Drought and saltwater intrusion in the Mekong Delta.* United Nations Vietnam, Catholic Relief Services, and Save the Children.

Vázquez-Rowe, I., Ita-Nagy, D., & Kahhat, R. (2021). Microplastics in fisheries and aquaculture: Implications to food sustainability and safety. *Current Opinions in Green and Sustainable Chemistry*, *29*, 100464. doi.org/10.1016/j.cogsc.2021.100464

Veettil, B. K., Ward, R. D., Quang, N. X., Trang, N. T. T., & Giang, T. H. (2019). Mangroves of Vietnam: Historical development, current state of research and future threats. *Estuarine, Coastal and Shelf Science*, *218*, 212-236. doi.org/10.1016/j.ecss.2018.12.021

Vermeulen, J. J., Luu, H. T., Theary, K., & Anker, K. (2019). New species of land snails (Mollusca: Gastropoda: Caenogastropoda and Pulmonata) of the Mekong Delta limestone hills (Cambodia, Vietnam). *Folia Malacologica*, *27* (1), 7-41. doi.org/10.12657/folmal.027.001

Viet Nam News. (2022, August 30). *Cà Mau tightens regulations on use of geographical indication for black tiger shrimp*. https://vietnamnews.vn/society/1085109/ca-mau-tightens-regulations-on-use-of-geographical-indication-for-black-tiger-shrimp.html

Vietnam Association of Seafood Exporters and Producers (2022). *Reports on Vietnam seafood exports in 2021*.

Vietnam Tourism Environment. (2022, July 22). *Mekong Delta teems with plant and animal life*. https://moitruongdulich.vn/en/index.php/item/721

Vu, D., Yamada, T., & Ishidaira, H. (2018). Assessing the impact of sea level rise due to climate change on seawater intrusion in Mekong Delta, Vietnam. *Water Science and Technology*, *77* (6), 1632-1639. doi.org / 10.2166/wst.2018.038

Wilbers, G.-J., Becker, M., Sebesvari, Z., & Renaud, F. G. (2014). Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam. *Science of the Total Environment*, *485-486*, 653-

665. doi.org/10.1016/j.scitotenv.2014.03.049

Wootton, N., Reis-Santos, P., & Gillanders, B. M. (2021). Microplastic in fish－a global synthesis. *Reviews in Fish Biology and Fisheries*, *31*, 753-771. doi.org/10.1007/s11160-021-09684-6

Wu, P., Lin, S., Cao, G., Wu, J., Jin, H., Wang, C., Wong, M. H., Yang, Z., & Cai, Z. (2022). Absorption, distribution, metabolism, excretion and toxicity of microplastics in the human body and health implications. *Journal of Hazardous Materials*, *437*, 129361. doi.org/10.1016/j.jhazmat.2022.129361

WWF (2022, July 17). *Scientists discover 224 new species in the Greater Mekong*. https://www.worldwildlife.org/stories/scientists-discover-224-new-species-in-the-greater-mekong

Wyban, J., Walsh, W. A., & Godin, D. M. (1995). Temperature effects on growth, feeding rate and feed conversion of the Pacific white shrimp（*Panaeus vannamei*）. *Aquaculture*, *138*, 267-279.