

1 **Interacting effects of land-use change and natural hazards on rice agriculture in the Mekong and Red River**  
2 **Deltas in Vietnam**

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9 **Abstract**

10 Vietnam is a major rice producer and much of the rice grown is concentrated in the Red River Delta (RRD) and  
11 the Mekong River Delta (MRD). While the two deltas are highly productive regions, they are vulnerable to  
12 natural hazards and the effects of human induced environmental change. To show that the processes and  
13 issues affecting food security are reinforcing, interdependent and operating at multiple scales, we used a  
14 systems-thinking approach to represent the major linkages between anthropogenic land-use and natural  
15 hazards and elaborate on how the drivers and environmental processes interact and influence rice growing  
16 area, rice yield and rice quality in the two deltas. On a local scale, demand for aquaculture and alternative  
17 crops, urban expansion, dike development, sand mining and groundwater extraction decrease rice production  
18 in the two deltas. Regionally, upstream dam construction impacts rice production in the two deltas despite  
19 being distally situated. Separately, the localized natural hazards that have adversely affected rice production  
20 include droughts, floods and typhoons. Outbreaks of pests and diseases are also common. Climate change  
21 induced sea level rise is a global phenomenon that will affect agricultural productivity. Notably, anthropogenic  
22 developments meant to improve agricultural productivity or increase economic growth can create many  
23 unwanted environmental consequences such as an increase in flooding, saltwater intrusion and land  
24 subsidence, which in turn decreases rice production and quality. In addition, natural hazards may amplify the  
25 problems created by human activities. Our meta-analysis highlights the ways in which a systems-thinking  
26 approach can yield more nuanced perspectives to tackle “wicked” and interrelated environmental challenges.  
27 Given that deltas worldwide are globally significant for food production and are highly stressed and degraded,  
28 a systems-thinking approach can be applied to provide a holistic and contextualized overview of the threats  
29 faced in each location.

30 **Key words:** system dynamics, rice, climate change, food security, Mekong Delta, Red River Delta, Vietnam

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39 **1. Introduction**

40 A delta is defined as a low-lying sedimentary landform located at the mouths of rivers. The mixing of  
41 fresh and saltwater in these sediment-rich land-ocean coastal zones provides fertile land for agricultural  
42 activities to support a large number of people. Besides agriculture, resources in deltas have also been tapped  
43 for fisheries, navigation, trade, forestry, fossil energy production and manufacturing. Unfortunately, deltas are  
44 highly vulnerable to a range of environmental hazards such as typhoons, floods, storm surges, tsunamis,  
45 coastal erosion and seasonal inundations (Syvitski and Saito, 2007). In addition, local human activities, land  
46 subsidence, water stresses and global sea level rise have exacerbated their environmental vulnerability (Day et  
47 al; 2016; Seto, 2011; Tessler et al. 2015). The threats faced by deltas are considered to be “wicked problems”  
48 with no easy solutions to counter them (DeFries and Nagendra, 2017).

49 In this paper, we focus on the Red River Delta (RRD) and the Mekong River Delta (MRD) in Vietnam as these  
50 two deltas are highly populated hubs of agricultural production that are highly vulnerable to environmental  
51 hazards. We use a systems-thinking approach to illustrate some of the “wicked problems” present in the two  
52 deltas in Vietnam and the implications of these anthropogenic and natural hazard drivers on rice agriculture.  
53 Although a variety of crops is cultivated in Vietnam, we focus on rice as it is a staple food for the Vietnamese  
54 (Nguyen et al., 2019b; USDA, 2012) and it is also a key export crop. In 2019, Vietnam exported US\$1.4 billion of  
55 rice and was the fourth largest rice exporter in the world contributing 6.6% of the world’s total rice exports  
56 (Workman, 2020).

57 Many studies have investigated how Vietnam is affected by natural hazards or anthropogenic land-use change  
58 (cf. Howie, 2005; Minderhoud et al., 2018; Nguyen et al., 2019a; Vinh et al., 2014). Several studies go a step  
59 further to examine how changes in anthropogenic land-use have affected rice productivity. For example,  
60 higher prices and rising demand for aquaculture and non-rice products have incentivized farmers to shift away  
61 from rice monoculture to embrace non-rice crops (Hai, 2019; Morton, 2020). In addition, environmental  
62 threats such as worsening saltwater intrusion has limited rice production areas and forced many farmers to  
63 convert their now-unusable rice fields into shrimp ponds (Kotera et al., 2005; Nguyen et al., 2017) or turn to  
64 growing salt tolerant crops such as coconut, mango and sugar cane (Nguyen and Vo, 2017). Urban expansion is  
65 also another key factor that has reduced rice growing areas although agricultural intensification has kept rice  
66 yields high despite shrinking growing areas (Drebold, 2017; Morton, 2020).

67 Meanwhile, the construction of high dikes to mitigate flooding in the Mekong Delta has facilitated triple  
68 cropping of rice and increased yields. However, these high dikes reduce the availability of fertile silt and force  
69 farmers to rely on costly agrochemicals to maintain yields (Chapman and Darby, 2016; Tran and Weger, 2018).  
70 Though there is substantial research on sand mining and upstream dam construction, these non-related  
71 anthropogenic factors are often not linked to agricultural productivity even though reduced sediment  
72 availability and increased channel erosion would have adverse implications on agricultural productivity (Binh et  
73 al., 2020; Park et al., 2020; Jordan et al., 2019)

74 Besides land-use change, rice grown in the RRD and MRD are susceptible to damage from natural hazards such  
75 as typhoons, floods and droughts (Chan et al., 2012; 2015; Grosjean et al., 2016; Terry et al., 2012). Rice crops  
76 can be damaged by strong winds and flooding from heavy rain associated with a typhoon event. Rice damage  
77 is worse if the typhoon occurs during the vulnerable heading or harvesting periods (Masutomi et al., 2012). In  
78 addition, floods can also be caused by heavy monsoonal rains. Notably, moderate levels of freshwater flooding  
79 may be beneficial to agricultural production (Chapman et al., 2016). On the other hand, droughts while  
80 uncommon have caused millions in economic loss, particularly in the agriculture sector (Grosjean et al., 2016).  
81 The most recent 2015-2016 drought affected all the Mekong Delta provinces and caused up to US\$360 million  
82 in damage, of which US\$300 million was agriculture and aquaculture-related damage (Nguyen, 2017).

83 Arias et al. (2019) conceptually integrated local and regional drivers of change to illustrate the factors  
84 contributing to environmental change in the Mekong floodplains. Similarly, Nguyen et al. (2019b) recognized

85 that there are various drivers of change associated with adapting to widespread salinity intrusion in the  
86 Mekong and Red River Deltas and these drivers are constantly interacting with and providing feedback to each  
87 other. On a more technical level, Chapman and Darby (2016) used system dynamics modelling to simulate the  
88 delays, feedbacks and tipping points between farmers' socioeconomic status and the practice of double or  
89 triple cropping in An Giang province in the MRD. Building on the framework provided by these studies, we use  
90 systems-thinking to present an overarching picture of how anthropogenic and natural hazard drivers can  
91 interact to reinforce or diminish rice production. While many studies may have highlighted the links between  
92 the various drivers and rice production, we seek to integrate the different drivers of anthropogenic change and  
93 natural hazards to show their inter-related and interdependent nature and how the processes associated with  
94 each driver affects rice growing areas, rice production and rice quality in general.

95 The use of systems-thinking is appropriate as the "wicked" environmental problems present in the deltas of  
96 Vietnam are caused by a range of interdependent anthropogenic and natural hazards drivers operating at  
97 multiple scales with no easily identifiable, predefined solutions. While interventions may be made to  
98 ameliorate problems, these interventions may create feedbacks and unanticipated outcomes (Rittel and  
99 Webber, 1973; DeFries and Nagendra, 2017). In addition, systems-thinking can be applied in a range of  
100 contexts and at multiple scales. Geist and Lambin (2002) and Lim et al. (2017) applied a system-dynamics  
101 approach to understand drivers of deforestation and forest degradation at the national and global scales while  
102 Ziegler et al. (2016) used a transdisciplinary learning approach to understand the role of environmental and  
103 cultural factors in driving the development of human diseases in Northeast Thailand at the landscape scale.

104 Our aim is to use a literature review to develop flow diagrams to represent the major linkages between  
105 anthropogenic land-use factors and natural hazards and elaborate on how they interact and influence rice  
106 productivity in these two deltas. Due to the importance of Vietnam as a major rice producer and exporter in  
107 Southeast Asia, as well as the range of threats faced by the rice sector from natural hazards and anthropogenic  
108 land-use, we hope to show how the processes and issues affecting food security are not one dimensional and  
109 linear but in fact reinforcing and interdependent. Lastly, given that deltas worldwide are globally significant for  
110 food production and are highly stressed and degraded landscapes, we argue that a systems-thinking approach  
111 can be applied to provide a holistic and contextualized overview of the threats faced in each location.

## 112 **2. Methods**

### 113 **2.1. Study sites**

114 The Mekong River Delta (MRD) is the world's third largest delta with a physical area of 4 million ha  
115 and it is the larger of the two deltas in Vietnam (Schneider and Asch, 2020; Figure 1). In 2018, the planted area  
116 for spring, autumn and winter paddies was 1,573.5 thousand ha, 2,336.5 thousand ha and 197.2 thousand ha  
117 respectively. In total, 4.1 million ha of rice was planted over the three planting seasons with 24,507 thousand  
118 tons of rice produced. The delta is home to 17.8 million people with many dependent on agriculture for their  
119 livelihoods. That 54% of Vietnam's rice is grown in the MRD and most of it is exported overseas makes it  
120 strategically important for the Vietnamese economy and for global food security (Chapman et al., 2016;  
121 Cosslett and Cosslett, 2018; General Statistics Office of Vietnam, 2020). Up north, the Red River Delta (RRD) is  
122 the next largest with a physical delta area of 1.5 million ha (Figure 1; Schneider and Asch, 2020). In 2018, 1  
123 million ha of planted rice produced 6,296.1 thousand tons of rice, the equivalent of 14% of Vietnam's total rice  
124 production (524.3 and 516.4 thousand ha of rice was planted in the spring and winter seasons respectively).  
125 Approximately 21.6 million people live in the RRD with many also dependent on agriculture (General Statistics  
126 Office of Vietnam, 2020).

127 Soils in the MRD are highly variable with alluvial, acid sulphate and saline soils dominant. Most of the rice  
128 grows on the highly fertile alluvial soils which are found in only 30% of the delta (GRSP, 2013). Conversely, soils  
129 in the RRD consist of Holocene delta sediments. These Holocene delta sediments are relatively fine-grained

130 muds and sands, up to 30 m thick that are the product of rapid progradation during the Holocene high sea  
131 level stand (Mathers and Zalasiewicz, 1999). The Holocene sequence overlies coarse-grained Pleistocene  
132 sediments dominated by braided river and alluvial fan deposits formed during the last glacial low sea level  
133 stand. The Quaternary sediments are underlain by a >400 m thick layer of Neogene sedimentary rocks that are  
134 made up of conglomerate sandstone, clay and siltstone (Berg et al., 2007).

135 Climatically, the MRD has a tropical monsoon climate with two distinct seasons, a dry season from December  
136 to April and a rainy season from May to November. It is generally warm year round with average temperatures  
137 in 2018 ranging from 26°C in December, January and Feb to 29°C in May. The annual rainfall is between 2,000  
138 to 2,400 mm (General Statistics Office, 2018; Kotera et al., 2008). Conversely, the RRD has a tropical monsoon  
139 climate with three seasons: (1) a hot and wet season from May to September, (2) a cool and dry season from  
140 October to January and (3) a cool and humid season from February to April. The hot and wet season is  
141 characterized by high temperatures and high rainfall, the cool and dry season has moderate to low  
142 temperatures and low rainfall while the cool and humid season has a low to moderate temperatures and low  
143 rainfall (Huong et al., 2013; Li et al., 2006). In 2018, the monthly average temperatures in the RRD ranged from  
144 17°C in Feb to 30°C in June. Average annual rainfall is between 1,300 to 1,800 mm (Li et al., 2016; General  
145 Statistics Office, 2018). Both deltas are low-lying with elevations ranging from 0.7 to 1.2 m above sea level  
146 (Binh et al., 2017).

147 In the MRD, favorable environmental conditions with ample rainfall, tropical temperatures and fertile alluvial  
148 soils, coupled with an extensive dike and irrigation system, have facilitated the production of three rice crops  
149 annually: winter-spring, summer-autumn and autumn-winter (Table 1; Figure 2). In 2018, the summer-autumn  
150 crop was the largest (12,763.7 thousand tons), the winter-spring crop was the second largest (10,833.7  
151 thousand tons), followed by the autumn-winter crop (909.6 thousand tons) (General Statistics Office of  
152 Vietnam, 2020). Compared to the MRD, rice is planted bi-annually in the RRD, first, from February to June  
153 (spring crop) and a second time from July to October (autumn crop) (Table 1; Figure 3). The chilly winters  
154 preclude the cultivation of a third crop of rice. Approximately 3,507 thousand tons of rice were produced  
155 during the spring cropping season while 2,789.1 thousand tons were produced during the autumn season in  
156 2018 (General Statistics Office of Vietnam, 2020).

## 157 **2.2. Literature review and causal loop diagrams**

158 We conducted an online search on Scopus, Web of Science, Google, Google Scholar and individual  
159 journal databases to find articles related to the effects of anthropogenic land-use change and natural hazards  
160 on rice agricultural systems in the RRD and/or MRD. Articles related to the environmental impacts of these  
161 anthropogenic interventions and natural hazards were included as these tend to explain the environmental  
162 processes in detail. A range of literature sources including peer-reviewed journal articles, book chapters and  
163 scientific reports from non-governmental organizations were included. In addition, we reviewed the  
164 bibliographies of our articles to follow up with any other relevant literature that was not listed in our search.  
165 Since sea level rise would affect the viability of the two deltas as major rice producing regions (Mainuddin et  
166 al., 2006), we also included relevant articles on sea level rise.

167 We obtained 126 articles through our literature search (cf. supplementary materials). Every article was  
168 considered to be a single case study and was read in detail by the lead author. Thereafter, the natural or  
169 anthropogenic drivers and/or the environmental process that would lead to a change in rice productivity  
170 directly or indirectly were identified. Adopting a systems-thinking approach, we constructed flow diagrams to  
171 identify and visualize the interconnections among the drivers of rice productivity in both deltas.

172 We first developed causal links which describe how an anthropogenic driver would influence rice productivity  
173 either directly or through an environmental process. We also documented if each driver had an increasing or  
174 decreasing effect on an environmental process that could influence rice productivity by affecting rice growing  
175 area, rice yield or rice quality. This relationship is represented by an arrow which indicates the direction of

176 influence, from cause to effect. The polarity of the arrows (plus or minus) indicates whether the effect is  
177 increasing or decreasing (Lim et al., 2017). A plus sign indicates that a link has “positive polarity” and a minus  
178 sign indicates “negative polarity.” The polarity of the causal link between A and B is said to be positive when an  
179 increase/decrease in A causes B to increase/decrease. A causal link is negative when an increase/decrease in A  
180 causes B to decrease/increase (Newell and Watson, 2002). We constructed two flow diagrams - the first flow  
181 diagram describes how anthropogenic land-use drivers affect rice growing area, rice yield per hectare and rice  
182 quality in the MRD and RRD (Figure 4), while the second causal flow diagram describes how natural hazards in  
183 the MRD and RRD affect rice growing area, rice yield per hectare and rice quality (Figure 6). The references we  
184 used are found in the Supplementary Materials.

### 185 **3. Results**

#### 186 **3.1. Local anthropogenic drivers**

##### 187 **3.1.1. Aquaculture and alternative crops**

188 Both deltas face widespread salinity intrusion that threatens rice production. In the Mekong Delta,  
189 salinity intrusion is a naturally occurring phenomenon during the dry season. Tides from the South China Sea  
190 and the Gulf of Thailand bring saltwater inland and salinity intrudes up to 70-90 km inland as the length of sea  
191 dikes is limited. There are 1,500 km of sea and estuary dikes in RRD versus 450 km of sea dikes in the MRD (Le  
192 et al., 2018; Preston et al., 2003; Pilarczyk and Nguyen, 2005). Thus, salinity intrusion extends up to 20 km  
193 from the main river in the RRD (Ca et al., 1994). As rice plants are unable to thrive in soils with soil salinities  
194 exceeding 4 g/L (Pham et al., 2018b), affected farmers have converted their paddy fields into aquaculture  
195 ponds to cultivate shrimp and fish instead. Other farmers have turned to planting salinity tolerant crops such  
196 as coconut, mango and sugarcane. In some cases, farmers have opted for a rice-aquaculture system whereby  
197 rice is planted in the wet season and fish/shrimp is cultivated in the dry season when soil salinities are high  
198 (Nguyen and Vo, 2017; Pham et al., 2017).

199 Besides environmental factors, the greater profitability of fruits, vegetables, fish and shrimp also incentivise  
200 farmers to plant more non-rice crops. The income per hectare of rice was USD 146 compared to pomelo (USD  
201 16,844) and coconut (USD 1,484) (Hoang and Tran, 2019). Meanwhile, farmers who practise shrimp-rice  
202 rotational systems earned 50% more than those who had two rice crops (Morton, 2020; Schneider and Asch,  
203 2020). In addition, high demand for fruits and vegetables for export and from growing urban populations with  
204 greater affluence and knowledge about nutrition, also encouraged farmers to diversify from rice monoculture  
205 leading to possible declines in the overall rice growing area (Hai, 2019; Nguyen and Vo, 2017; Figure 4).

206 Finally, government policies encouraging farmers to move away from growing rice also contributed to the  
207 planting of more non rice crops on paddy land. As a result, there is increased use of paddy land for non-rice  
208 crops, orchards, freshwater and brackish aquaculture (Van Kien et al., 2020). Using remote sensing to assess  
209 land use and land cover change in the Mekong Delta, Liu et al. (2020) found that aquaculture had become the  
210 second largest land use type following planted land. This was facilitated by government regulations, salt  
211 intrusion and higher profitability of aquaculture productions. In any case, even though farmers may have  
212 moved on from growing rice, many still continue to apply excessive amounts of pesticides on their crops  
213 (Normile, 2017; Figure 4)

##### 214 **3.1.2. Urban expansion**

215 Rapid urbanization is accelerating the loss of agricultural land in both the Red River Delta and Mekong  
216 River Delta. In Hanoi, a major city in the Red River Delta, 1,420 ha of agricultural land was lost per year from  
217 2000-2007, equivalent to a yearly loss of 3%. By 2025, up to 450,000 ha of agricultural land are expected to be  
218 converted to urban land. Most of this land use conversion occurs in peri-urban areas 5-15 km from the city  
219 centre. The same peri-urban land is often used to grow food, flowers and livestock to supply food for the

220 urban population in Hanoi. However, this land is considered by local authorities to be land reserve for urban  
221 planning, instead of resources for food supply (Drebold, 2017; Pham et al., 2015). Most of this peri-urban  
222 agricultural land is often forcibly obtained with minimal compensation given to farmers and then sold to  
223 foreign developers (Drebold, 2017). Similar urban expansion is also occurring in Can Tho city in the Mekong  
224 Delta with corresponding losses of agricultural land (cf. Garschagen et al., 2011; Pham et al., 2010). A decline  
225 in agricultural land means a decline in rice growing areas as well (Figure 4).

226 High land prices and a shrinking availability of arable land have forced farmers to practise agricultural  
227 intensification. In the RRD, rice production grew more than 25% from 2000-2011 without corresponding  
228 increases in rice growing areas due to intensified cropping practices involving the use of new high yielding rice  
229 varieties, irrigation during dry season and high inputs of agrochemicals (Drebold, 2017; Morton, 2020). The  
230 high pesticide use was reflected in a study in Nam Dinh province in the RRD where 8 out of 12 target pesticides  
231 were found in agricultural soils. In this study, frequently detected pesticides include isoprothiolane,  
232 chlorpyrifos and propiconazole and besides polluting the environment, the presence of high concentrations of  
233 pesticide residues also lowers the quality of rice sold for consumption (Braun et al., 2018; Figure 4).

234 In general, pests such as the brown planthopper are naturally occurring and are not a threat at low densities.  
235 However, intensive rice production with high seeding densities and the use of susceptible varieties creates a  
236 constant supply of food which allows their numbers to balloon. This is exacerbated by the asynchronous  
237 planting which creates a continuous supply of rice plants throughout the year in the Mekong Delta. In addition,  
238 the over-use of nitrogen fertilizers increase the pests' reproductive potential. Thirdly, the excessive use of  
239 pesticides also kills the natural enemies of pests such as spiders, ants, bees, beetles, dragonflies, frogs, lady  
240 bugs and wasps. Besides killing the natural predators of rice pests, the pests targeted by the pesticides may  
241 also become resistant to the pesticide. As a result, higher doses of the pesticide may be needed to kill them in  
242 future. For example, killing plant hoppers now requires a pesticide dose 500 times more than was needed in  
243 the past (Normile, 2013). The overuse of pesticide is due to a combination of factors such as insufficient  
244 knowledge of its proper use as well as aggressive marketing by agrochemical companies (Bottrell and Schoenly,  
245 2012; Normile, 2013; Sebesvari et al., 2011). The hashed lines in Figure 4 show that pesticide use may not  
246 necessarily reduce the incidence of pests and diseases if excessive volumes were applied.

### 247 **3.1.3. Dikes**

248 Wet season flooding is a naturally occurring phenomenon in the two deltas of Vietnam (Chan et al.,  
249 2012; 2015). To facilitate the planting of rice during the wet season, flood prevention dikes were constructed  
250 to keep floodwaters out (Figure 5). The MRD has more than 13,000 km of flood prevention dikes; of which  
251 8,000 km are low dikes below two meters tall. These low dikes were mostly constructed before 2000 to delay  
252 the entry of floodwaters at the start of the monsoon season to allow two rice crops to be grown. A severe  
253 flood in 2000 provided the impetus for river dikes to be heightened to 3.5 m to completely keep floodwaters  
254 out. These high dikes have facilitated triple cropping in the MRD, particularly in Dong Thap and An Giang  
255 provinces (Chapman et al, 2016; Howie, 2005; Le et al., 2018; Triet et al., 2017). However, the presence of high  
256 dikes in the MRD has reduced the supply of fertile alluvium, increasing the need for artificial fertilizers and  
257 pesticides to maintain yields (Chapman et al., 2017; Figure 4).

258 A study comparing sediment deposition in areas of high and low dikes in An Giang Province found that double  
259 cropping farmers who cultivate their crops in areas with low dikes have an average of 2.5 cm of sediment  
260 deposition. This deposition by floodwaters improved their average annual input efficiency by 0.3 tons of yield  
261 per ton of fertilizer. Conversely, triple cropping farmers had very little deposition, averaging 0.5 cm as the high  
262 dikes kept floodwaters out. Some deposition was found only if there had been a dike breach which also caused  
263 crop damage (Chapman et al., 2016). The value of flood deposits is reiterated by Manh et al. (2015)'s study  
264 which estimated that the annual deposition of sediment bound nutrient can naturally supply over half of the  
265 fertilizers needed for a season of rice crop. The provision of "free" fertilizers by the encroaching flood waters

266 benefits the less economically endowed farmers who must purchase artificial fertilizers to maintain yields  
267 (Chapman et al., 2017; Kondolf et al., 2018; Figure 4).

268 However, poorly planned and/or maintained dikes are not only functionally ineffective against floodwaters or  
269 coastal surges, they may become an amplifier of destruction when their presence creates a false sense of  
270 security which results in intensive development of low lying areas (Mai et al., 2009; Tran et al., 2018). In  
271 addition, areas unprotected by dikes may be more vulnerable to flooding as the excess water has to flow  
272 somewhere. Using a GIS-linked numerical model, Le et al. (2007) confirmed that engineering structures in the  
273 MRD increased water levels and flow velocities in rivers and canals. This in turn increased the risk of flooding in  
274 both non-protected areas and protected areas (due to dike failure). Hashed lines were used in Figure 4 to  
275 show that dikes do not necessarily reduce flooding.

276 Likewise, the RRD is also heavily diked with 3,000 km of river dikes (Figure 5) but unlike the MRD, high dikes  
277 are absent (Pilarczyk and Nguyen, 2005). Besides river and flood control dikes, there are also sea dikes and  
278 salinization prevention dikes in both deltas to protect the area from salinity intrusion. There are 1,500 km of  
279 sea and estuary dikes in the RRD. In the MRD, there are 1,290 km of salinization prevention dikes and 450 km  
280 of sea dikes (Le et al., 2018; Pilarczyk and Nguen, 2005; Figure 4).

#### 281 **3.1.4. Sand mining**

282 Sand mining is carried out on a large scale in the Mekong (Kondolf et al., 2018). Fueled by demand  
283 from reclamation, export and construction, 55.2 million tons of sediment were extracted from the Mekong  
284 main stem in Laos, Thailand, Cambodia and Vietnam from 2011 to 2012 (Bravard and Gaillot, 2013; Robert,  
285 2017). A more recent analysis of bathymetric maps and the local refilling processes by Jordan et al. (2019) put  
286 the amount of sand extracted from the Mekong Delta in 2018 at 17.77 Mm<sup>3</sup>.  
287

288 Besides removing large quantities of riverbed sediments, sand mining operations have created numerous pits  
289 and pools. These pits and pools which can be up to 45 m deep then become sediment traps, trapping bedload  
290 from upstream reaches and preventing them from travelling downstream and contributing to the continued  
291 presence and growth of the delta. In addition, bed incision also occurs as the water is sediment starved. The  
292 down-cutting of river banks can propagate upstream and downstream from the extraction sites for many  
293 kilometers in turn affecting river ecosystems over a large area (Kondolf et al., 2018). This bank incision results  
294 in land loss which threatens rice growing areas (Figure 4).

295 Aggressive sand mining also disrupts natural flooding. A recent study of riverine mining on flood frequency in  
296 the Long Xuyen Quadrangle (LXQ) in the Mekong Delta found that flood frequency had dropped by 7.8% from  
297 2005-2015. Water levels at local gauge stations also showed an overall decreasing trend indicating that the  
298 lowering of the riverbed had reduced the frequency of flooding. Disrupted flood regimes result in reduced  
299 volumes of water and sediments for agricultural production. In addition, floodwaters typically deposit fertile  
300 sediments while flushing the pesticides and fertilizers accumulated from intensive agricultural production.  
301 When the flood frequency decreases, the frequency at which farmlands benefit from these natural soil quality  
302 enhancement decreases. Consequently, soil fertility may decrease over time and lead to declines in rice yields  
303 unless artificial fertilizers are added (Park et al., 2020; Figure 4).

304 While there are several studies on the diffuse, yet insidious nature of sand mining in the Mekong (cf. Bravard  
305 and Gaillot, 2013; Bruiner et al., 2014; Jordan et al., 2019; Kondolf et al., 2018; Park et al., 2020; Robert, 2017;  
306 Schmitt et al., 2017), the extent of sand mining in the Red River Delta is unclear as there is almost no research  
307 on this issue. We did however come across an article in a Vietnamese newspaper about rampant sand mining  
308 in the Red River and how mining operations have caused erosion in nearby villages (Chinh, 2018). Similar to  
309 the situation in the MRD, the authorities have turned a blind eye to this illegal business (Bravard and Gaillot,  
310 2013; Chinh, 2018).

311 **3.1.5. Groundwater extraction**

312 Another example of an anthropogenic development creating other interrelated problems is that of  
313 groundwater extraction. While groundwater extraction has increased the availability of water for human  
314 activities, it has exacerbated land subsidence which has increased the severity and extent of saltwater  
315 intrusion and reduced the suitability of land for rice cultivation (Figure 4). Minderhoud et al. (2017) developed  
316 a 3D numerical groundwater flow model of the MRD surface and found that subsidence rates from  
317 groundwater extraction were between 1.1 and 2.5 cm/year. The model also showed that 25 years of  
318 groundwater extraction since 1991 had resulted in a cumulative average of 18 cm of subsidence with some  
319 hotspots recording over 30 cm of subsidence. Land subsidence from excessive groundwater extraction acts as  
320 a catalyst that increases vulnerability to saltwater intrusion and reduces the availability of land suitable for rice  
321 production.

322 Moreover, rice crops become contaminated with arsenic when arsenic-rich groundwater used for non-  
323 agricultural use is discharged into rivers and the river water is used for rice irrigation (Lan and Giao, 2017;  
324 Minderhoud et al., 2018). High arsenic concentrations in groundwater seem to be of natural origin. In the  
325 Mekong Delta, naturally occurring biochemical and hydrological processes cause As to be released from Fe  
326 oxides in rocks and sediments into groundwater reservoirs (Fendorf et al., 2010). In addition, deep  
327 groundwater extraction causes interbedded clays to compact and expel water containing dissolved As (Erban  
328 et al., 2013). Crop quality is reduced when the arsenic enriched water is deposited on topsoils and absorbed by  
329 rice plants during growth (Rahman and Hasegawa, 2011; Figure 4).

330 Similarly, prevalence of groundwater extraction is also high in the Red River Delta. Approximately 70% of the  
331 population living in the RRD access water from Holocene and Pleistocene aquifers (Berg et al., 2007; Winkel  
332 et al., 2011). Groundwater in the Red River Delta is also contaminated with high levels of As due to reductive  
333 dissolution of As from iron oxyhydroxides in buried sediment (Berg et al., 2007; Luu, 2019). Berg et al. (2007)  
334 sampled 196 tubewells randomly over a 700 km<sup>2</sup> area in the Red River Delta and the concentrations of As in  
335 groundwater ranged from 1 to 3050 µg/L with an average of 159 µg/L. Separately, Winkel et al. (2011)  
336 collected 512 water samples from private wells in the Red River floodplain and found As concentrations  
337 varying from <0.1 to 810 µg/L with 27% of the samples exceeding the WHO guideline value of 10 µg/L. The  
338 high concentrations of As reduce the quality of rice harvested in the RRD if As gets into soils and river waters  
339 indirectly through the usage of As enriched groundwater (Figure 4). In a study on As accumulation in white rice  
340 from the Red River Region in Vietnam, Phuong et al. (1999) reported As values of between 0.03 to 0.47 µg g<sup>-1</sup> d.  
341 wt with the mean value at 0.21 µg g<sup>-1</sup> d. wt. The mean value was higher than the mean value reported for Thai  
342 rice (0.14 µg g<sup>-1</sup> d. wt; range: 0.01 to 0.39 µg g<sup>-1</sup>) (Meharg et al., 2009).

343 Lastly, although high As concentrations in groundwater is common in in the RRD (cf. Berg et al., 2007; Luu,  
344 2019; Pham et al., 2018a; Winkel et al., 2011), there is no research on (groundwater induced) land subsidence  
345 in the Red River Delta. Thus, the magnitude of land subsidence in the delta is uncertain and should be an area  
346 for future research.

347 **3.2. Regional anthropogenic drivers**

348 **3.2.1. Upstream dams**

349 The Mekong River originates in the Tibetan Plateau and flows through China, Myanmar, Laos,  
350 Thailand, Cambodia and southern Vietnam. To meet growing demands for electricity, many small and large  
351 scale hydropower projects have been commissioned in each country to take advantage of this supposedly  
352 green and clean source of energy (Nhan and Cao, 2019; Manh et al., 2015). A total of 241 dams have been  
353 completed in the entire Mekong Basin with another 29 under construction. A further 91 is currently being  
354 planned. These 361 dams consist of 176 hydropower dams and 185 irrigation dams. Of the 364 dams in the  
355 Mekong, 20 are in Vietnamese territory (WLE Mekong CGIAR, 2020a). Conversely, the Red River originates in  
356 Yunnan province in China and flows towards northern Vietnam. It is less heavily dammed with a total of 105

357 dams in China and Vietnam. There are 25 hydropower dams, 3 multi-purpose dams and 9 irrigation dams in  
358 the Red River Basin in Vietnam (Vinh et al., 2014; WLE Mekong CGIAR, 2020b). While there are no dams in the  
359 Mekong River Delta or the Red River Delta due to its relatively flat elevation, upstream dam development  
360 influences downstream regions in many ways with the environmental impacts extending far beyond the dam  
361 itself (Kondolf et al., 2014).

362 Firstly, a substantial amount of coarse sand, gravel and suspended sediment is impounded in reservoirs behind  
363 the dams instead of being transported downstream. This diminished sediment load may aggravate erosion  
364 downstream from the dam (Nhan and Cao, 2019; Figure 4). Using a network model, under a “definitive future”  
365 scenario of 38 new dams, the cumulative sediment reduction in the Mekong Delta would be 51%. Conversely,  
366 under full build-up of 133 new dams, only 4% of the pre-dam sediment load will reach the Delta (Kondolf et al.,  
367 2014). Manh et al. (2015) also reached similar conclusions with a quasi-2D hydrodynamic model of suspended  
368 sediment dynamics. Floodplain sedimentation would decrease by about 21 to 96% while sediment load  
369 supplied to the sea at the river will diminish by 14 to 95% with the extreme values representing full dam build-  
370 up. Even if dam construction was limited to the river tributaries instead of the main stem, the cumulative  
371 sediment trapped could be as high as 68% meaning that only about 32% of the sediment load would reach the  
372 Mekong River delta (Kondolf et al., 2014).

373 Indeed, Binh et al. (2020) found that the suspended sediment loads in the MRD had decreased by 74.1% in  
374 2012-2015 primarily due to six mainstream dams in the Lancang cascade in China. In particular, the Manwan  
375 and Dachaoshan dams contributed to 32% of the reduction. In addition, from 2014-2017, the average incision  
376 rate of the Tien River in the MRD was three times higher than the previously recorded value. Sand mining was  
377 responsible for a max of 14.8% of the annual riverbed incision while the remainder was caused by hydropower  
378 dams upstream.

379 The deleterious impacts of dams on sediment loads can also be found in the Red River Delta in spite of the  
380 smaller number of dams. While the Hoa Binh dam is located on a tributary of the Red River in Vietnam, its  
381 large size has influenced suspended sediment distribution in the lower Red River Basin. For example, an  
382 analysis of the suspended sediment concentration over a 50 year period from 1960 to 2010 showed that yearly  
383 suspended sediment flux had dropped by 61% at Son Tay near Hanoi (Vinh et al., 2014). Similarly, Duc et al.  
384 (2012) calculated that the suspended sediment budget at Son Tay and Hanoi Hydrological monitoring stations  
385 was reduced by 56% after the Hoa Binh Dam became operational in 1989. The reduction in sediment loads at  
386 the Red River Delta would likewise have a similar impact on delta size and rice growing areas.

387 Besides a change in sediment loads, dams also alter stream discharge and water levels with concurrent effects  
388 on water supplies (not shown in Figure 4). When water levels are high during the rainy season, dams can be  
389 used to impound the excess water in the reservoir behind. During dry season when water levels are lower, the  
390 dams can release water downstream. In doing so, dams increase dry season discharge and decrease wet  
391 season discharge. The modification of seasonal water flows is problematic as changes in natural flow patterns,  
392 such as higher flows in dry season and lower flows in wet season would affect rice production as rice growing  
393 calendars are currently linked to the natural fluctuations of high and low flows (Robert, 2017). Hence, changes  
394 in water levels due to anthropogenic interventions may create unfavorable conditions for crop growth if  
395 planting calendars remain unchanged. In addition, lowered water levels during dry seasons due to upstream  
396 water impoundment can also lead to increased saltwater intrusion and create unfavorable growing conditions  
397 for rice farmers.

### 398 **3.3. Local natural hazard drivers**

#### 399 **3.3.1. Drought**

400 Droughts do not result solely from a lack of rainfall; they can also result from changes in the arrival of rains and  
401 the length of the wet season (Adamson and Bird, 2010; Lassa et al., 2016). Vietnam was affected by droughts

402 in 1997-1998, 2002-2003, 2009-2010 and most recently in 2015-2016. The 2015-2016 drought was the most  
403 severe in 90 years (Grosjean et al., 2016). All thirteen provinces in the Mekong Delta were affected by the 2015  
404 drought. Besides a lack of water for irrigation, the drought caused saltwater to intrude up to 70 km inland.  
405 Cumulatively, the drought and accompanying saltwater intrusion damaged 400,000 ha of rice crops including  
406 50,000 ha of paddy in Kieng Giang and Ca Mau provinces in the MRD (Grosjean et al., 2016; Nguyen, 2017).  
407 Although there is no research on how droughts and salinity intrusion have affected rice quality in Vietnam,  
408 research from elsewhere has shown that water shortages and salt stress induces physiochemical alterations  
409 which affect the rice grains produced (Pandey et al., 2014; Razzaq et al., 2019; Figure 6).

410 Compared to the MRD, there is not much research or reports on droughts in the Red River Delta. The UNW-  
411 DPC (2014) reported that the RRD experienced droughts from the end of 1998 to April 1999 which affected  
412 86,140 ha of rice. Another drought occurred from January to February 2004 with the water level of the Red  
413 River at the lowest in 40 years. Low water levels were also reported in 2010, however drought conditions and  
414 saltwater intrusion were more severe in the MRD (Overland, 2010). The effect of droughts on rice agriculture –  
415 reduced yields from a lack of water and salinity intrusion would also be similar in the RRD.

### 416 **3.3.2. Freshwater flooding**

417 Ranked as the second most severe natural hazard after typhoons, freshwater floods are caused by  
418 overflowing rivers, heavy monsoonal rains or associated with heavy rain from typhoons (Chan et al., 2012;  
419 2015; Hung et al., 2012; McElwee et al., 2017). Theoretically, flooding reduces rice growing areas but it is  
420 simplistic to assume that flooded fields result in immediate loss of rice crops. A study by Kotera et al. (2005) in  
421 the RRD showed that the type of rice, stage of rice growth, lengths and depths of submergence were factors  
422 that influence the survival rates of rice crops. For example, the local variety Moc Tuyen was less resilient to  
423 submergence than the two other genetically improved high yielding varieties. In terms of growth stage, rice  
424 plants at the tillering stage are more likely to succumb to submergence than those at the vegetative stage.  
425 Plants fully submerged for short durations (two days) also had lower chances of survival than those that were  
426 partially submerged in floodwaters for longer durations (up to eight days). As such the effect of flooding on  
427 rice growing areas is uncertain as other factors that affect crop mortality include the type of rice grown, the  
428 stage of rice growth as well as the depth and length of submergence in floodwaters (Figure 6).

429 Although severe flooding can disrupt agricultural activities, moderate levels of freshwater flooding bring  
430 benefits to (rural) farmers (EEPSEA, 2011). Floodwaters from rivers improve agricultural productivity by  
431 depositing nutrient rich flood sediments on agricultural soils (Chapman et al., 2016). In addition, floods wash  
432 away contaminants, purify and recharge aquifers, kill pests and mitigate saltwater intrusion (EEPSEA, 2011;  
433 Hoang et al., 2018; Figure 6). Aquatic resources such as fish, crabs and snails also come in with the floodwaters  
434 which local farmers can collect to supplement their incomes. Besides growing rice, it is also possible to  
435 cultivate vegetables, fish, prawns and ducks in the flooded fields (Nguyen and James, 2013). Towards the end  
436 of the flooding season and the start of the rice cultivation season, floodwaters provide the water needed to  
437 start growing rice (Hoa et al., 2008).

438 While there are investments in flood prevention measures with the construction and upgrading of river dikes,  
439 the construction and dredging of reservoirs and drainage canals as well as the raising of roads and  
440 embankments, recent floods have caused substantial agricultural losses as current measures have proved to  
441 be inadequate (Hoa et al., 2008; Pilarczyk and Nguyen, 2005). In 2018, 39,000 ha of rice in the RRD was  
442 inundated by heavy rains and floods triggered by Typhoon Son Tinh (VNA, 2018a). Similarly, due to a lack of  
443 embankments and/or poor construction and maintenance of existing embankments, more than 2,000 ha of  
444 rice were lost during the annual floods in 2018. An Giang province was the worst affected, losing 1,270 ha of  
445 rice (VNA, 2018b).

446 **3.3.3. Typhoons**

447 Typhoons are the most severe natural hazard that affects Vietnam. When a typhoon occurs, affected  
448 areas are exposed to strong winds of up to 50 m/s and up to 300 mm of rainfall in a day. As the rainy season in  
449 Vietnam coincides with the typhoon season, widespread flooding can be expected from heavy rain and  
450 overflowing rivers (CCFSC, 2005; Mai et al., 2009; Nguyen et al., 2019a). Storm surges can also occur when high  
451 winds pushing on the ocean's surface is combined with the effect of low pressure in the center of a typhoon  
452 (Takagi et al., 2013). Imamura and Dang (1997)'s study of typhoon disasters in Vietnam since 1950 found that  
453 half of the 450 typhoons recorded during the study period were accompanied by a storm surge of over 1 m  
454 and 11% were over 2.5 m high. In the Red River Delta, Quynh et al. (1998) found that the maximum storm  
455 surge is usually between 1 to 1.5 m above mean sea level. In short, rice production will be adversely affected  
456 by strong winds and widespread flooding from heavy precipitation and storm surges in the event of a typhoon.  
457 Saltwater flooding may reduce the rice growing areas as rice is not adapted to withstand prolonged  
458 submergence and/or saline conditions. Additionally, strong winds damage rice plants with both effects  
459 contributing to a reduction in rice yields (Figure 6).

460 Although a stronger typhoon usually bring higher wind speeds, more rainfall, larger waves and higher storm  
461 surges (Larson et al., 2014), the quantity of agricultural losses depends on factors such as landfall location(s)  
462 and whether the typhoon occurs during the vulnerable heading or harvesting periods (Masutomi et al., 2012).  
463 For example, Typhoon Mirinae (2016) which made landfall in Nam Dinh as a tropical storm damaged or  
464 submerged 225,216 ha of rice. Meanwhile Typhoon Nesat (2011) which made landfall in Hai Phong with a  
465 similar intensity caused only 3,500 ha of rice damage. Conversely, Typhoon Kalmi (2014) which made landfall  
466 in Quang Ninh as a slightly stronger category 1 storm caused 20,000 ha of rice damage (Nhân Dân, 2014;  
467 United Nations Vietnam, 2016; Việt Nam News, 2011).

468 An average of five to six typhoons affects Vietnam between June and November every year (Larson et al., 2014;  
469 Nguyen et al., 2007). Typhoon activity shifts from the north to the South as the year progresses. Therefore,  
470 peak activity in the north and southern part of Vietnam is in August and November respectively (Imamura and  
471 Dang, 1997). We reviewed the Digital Typhoon Database and found 303 typhoons that came within 500 km of  
472 Vietnam's coastline from 1995 to 2018. 29 cyclones made their initial landfall in the Red River Delta while only  
473 four cyclones made landfall in the Mekong Delta during the study period – one each in 1973, 1996, 1997 and  
474 2006 (Unpublished results). Although the MRD is less prone to typhoons, the two of the most recent typhoons  
475 caused significant damage despite each being classified as a tropical storm upon landfall. Typhoon Linda (1997)  
476 caused some 349,232 ha of rice to be submerged while Typhoon Durian (2006) damaged 6,978 ha of  
477 agricultural land (International Federation of Red Cross and Red Crescent Societies, 2006; UN Department of  
478 Humanitarian Affairs, 1997).

479 Lastly, typhoons may not necessarily be bad all the time. Darby et al. (2016) combined suspended sediment  
480 load data from the Mekong River with hydrological model simulations to examine the role of typhoons in  
481 transporting suspended sediments and found that one-third (32%) of the suspended sediment reaching the  
482 delta is delivered by runoff generated by rainfall associated with typhoons. When a typhoon affects areas  
483 upstream, the land receives higher than usual levels of rainfall which may trigger landslides. This sediment can  
484 be transferred into rivers and delivered downstream. While the role of tropical typhoons in sediment  
485 mobilization is unclear given the lack of research in this area, such findings have important implications for the  
486 MRD as sand mining and upstream dams have caused sharp declines in fluvial sediment loads with  
487 corresponding impacts on channel incision and flood frequencies (Brunier et al., 2014; Rubin et al., 2015; Park  
488 et al., 2020).

489 **3.3.4. Pests and diseases**

490 Examples of pests that occur in rice fields of Vietnam include the brown planthopper (BPH,  
491 *Nilaparvata lugens* Stål), white backed planthopper (WBPH, *Sogatella furcifera* Horvath) and small brown

492 planthopper (SBPH, *Laodelphax striatellus* Fallen). These planthoppers not only damage plants by ingesting its  
493 sap, they also transmit pathogenic viruses that kill the plants. The BPH is a vector for the rice grassy stunt virus  
494 (RGSV) and the rice ragged stunt virus (RRSV); the WBH transmits the southern rice black streak dwarf virus  
495 while the SBH vectors the rice stripe virus (RSV) and the rice black streaked dwarf virus (RBSDV) (Bottrell and  
496 Schoenly, 2012; Matsukawa-Nakata et al., 2019). Other pests that affect rice include parasitic worms called  
497 nematodes. Root nematodes that affect deepwater and irrigated rice fields in the MRD include  
498 *Hirschmanniella oryzae* (rice root nematode), *Hirschmanniella mucronata* and *Meloidogyne graminicola* (rice  
499 root knot nematode). Stem nematodes like the *Ditylenchus angustus* infect floating, deepwater and rainfed  
500 lowland rice in the MRD (Nguyen and Prot, 1995). Other significant pests of rice in Vietnam include rice leaf  
501 folders, rice thrips and stem borers (Sebesvari et al., 2011). Meanwhile, common rice diseases include bacterial  
502 leaf blight, bakanae, black rot of grain, brown spot, leaf yellowing disease, neck blast, rice blast disease, root  
503 rot, sheath blight, sheath rot and stem rot (Pinnschmid et al., 1995; Sebesvari et al., 2011; Trung et al., 1995;  
504 Kim et al., 1995).

505 Between 2005 and 2008, rice production in the Mekong Delta was severely reduced by outbreaks of brown  
506 planthopper and the associated virulent diseases. The problem was particularly severe in An Giang, Dong Thap  
507 and Tien Giang provinces with more than 50% of the cultivated areas affected (Berg and Tam, 2012). In 2009,  
508 the Southern rice black streaked dwarf virus affected 19 provinces in North Vietnam including those in the Red  
509 River Delta. More than 80% of the rice fields in Nam Dinh, Nghe An, Quang Ninh and Thai Binh provinces were  
510 infested and yield was non-existent (Hoang et al., 2011). In short, an increase in pest and/or disease outbreaks  
511 will likely cause a reduction in rice yield (Figure 6).

### 512 **3.4. Global natural hazard driver**

#### 513 **3.4.1. Sea level rise (SLR)**

514 Besides creating new environmental challenges, pre-existing threats to rice production and food  
515 security will be exacerbated by climate change. One of the effects of climate change includes rising sea levels.  
516 Globally, The IPCC has projected sea levels to rise from a rate of 3.2 mm/year from 1993 to 2010 to as much as  
517 10 mm/year or more by 2100 (Church et al., 2013). This may result in a 0.98 m increase in sea level by 2100  
518 (Lassa et al., 2016). To quantify sea level rise locally, observations at tide gauges across Vietnam have recorded  
519 an average yearly increase of 3.3 mm from 1993-2014 (Hens et al., 2018). SLR may also increase the risk of  
520 storm surges (Hanh and Furukawa, 2007). In the Red River Delta, Neumann et al. (2015) found that sea level  
521 rise through 2050 could reduce the recurrence interval of the current 100 year storm surge with a 5 m height  
522 to once every 49 years. Inadequately constructed and poorly maintained dikes and embankments may be  
523 breached resulting in saltwater flooding which will damage rice growing areas and other properties (Hanh and  
524 Furukawa, 2007; Figure 6).

525 Rising sea levels coupled with accelerated coastal subsidence caused by excessive groundwater extraction will  
526 cause large portions of the low lying RRD and MRD to be inundated and flooded (Allison et al., 2017). This  
527 facilitates the infiltration of saltwater into groundwater aquifers and this may increase salinity gradients in the  
528 MRD and RRD. In particular, salinity intrusion will worsen during the dry season. Approximately 1.8 million ha  
529 in the MRD are already affected by dry season salinity of which 1.3 million ha are affected by salinity levels  
530 above 5 g/L (Lassa et al., 2016). This area is predicted to increase to 2.2 million ha with rising sea levels.  
531 Meanwhile, in the northeast part of the RRD, the 1% salinity contour has migrated landwards by 4 to 10 km  
532 (Hanh and Furukawa, 2007). Increased soil salinization leads to a loss of land available for rice production  
533 (Figure 6). Though there are already sea dikes and saline water intrusion slices in both the MRD and RRD to  
534 reduce incursions of seawater (Braun et al., 2018; Tuong et al, 2003), they may be inadequate if they are not  
535 well maintained and upgraded.

536 **4. Discussion**

537 **4.1. Untangling complexity**

538 Relevant information on the different drivers and environmental processes affecting rice production  
539 in Vietnam are fragmented in a range of academic and non-academic sources (Bosch et al., 2007) making it  
540 difficult for policymakers and managers to have a good overview of the reinforcing and interdependent  
541 processes and issues affecting food security in Vietnam. Using a systems-thinking approach, we amalgamated  
542 the various drivers and created flow diagrams to consider how rice productivity can be positively or negatively  
543 impacted by the various drivers and environmental processes (Figures 4, 6). Rice growing areas are negatively  
544 affected by the expansion of aquaculture and alternative crops and urban expansion. But with agricultural  
545 intensification facilitated by high agrochemical inputs, it was possible to maximize rice yields in spite of a  
546 smaller growing area. However excessive agrochemical use affects rice quality and may have an opposite  
547 effect on the prevalence of pests and diseases. Next, anthropogenic developments meant to improve  
548 agricultural productivity or increase economic growth can create many unwanted environmental  
549 consequences. Dikes keep floodwaters and salt intrusion out but there is a reduction in fertile silt deposits.  
550 Sand mining increases channel erosion and reduce the frequency of natural freshwater flooding. Similar to  
551 sand mining, upstream dams affect sediment accumulation as sediments are trapped in reservoirs upstream  
552 but the impacts of upstream dams extend over a larger geographical area. Lastly, groundwater extraction  
553 causes land subsidence, saltwater intrusion and arsenic contamination with negative feedbacks on rice  
554 growing areas and the quality of rice produced.

555 Natural hazards not only affect rice quality and quantity but may also amplify some the problems created by  
556 human activities – for instance, typhoons and sea level rise may induce saltwater flooding and aggravate  
557 salinity intrusion. Conversely, droughts also worsen the extent of salinity intrusion but due to a lack of fresh  
558 water. Overall, a substantial reduction in sediment from sand mining and upstream dams, coupled with the  
559 process of land subsidence from groundwater extraction and rising sea levels will potentially reduce rice  
560 growing areas in future. Besides sea level rise, climate change may also exacerbate the effects of natural  
561 hazards by increasing the frequency and severity of natural disasters (cf. Hausfather et al., 2017; Grosjean et  
562 al., 2016; Terry et al., 2012). As such, the problems such as excessive saltwater flooding and saltwater intrusion  
563 may intensify.

564 The use of flow diagrams provides a visual overview of the key anthropogenic drivers and natural hazards that  
565 affect rice production but we caution that Red River Delta and the Mekong River Delta are vast and diverse  
566 regions and there are differences in the ways each delta is affected by natural hazards and anthropogenic  
567 drivers. For example, high dikes and the associated problem of sediment exclusion are a problem unique to the  
568 Mekong Delta (Chapman et al., 2017). Next, compared to the Mekong, the Red River has substantially fewer  
569 dams (361 vs 105). In addition, typhoons are less common in the Mekong Delta and droughts occur less  
570 frequently in the Red River Delta.

571 Within each delta, typhoons tend to affect coastal provinces more than those further inland. Similarly, arsenic  
572 contamination and saltwater intrusion is not an issue everywhere across the two deltas. A comparison study of  
573 arsenic pollution in the Mekong and Red River Deltas showed that groundwater arsenic concentrations ranged  
574 from 1-845 µg/L in the MRD and from 1-3050 µg/L in the RRD. Hotspots with high arsenic concentrations were  
575 likely due to local geogenic conditions (Berg et al., 2007). For salinity intrusion, Kotera et al. (2005) measured  
576 salinity concentrations in river and canal water across four Mekong Delta provinces and showed that the  
577 salinity levels ranged from 0.6 to 14.4 g/L while a localized study in the Nam Dinh province in the RRD showed  
578 that salt concentration in river water was higher at the river mouth than in upstream locations. Hence, given  
579 the possibility of spatial variations within a large landscape, it is important for local conditions to be taken into  
580 consideration.

581 One limitation of our study is that it was not possible to include all the problems that can potentially affect rice  
582 cultivation in our flow diagrams. We acknowledge issues related to industrial pollution, which may reduce rice  
583 quality and rice productivity (Khai and Yabe, 2012; 2013; Huong et al., 2008). In spite of this, our study  
584 presents the major issues that are common in both deltas and describes how the issues and processes  
585 affecting rice production are interrelated and may operate at different scales. Additionally, a systems-thinking  
586 approach has allowed the multitude of drivers and environmental processes affecting rice production to be  
587 visualized and mapped in a manner that is easy to understand. As ameliorating problems require policymakers  
588 and managers to have a good grasp of the different factors and processes present, a method that considers all  
589 the different drivers and possible unintended consequences from the outset can avoid oversimplifying a  
590 problem and assuming a straightforward solution can be found (DeFries and Nagendra, 2007). For example, to  
591 solve the problem of a shrinking delta, the effects of (high) dikes, sand mining, upstream dams and  
592 groundwater extraction have to be considered. While typhoons may provide some fluvial sediment to offset a  
593 shrinking delta (Darby et al., 2016), the sediment load provided may not be sufficient to offset sediment loss  
594 from sand mining and upstream dams.

#### 595 **4.2. Adaptation and soft solutions**

596 Recognizing the environmental challenges limiting agricultural production, farmers in both deltas  
597 have adapted and improvised. Instead of accepting their fate, farmers overcome high soil salinities by  
598 implementing measures such as replacing rice with salinity tolerant crops, transiting to shrimp aquaculture, or  
599 turning to rice-shrimp farming whereby rice is grown in the wet season and shrimp is cultivated in the dry  
600 season. For those unable to switch from rice monoculture, farmers have sought to grow rice on higher ground,  
601 shift crop calendars or dig additional ditches to drain saltwater and store freshwater. In addition, to prevent  
602 water storage ponds from becoming contaminated with saltwater, canvas sheets are placed on the soil surface  
603 to create a protective barrier (Tran et al., 2019; Nguyen et al., 2012). Similarly, farmers in peri-urban areas who  
604 are faced with shrinking agricultural lands have turned to practicing agricultural intensification and/or  
605 switched to planting high value crops such as fruits and vegetables (Morton, 2020; van den Berg et al., 2003).  
606 In short, farmers are constantly experimenting, learning and sharing knowledge and experiences with other  
607 farmers to come up with solutions for overcoming environmental limitations (Tran et al., 2019; Nguyen et al.,  
608 2012).

609 Unfortunately, adaptations are not successful all the time. For example, the widespread conversion of paddy  
610 fields to shrimp ponds will increase soil salinity and reduce the availability of freshwater. Over time, neighbors  
611 who have not switched to aquaculture may be unable to plant rice and would have to seek alternative  
612 livelihoods (Nguyen et al., 2012). In addition, rice-shrimp systems are not problem free as well. Leigh et al.  
613 (2017) found that environmental conditions in rice-shrimp systems were suboptimal and contributed to low  
614 yields and survival. Water temperature and salinity tended to be too high in the dry season and dissolved  
615 oxygen too low, causing most shrimps to die. For rice, the high soil salinity caused by having the aquaculture  
616 pond was a major limitation – in their study, only three out of 18 ponds produced a harvestable rice crop.

617 Apart from farmer-led initiatives related to crop and land use change, integrated pest management (IPM)  
618 should also be adopted to reduce the use of pesticides to rid pests. Farmers who practise IPM use a  
619 combination of pest resistant cultivars, fertilizer management and agronomic practices to increase the effects  
620 of predators and other naturally occurring biological control agents. For example, farmers can grow flowers,  
621 okra and beans along their paddy fields to attract bees and wasps that infest planthopper pests' eggs. With  
622 more natural predators around, pesticides are only used when necessary (Bottrell and Schoenly, 2012; Normile,  
623 2013). Alternatively, rice-fish farming and duck-rice systems can also be implemented to provide a more  
624 economically and ecologically sustainable alternative to intensive rice monoculture (Berg and Tam, 2012; Men  
625 et al., 2002).

626 In rice-fish farming, farmers use minimal pesticide as it kills the fish and the natural predators of rice pests.  
627 Instead, fish help to control pests and fish droppings keep the soil fertile. Upon maturity, the fish can be sold  
628 to increase the farmer's income by up to 30% (Berg et al., 2017; Bosma et al., 2012). Ducks can also be reared  
629 in immature rice fields. Besides providing food, the ducks serve as biological controls for insects and weeds.  
630 Their droppings fertilize the soils and their movement aerates the water to benefit the rice plants (Men et al.,  
631 1999; 2002). Men et al. (2002) showed that a duck-rice system in Can Tho province in the Mekong eliminated  
632 the use of pesticides, halved the use of fertilizers and the additional income from the sale of ducks increased  
633 farmers' incomes by 50 to 150%. Overall, the higher incomes and ecosystem services provided by the fish or  
634 ducks, coupled with reduced agrochemical use benefit farmers.

635 Increasingly, there are calls to move away from three to two rice crops a year in the MRD. Instead of planting a  
636 third crop, floodwaters are allowed to enter the fields to replenish soil nutrients, wash away contaminants, kill  
637 pests and mitigate salinity intrusion. Fish, crabs and snails that arrive with the floodwaters can be collected for  
638 additional income. Triple cropping of rice provides only a single ecosystem service which is marketable rice. On  
639 the other hand, the integration of rice cropping with natural flooding creates a series of positive feedback  
640 mechanisms and ecosystem services that include providing natural pest control and facilitating nutrient cycling  
641 (Nikula, 2018; Tong, 2017). However, a study by Tran and Weger (2018) in An Giang province revealed that  
642 despite official encouragement to move away from triple cropping, most farmers have largely ignored the  
643 directive as they preferred to earn money from the additional rice crop. In addition, many of them felt that the  
644 benefits of flooding the land were minimal as upstream dams have drastically reduced fertile sediment and  
645 fish. Evidently, farmers are willing to make changes to their farming practices only if it benefits them.

646 To mitigate "wicked" environmental challenges, there is a need for holistic land use planning and soft  
647 measures (eg. implementing crop and land use change) on top of hard engineering structures. Previously,  
648 management options to increase agricultural productivity and mitigate the threats posed by natural hazards  
649 were largely characterized by hard options such as the construction of dikes, sea walls and sluice gates. These  
650 were typically top-down projects spearheaded by the local government (Neumann et al., 2015; Smajgl et al.,  
651 2015). While highly visible engineering structures are easily constructed and generally effective, unwanted side  
652 effects may be created. For example, flooding and sediment exclusion were some problems that were  
653 inadvertently created due to the presence of high dikes. In the long term, (costly) maintenance is needed to  
654 maintain the functionality of engineered structures (Hoang et al., 2018; Neumann et al., 2015). In addition,  
655 during the pre-construction phase, natural vegetation may be cleared (Geist and Lambin, 2002). Adopting a  
656 systems-thinking approach would allow policymakers and managers to situate the range of mitigation  
657 measures within broader environmental processes. In doing so, a clearer view of the possibilities and  
658 challenges present in an era of widespread anthropogenic development and changing climates is provided.

## 659 **5. Conclusions**

660 The focus of this paper is on the impacts of land use patterns and natural hazards on rice agriculture  
661 in the Mekong and Red River Deltas in Vietnam. While we focused on rice agriculture, these two deltas, like  
662 many other deltas worldwide, are also major production hubs for fruits and vegetables (Day et al., 2016; Nhan  
663 and Cao, 2019). Hence, the natural hazards and anthropogenic factors listed will have an effect on other  
664 agricultural produce as well.

665 A key finding is that demand for aquaculture and alternative crops and urban expansion has diminished rice  
666 growing areas. The problem of shrinking agricultural land is ameliorated by agricultural intensification which  
667 has increased land efficiency. However, widespread agrochemical use causes land and water pollution and  
668 reduces crop quality. In addition, anthropogenic developments such as dike construction can improve  
669 agricultural productivity but also create unintended environmental problems. Even human activities that are  
670 unrelated to agriculture such as sand mining, groundwater extraction and dam construction can reduce rice

671 productivity. In addition, natural hazards not only affect rice quality and quantity but may also amplify some  
672 of the problems created by human activities – for instance, typhoons and sea level rise may induce saltwater  
673 flooding and worsen salinity intrusion. In the future, climate change may exacerbate the effects of natural  
674 hazards by increasing the frequency and severity of natural disasters. Therefore, the problems associated with  
675 some of the natural hazards such as excessive saltwater flooding and saltwater intrusion may be more  
676 frequent and possibly worse. In sum, the processes and issues affecting food security are multidimensional and  
677 interdependent and we used a systems-thinking approach to develop a visual representation of the ways in  
678 which anthropogenic land-use factors and natural hazards can affect rice quantity and quality in the MRD and  
679 the RRD in Vietnam. We have also sought to define whether the anthropogenic or natural hazard driver was a  
680 local, regional or global driver to highlight the scale at which each driver operates.

681 Our review focuses on food security in Vietnam’s two deltas but can be applied to other contexts. The  
682 problems present in the two deltas in Vietnam are hardly unique. Across the world, deltas are global food  
683 production hubs that support large populations. Nearly half a billion people live in deltaic regions. Similar to  
684 the Mekong and Red River Delta, large tracts of deltaic wetlands in other countries have been reclaimed for  
685 agriculture, aquaculture, urban and industrial land use. Resultantly, many deltas suffer from flooding,  
686 retreating shorelines due to upstream dams, pollution problems and increasing land subsidence due to  
687 groundwater and mineral extraction. With climate change, rising sea levels will further threaten the viability of  
688 the deltaic landform (Chan et al., 2012; 2015; Day et al., 2016; Giosan et al., 2014; Syvitski et al., 2009).

689 Given that river deltas worldwide are highly stressed and degraded, a systems-thinking approach can provide a  
690 holistic overview of the “wicked problems” faced in each location and how the various environmental  
691 processes interact with each other. Although our study has focused on rice agriculture in the two deltas in  
692 Vietnam, the application of a systems-thinking approach to evaluate other pertinent phenomena in deltas  
693 elsewhere is a useful tool for understanding how human activities, natural hazards and climate change have  
694 compromised deltaic sustainability.

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## 698 **6. References**

699 Adamson, P., and Bird, J.: The Mekong: A drought-prone tropical environment?, *International Journal of Water*  
700 *Resources Development*, 26, 579-594, 10.1080/07900627.2010.519632, 2010.

701  
702 Allison, M. A., Nittrouer, C. A., Ogston, A. S., Mullarney, J. C., and Nguyen, T. T.: Sedimentation and survival of  
703 the Mekong Delta. A case study of decreased sediment supply and accelerating rates of relative sea level rise,  
704 *Oceanography*, 30, 98-109, 2017.

705  
706 Arias, M. E., Holtgrieve, G. W., Ngor, P. B., Dang, T. D., and Piman, T.: Maintaining perspective of ongoing  
707 environmental change in the Mekong floodplains, *Current Opinion in Environmental Sustainability*, 37, 1-7,  
708 <https://doi.org/10.1016/j.cosust.2019.01.002>, 2019.

709  
710 Berg, H., and Tam, N. T.: Use of pesticides and attitude to pest management strategies among rice and rice-fish  
711 farmers in the Mekong Delta, Vietnam, *International Journal of Pest Management*, 58, 153-164,  
712 10.1080/09670874.2012.672776, 2012.

713  
714 Berg, H., Ekman Söderholm, A., Söderström, A.-S., and Tam, N. T.: Recognizing wetland ecosystem services for  
715 sustainable rice farming in the Mekong Delta, Vietnam, *Sustainability Science*, 12, 137-154, 10.1007/s11625-  
716 016-0409-x, 2017.

717

718 Berg, M., Stengel, C., Trang, P. T. K., Hung Viet, P., Sampson, M. L., Leng, M., Samreth, S., and Fredericks, D.:  
719 Magnitude of arsenic pollution in the Mekong and Red River Deltas — Cambodia and Vietnam, *Science of The*  
720 *Total Environment*, 372, 413-425, <https://doi.org/10.1016/j.scitotenv.2006.09.010>, 2007.  
721

722 Binh, D. V., Kantoush, S., and Sumi, T.: Changes to long-term discharge and sediment loads in the Vietnamese  
723 Mekong Delta caused by upstream dams, *Geomorphology*, 353, 107011,  
724 <https://doi.org/10.1016/j.geomorph.2019.107011>, 2020.  
725

726 Binh, D. V. K., Sameh, Sumi, T., and Mai, N. T. P. T., La Vinh: Study on the impacts of river-damming and climate  
727 change on the Mekong Delta of Vietnam, *DPRI Annuals*, 2017.  
728

729 Bosch, O. J. H., King, C. A., Herbohn, J. L., Russell, I. W., and Smith, C. S.: Getting the big picture in natural  
730 resource management—systems thinking as ‘method’ for scientists, policy makers and other stakeholders,  
731 *Systems Research and Behavioral Science*, 24, 217-232, 10.1002/sres.818, 2007.  
732

733 Bosma, R. H., Nhan, D. K., Udo, H. M. J., and Kaymak, U.: Factors affecting farmers’ adoption of integrated rice–  
734 fish farming systems in the Mekong delta, Vietnam, *Reviews in Aquaculture*, 4, 178-190, 10.1111/j.1753-  
735 5131.2012.01069.x, 2012.  
736

737 Bottrell, D. G., and Schoenly, K. G.: Resurrecting the ghost of green revolutions past: The brown planthopper as  
738 a recurring threat to high-yielding rice production in tropical Asia, *Journal of Asia-Pacific Entomology*, 15, 122-  
739 140, <https://doi.org/10.1016/j.aspen.2011.09.004>, 2012.  
740

741 Braun, G., Sebesvari, Z., Braun, M., Kruse, J., Amelung, W., An, N. T., and Renaud, F. G.: Does sea-dyke  
742 construction affect the spatial distribution of pesticides in agricultural soils? – A case study from the Red River  
743 Delta, Vietnam, *Environmental Pollution*, 243, 890-899, <https://doi.org/10.1016/j.envpol.2018.09.050>, 2018.  
744

745 Bravard, J.-P., and Gaillot, M. G. E. S.: Geography of sand and gravel mining in the Lower Mekong River,  
746 *EchoGéo*, 26, 1-20, <https://doi.org/10.4000/echogeo.13659>, 2013.  
747

748 Brunier, G., Anthony, E. J., Goichot, M., Provansal, M., and Dussouillez, P.: Recent morphological changes in the  
749 Mekong and Bassac river channels, Mekong delta: The marked impact of river-bed mining and implications for  
750 delta destabilisation, *Geomorphology*, 224, 177-191, <https://doi.org/10.1016/j.geomorph.2014.07.009>, 2014.  
751

752 Ca, V. T., Vongvisessomjai, S., and Asaeda, T.: Study on Salinity Intrusion in the Red River Delta, 環境システム  
753 研究 (Environmental System Research), 22, 213-218, 10.2208/proer1988.22.213, 1994.

754 CCFSC: National report on disasters in Vietnam, Vietnam Central Committee for flood and storm control,  
755 working paper for the World Conference on disaster reduction, 18-22 Jan 2005, Kobe-Hyogo., 2005.  
756

757 Chan, F. K. S., Friess, D. A., Terry, J. P., and Mitchell, G.: Climate change & flood risk: challenges for the coastal  
758 regions of East Asia, in: *Routledge Handbook of East Asia and the Environment*, edited by: Harris, P. G., and  
759 Land, G., Routledge, 367-384, 2015.

760 Chan, F. K. S., Mitchell, G., Adekola, O., and McDonald, A.: Flood risk in Asia’s urban mega-deltas: Drivers,  
761 impacts and response, *Environment and Urbanization ASIA*, 3, 41-61, 10.1177/097542531200300103, 2012.  
762

763 Chapman, A., and Darby, S.: Evaluating sustainable adaptation strategies for vulnerable mega-deltas using  
764 system dynamics modelling: Rice agriculture in the Mekong Delta’s An Giang Province, Vietnam, *Science of The*  
765 *Total Environment*, 559, 326-338, <https://doi.org/10.1016/j.scitotenv.2016.02.162>, 2016.  
766

767 Chapman, A. D., Darby, S. E., Hông, H. M., Tompkins, E. L., and Van, T. P. D.: Adaptation and development  
768 trade-offs: fluvial sediment deposition and the sustainability of rice-cropping in An Giang Province, Mekong  
769 Delta, *Climatic Change*, 137, 593-608, 10.1007/s10584-016-1684-3, 2016.  
770

771 Chapman, A., Darby, S., Tompkins, E., Hackney, C., Leyland, J., Van, P. D. T., Pham, T. V., Parsons, D., Aalto, R.,  
772 and Nicholas, A.: Sustainable rice cultivation in the deep flooded zones of the Vietnamese Mekong Delta,  
773 Vietnam Journal of Science, Technology and Engineering, 59, 5,  
774 <https://doi.org/10.31276/VJSTE.59%282%29.34>, 2017.  
775

776 Chinh, G.: Illegal sand mining rampant in Vietnam's Red River, authorities do nothing:  
777 [https://e.vnexpress.net/news/news/illegal-sand-mining-rampant-in-vietnam-s-red-river-authorities-do-](https://e.vnexpress.net/news/news/illegal-sand-mining-rampant-in-vietnam-s-red-river-authorities-do-nothing-3773904.html)  
778 [nothing-3773904.html](https://e.vnexpress.net/news/news/illegal-sand-mining-rampant-in-vietnam-s-red-river-authorities-do-nothing-3773904.html), access: 19 Nov 2018, 2018.  
779

780 Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G.  
781 A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S.: Sea level change,  
782 in: Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment  
783 Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K.,  
784 Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press,  
785 Cambridge, United Kingdom and New York, USA, 1137-1216, 2013.  
786

787 Cosslett, T. L., and Cosslett, P. D.: Rice cultivation, production, and consumption in Mainland Southeast Asian  
788 Countries: Cambodia, Laos, Thailand, and Vietnam, in: Sustainable development of rice and water resources in  
789 Mainland Southeast Asia and Mekong River Basin, Springer Singapore, Singapore, 29-53, 2018.  
790

791 Darby, S. E., Hackney, C. R., Leyland, J., Kummu, M., Lauri, H., Parsons, D. R., Best, J. L., Nicholas, A. P., and  
792 Aalto, R.: Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity, Nature, 539,  
793 276, [10.1038/nature19809](https://doi.org/10.1038/nature19809), 2016.  
794

795 Day, J. W., Agboola, J., Chen, Z., D'Elia, C., Forbes, D. L., Giosan, L., Kemp, P., Kuenzer, C., Lane, R. R.,  
796 Ramachandran, R., Syvitski, J., and Yañez-Arancibia, A.: Approaches to defining deltaic sustainability in the 21st  
797 century, Estuarine, Coastal and Shelf Science, 183, 275-291, <https://doi.org/10.1016/j.ecss.2016.06.018>, 2016.  
798

799 DeFries, R., and Nagendra, H.: Ecosystem management as a wicked problem, Science, 356, 265,  
800 [10.1126/science.aal1950](https://doi.org/10.1126/science.aal1950), 2017.  
801

802 Drebold, H.: Food security and rapid urbanization. A case study of urban agriculture in Hanoi, Institute of  
803 Natural Science, Environmental Studies and Technology, Södertörns University, Södertörns University,  
804 Stockholm, 2017.  
805

806 Duc, D. M., Nhuan, M. T., and Ngoi, C. V.: An analysis of coastal erosion in the tropical rapid accretion delta of  
807 the Red River, Vietnam, Journal of Asian Earth Sciences, 43, 98-109,  
808 <https://doi.org/10.1016/j.jseaes.2011.08.014>, 2012.  
809

810 EEPSEA: The winners and losers of the floods in the Mekong Delta - A study from Vietnam. EEPSEA Policy Brief  
811 No. 2011-PB10, Singapore, 2011.  
812

813 Erban, L. E., Gorelick, S. M., Zebker, H. A., and Fendorf, S.: Release of arsenic to deep groundwater in the  
814 Mekong Delta, Vietnam, linked to pumping-induced land subsidence, Proceedings of the National Academy of  
815 Sciences, 110, 13751-13756, [10.1073/pnas.1300503110](https://doi.org/10.1073/pnas.1300503110), 2013.  
816

817 Fendorf, S., Michael, H. A., and van Geen, A.: Spatial and temporal variations of groundwater arsenic in South  
818 and Southeast Asia, Science, 328, 1123-1127, [10.1126/science.1172974](https://doi.org/10.1126/science.1172974), 2010.  
819

820 Garschagen, M., Renaud, F. G., and Birkmann, J.: Dynamic Resilience of Peri-Urban Agriculturalists in the  
821 Mekong Delta Under Pressures of Socio-Economic Transformation and Climate Change, in: Environmental  
822 Change and Agricultural Sustainability in the Mekong Delta, edited by: Stewart, M. A., and Coclanis, P. A.,  
823 Springer Netherlands, Dordrecht, 141-163, 2011.  
824  
825  
826

827 Geist, H. J., and Lambin, E. F.: Proximate causes and underlying driving forces of tropical deforestation: Tropical  
828 forests are disappearing as the result of many pressures, both local and regional, acting in various  
829 combinations in different geographical locations, *BioScience*, 52, 143-150, 10.1641/0006-  
830 3568(2002)052[0143:PCAUDF]2.0.CO;2, 2002.

831  
832 General Statistics Office: Statistical Yearbook of Vietnam 2018, Statistical Publishing House, 2018.

833 General Statistics Office of Vietnam: Agriculture, forestry and fishery: [https://www.gso.gov.vn/en/agriculture-  
834 forestry-and-fishery/](https://www.gso.gov.vn/en/agriculture-forestry-and-fishery/), access: 19 Nov 2020, 2020.

835  
836 Giosan, L., Syvitski, J., Constantinescu, S., and Day, J.: Climate change: protect the world's deltas, *Nature News*,  
837 516, 31, 10.1038/516031a, 2014.

838  
839 GRSP (Global Rice Science Partnership): Rice almanac. 4th edition, International Rice Research Institute, Los  
840 Baños, 2013.

841  
842 Grosjean, G., Monteils, F., Hamilton, S. D., Blaustein-Rejto, D., Gatto, M., Talsma, T., Bourgoïn, C., Sebastian,  
843 L.S. , Catacutan, D., Mulia, R., Bui, Y., Tran, D. N., Nguyen, K. G., Pham, M. T., Lan, L. N., and Läderach, P.:  
844 Increasing resilience to droughts in Vietnam; The role of forests, agroforests and climate smart agriculture.  
845 CCAFS-CIAT-UN-REDD Position Paper n.1, Hanoi, 2016.

846  
847 Hai, T. T. B.: Fruit production and business in the Mekong Delta, *Journal of Economic Development*, 18-20,  
848 2019.

849  
850 Hanh, P. T. T., and Furukawa, M.: Impact of sea level rise on coastal zone of Vietnam, *Bulletin of the Faculty of  
851 Science, University of the Ryukyus*, 84, 45-49, 2007.

852  
853 Hausfather, Z., Cowtan, K., Clarke, D. C., Jacobs, P., Richardson, M., and Rohde, R.: Assessing recent warming  
854 using instrumentally homogeneous sea surface temperature records, *Science Advances*, 3,  
855 10.1126/sciadv.1601207, 2017.

856  
857 Hens, L., Thinh, N. A., Hanh, T. H., Cuong, N. S., Lan, T. D., Thanh, N. V., and Le, D. T.: Sea-level rise and  
858 resilience in Vietnam and the Asia-Pacific: A synthesis, *Vietnam Journal of Earth Sciences*, 40, 27,  
859 10.15625/0866-7187/40/2/11107, 2018.

860  
861 Hoa, L. T. V., Shigeko, H., Nhan, N. H., and Cong, T. T.: Infrastructure effects on floods in the Mekong River  
862 Delta in Vietnam, *Hydrological Processes*, 22, 1359-1372, 10.1002/hyp.6945, 2008.

863  
864 Hoang, A. T., Zhang, H.-m., Yang, J., Chen, J.-p., Hébrard, E., Zhou, G.-h., Vinh, V. N., and Cheng, J.-a.:  
865 Identification, characterization, and distribution of southern rice black-streaked dwarf virus in Vietnam, *Plant  
866 Disease*, 95, 1063-1069, 10.1094/pdis-07-10-0535, 2011.

867  
868 Hoang, L. P., Biesbroek, R., Tri, V. P. D., Kumm, M., van Vliet, M. T. H., Leemans, R., Kabat, P., and Ludwig, F.:  
869 Managing flood risks in the Mekong Delta: How to address emerging challenges under climate change and  
870 socioeconomic developments, *Ambio*, 47, 635-649, 10.1007/s13280-017-1009-4, 2018.

871  
872 Howie, C.: High dykes in the Mekong Delta in Vietnam bring social gains and environmental pains, *Aquaculture  
873 News*, 32, 15-17, 2005.

874  
875 Hung, N. N., Delgado, J. M., Tri, V. K., Hung, L. M., Merz, B., Bárdossy, A., and Apel, H.: Floodplain hydrology of  
876 the Mekong Delta, Vietnam, *Hydrological Processes*, 26, 674-686, <https://doi.org/10.1002/hyp.8183>, 2012.

877  
878 Huong, N. T. L., Ohtsubo, M., Li, L., Higashi, T., Kanayama, M., and Nakano, A.: Heavy metal contamination of  
879 soil and rice in a wastewater-irrigated paddy field in a suburban area of Hanoi, Vietnam, *Clay Science*, 13, 205-  
880 215, 10.11362/jcssjclayscience1960.13.205, 2008.

881

882 Huong, P. T. T., Everaarts, A. P., Neeteson, J. J., and Struik, P. C.: Vegetable production in the Red River Delta of  
883 Vietnam. I. Opportunities and constraints, *NJAS - Wageningen Journal of Life Sciences*, 67, 27-36,  
884 <https://doi.org/10.1016/j.njas.2013.09.002>, 2013.

885

886 Imamura, F., and Van To, D.: Flood and typhoon dsasters in Viet Nam in the half Century since 1950, *Natural*  
887 *Hazards*, 15, 71-87, 10.1023/A:1007923910887, 1997.

888

889 International Federation of the Red Cross and Red Crescent Society: Viet Nam: Typhoons revised appeal no.  
890 MDRVN001 - 22 Dec 2006: [https://reliefweb.int/report/viet-nam/viet-nam-typhoons-revised-appeal-no-](https://reliefweb.int/report/viet-nam/viet-nam-typhoons-revised-appeal-no-mdrvn001-22-dec-2006)  
891 [mdrvn001-22-dec-2006](https://reliefweb.int/report/viet-nam/viet-nam-typhoons-revised-appeal-no-mdrvn001-22-dec-2006), access: 20 Nov 2018, 2006.

892

893 Jordan, C., Tiede, J., Lojek, O., Visscher, J., Apel, H., Nguyen, H. Q., Quang, C. N. X., and Schlurmann, T.: Sand  
894 mining in the Mekong Delta revisited - current scales of local sediment deficits, *Scientific Reports*, 9, 17823,  
895 10.1038/s41598-019-53804-z, 2019.

896

897 Khai, H. V., and Yabe, M.: Rice Yield Loss Due to Industrial Water Pollution in Vietnam, *Journal of US-China*  
898 *Public Administration*, 9, 248-256, 2012.

899

900 Khai, H. V., and Yabe, M.: Impact of industrial water pollution on rice production in Vietnam, in: *International*  
901 *perspectives on water quality management and pollutant control*, IntechOpen, 2013.

902

903 Kim, P. V., Cu, R. M., Teng, P. S., Cassman, K. G., Mew, T. W., Nga, T. T., Ve, N. B., and Bien, P. V.: Relationships  
904 between rice intensification, rice plant nutrition, and leaf-yellowing disease in the Mekong River Delta.  
905 Vietnam and IRRI: A partnership in rice research. Proceedings of a conference held in Hanoi, Vietnam, 4-7 May  
906 1994, 1995, 211-216,

907

908 Kondolf, G. M., Rubin, Z. K., and Minear, J. T.: Dams on the Mekong: Cumulative sediment starvation, *Water*  
909 *Resources Research*, 50, 5158-5169, 10.1002/2013WR014651, 2014.

910

911 Kondolf, G. M., Schmitt, R. J. P., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A., Cochrane, T. A., Gibson,  
912 S., Kumm, M., Oeurng, C., Rubin, Z., and Wild, T.: Changing sediment budget of the Mekong: Cumulative  
913 threats and management strategies for a large river basin, *Science of The Total Environment*, 625, 114-134,  
914 <https://doi.org/10.1016/j.scitotenv.2017.11.361>, 2018.

915

916 Kotera, A., Nawata, E., Thao, L. V., Vuong, N. V., and Sakuratani, T.: Effect of submergence on rice yield in the  
917 Red River Delta, Vietnam, *Japanese Journal of Tropical Agriculture*, 49, 197-206, 10.11248/jsta1957.49.197,  
918 2005.

919

920 Kotera, A., Sakamoto, T., Nguyen, D. K., and Yokozawa, M.: Regional consequences of seawater intrusion on  
921 rice productivity and land use in coastal area of the Mekong River Delta, *Japan Agricultural Research Quarterly:*  
922 *JARQ*, 42, 267-274, 10.6090/jarq.42.267, 2008.

923

924 Lan, N. X., and Giao, N. T.: Arsenic dynamics within rice production systems in the Mekong Delta, Viet Nam,  
925 *Imperial Journal of Interdisciplinary Research*, 3, 2017.

926

927 Larson, M., Hung, N. M., Hanson, H., Sundström, A., and Södervall, E.: 2 - Impacts of Typhoons on the  
928 Vietnamese Coastline: A Case Study of Hai Hau Beach and Ly Hoa Beach, in: *Coastal Disasters and Climate*  
929 *Change in Vietnam*, edited by: Thao, N. D., Takagi, H., and Esteban, M., Elsevier, Oxford, 17-42, 2014.

930

931 Lassa, J. A., Lai, A. Y.-H., and Goh, T.: Climate extremes: an observation and projection of its impacts on food  
932 production in ASEAN, *Natural Hazards*, 84, 19-33, 10.1007/s11069-015-2081-3, 2016.

933

934 Le, T. N., Bregt, A. K., van Halsema, G. E., Hellegers, P. J. G. J., and Nguyen, L.-D.: Interplay between land-use  
935 dynamics and changes in hydrological regime in the Vietnamese Mekong Delta, *Land Use Policy*, 73, 269-280,  
936 <https://doi.org/10.1016/j.landusepol.2018.01.030>, 2018.

937

938 Le, T. V. H., Nguyen, H. N., Wolanski, E., Tran, T. C., and Haruyama, S.: The combined impact on the flooding in  
939 Vietnam's Mekong River delta of local man-made structures, sea level rise, and dams upstream in the river  
940 catchment, *Estuarine, Coastal and Shelf Science*, 71, 110-116, <https://doi.org/10.1016/j.ecss.2006.08.021>,  
941 2007.  
942  
943 Leigh, C., Hiep, L. H., Stewart-Koster, B., Vien, D. M., Condon, J., Sang, N. V., Sammut, J., and Burford, M. A.:  
944 Concurrent rice-shrimp-crab farming systems in the Mekong Delta: Are conditions (sub) optimal for crop  
945 production and survival?, *Aquaculture Research*, 48, 5251-5262, <https://doi.org/10.1111/are.13338>, 2017.  
946  
947 Li, Z., Saito, Y., Matsumoto, E., Wang, Y., Tanabe, S., and Lan Vu, Q.: Climate change and human impact on the  
948 Song Hong (Red River) Delta, Vietnam, during the Holocene, *Quaternary International*, 144, 4-28,  
949 <https://doi.org/10.1016/j.quaint.2005.05.008>, 2006.  
950  
951 Lim, C. L., Prescott, G. W., De Alban, J. D. T., Ziegler, A. D., and Webb, E. L.: Untangling the proximate causes  
952 and underlying drivers of deforestation and forest degradation in Myanmar, *Conservation Biology*, 31, 1362-  
953 1372, 10.1111/cobi.12984, 2017.  
954  
955 Liu, S. a., Li, X., Chen, D., Duan, Y., Ji, H., Zhang, L., Chai, Q., and Hu, X.: Understanding land use/land cover  
956 dynamics and impacts of human activities in the Mekong Delta over the last 40 years, *Global Ecology and  
957 Conservation*, 22, e00991, <https://doi.org/10.1016/j.gecco.2020.e00991>, 2020.  
958  
959 Luu, T. L.: Remarks on the current quality of groundwater in Vietnam, *Environmental Science and Pollution  
960 Research*, 26, 1163-1169, 10.1007/s11356-017-9631-z, 2019.  
961  
962 Mai, C. V., Stive, M. J. F., and Van Gelder, P. H. A. J. M.: Coastal protection strategies for the Red River Delta,  
963 *Journal of Coastal Research*, 105-116, 10.2112/07-0888.1, 2009.  
964  
965 Mainuddin, M., Kirby, M., and Hoanh, C. T.: Adaptation to climate change for food security in the lower  
966 Mekong Basin, *Food Security*, 3, 433-450, 10.1007/s12571-011-0154-z, 2011.  
967  
968 Manh, N. V., Dung, N. V., Hung, N. N., Kummu, M., Merz, B., and Apel, H.: Future sediment dynamics in the  
969 Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise, *Global and  
970 Planetary Change*, 127, 22-33, <https://doi.org/10.1016/j.gloplacha.2015.01.001>, 2015.  
971  
972 Masutomi, Y., Iizumi, T., Takahashi, K., and Yokozawa, M.: Estimation of the damage area due to tropical  
973 cyclones using fragility curves for paddy rice in Japan, *Environmental Research Letters*, 7, 014020, 2012.  
974  
975 Mathers, S., and Zalasiewicz, J.: Holocene sedimentary architecture of the Red River Delta, Vietnam, *Journal of  
976 Coastal Research*, 15, 314-325, 1999.  
977  
978 Matsukawa-Nakata, M., Nguyen, H. C., and Kobori, Y.: Insecticide application and its effect on the density of  
979 rice planthoppers, *Nilaparvata lugens* and *Sogatella furcifera*, in paddy fields in the Red River Delta, Vietnam,  
980 *Journal of Pesticide Science*, 44, 129-135, 10.1584/jpestics.D18-080, 2019.  
981  
982 McElwee, P., Nghiem, T., Le, H., and Vu, H.: Flood vulnerability among rural households in the Red River Delta  
983 of Vietnam: implications for future climate change risk and adaptation, *Natural Hazards*, 86, 465-492,  
984 10.1007/s11069-016-2701-6, 2017.  
985  
986 Meharg, A. A., Williams, P. N., Adomako, E., Lawgali, Y. Y., Deacon, C., Villada, A., Cambell, R. C. J., Sun, G., Zhu,  
987 Y.-G., Feldmann, J., Raab, A., Zhao, F.-J., Islam, R., Hossain, S., and Yanai, J.: Geographical Variation in Total and  
988 Inorganic Arsenic Content of Polished (White) Rice, *Environmental Science & Technology*, 43, 1612-1617,  
989 10.1021/es802612a, 2009.  
990  
991 Men, B. X., Tinh, T. K., Preston, T. R., Ogle, R. B., and Lindberg, J. E.: Use of local ducklings to control insect  
992 pests and weeds in the growing rice field, *Livestock Research for Rural Development*, 11, 1999.

993 Men, B. X., Ogle, R. B., and Lindberg, J. E.: Studies on integrated duck-rice systems in the Mekong Delta of  
994 Vietnam, *Journal of Sustainable Agriculture*, 20, 27-40, 10.1300/J064v20n01\_05, 2002.  
995

996 Minderhoud, P. S. J., Erkens, G., Pham, V. H., Bui, V. T., Erban, L., Kooi, H., and Stouthamer, E.: Impacts of 25  
997 years of groundwater extraction on subsidence in the Mekong delta, Vietnam, *Environmental Research Letters*,  
998 12, 064006, 10.1088/1748-9326/aa7146, 2017.  
999

1000 Minderhoud, P. S. J., Coumou, L., Erban, L. E., Middelkoop, H., Stouthamer, E., and Addink, E. A.: The relation  
1001 between land use and subsidence in the Vietnamese Mekong delta, *Science of The Total Environment*, 634,  
1002 715-726, <https://doi.org/10.1016/j.scitotenv.2018.03.372>, 2018.  
1003

1004 Morton, L. W.: Working toward sustainable agricultural intensification in the Red River Delta of Vietnam,  
1005 *Journal of Soil and Water Conservation*, 75, 109A-116A, 10.2489/jswc.2020.0304A, 2020.  
1006

1007 Nelson, A., and Gumma, M. K.: A map of lowland rice extent in the major rice growing countries of Asia:  
1008 <http://irri.org/our-work/research/policy-and-markets/mapping>, access: 19 Nov 2018, 2015.

1009 Neumann, J. E., Emanuel, K. A., Ravela, S., Ludwig, L. C., and Verly, C.: Risks of coastal storm surge and the  
1010 effect of sea level rise in the Red River Delta, Vietnam, *Sustainability*, 7, 6553-6572, 2015.  
1011

1012 Newell, B., and Wasson, R.: Social system vs solar system: Why policy makers need history. Conflict and  
1013 Cooperation related to International Water Resources: Historical Perspectives. Selected Papers of the  
1014 International Water History Association's Conference on The Role of Water in History and Development. A  
1015 contribution to IHP-VI, Theme 4 "Water and Society" and the UNESCO/Green Cross International Initiative  
1016 from Potential Conflict to Co-operation Potential: Water for Peace, a sub-component of the World Water  
1017 Assessment Programme, Bergen, Norway, 10-12 Aug 2001, 2002.  
1018

1019 Nguyen, H. N. V., Kien Trung, and Nguyen, X. N.: Flooding the the Mekong River Delta, Viet Nam. Human  
1020 Development Report 2007/2008. Fighting climate change: Human solidarity in a divided world. Human  
1021 Development Report Office Occassional Paper, 2007.  
1022

1023 Nguyen, K.-A., Liou, Y.-A., and Terry, J. P.: Vulnerability of Vietnam to typhoons: A spatial assessment based on  
1024 hazards, exposure and adaptive capacity, *Science of The Total Environment*, 682, 31-46,  
1025 <https://doi.org/10.1016/j.scitotenv.2019.04.069>, 2019a.  
1026

1027 Nguyen, K. V., and James, H.: Measuring household resilience to floods: A case study in the Vietnamese  
1028 Mekong River Delta, *Ecology and Society*, 18, 2013.

1029 Nguyen, M. T., Renaud, F. G., and Sebesvari, Z.: Drivers of change and adaptation pathways of agricultural  
1030 systems facing increased salinity intrusion in coastal areas of the Mekong and Red River deltas in Vietnam,  
1031 *Environmental Science & Policy*, 92, 331-348, <https://doi.org/10.1016/j.envsci.2018.10.016>, 2019b.  
1032

1033 Nguyen, N. A.: Historic drought and salinity intrusion in the Mekong Delta in 2016: Lessons learned and  
1034 response solutions, *Vietnam Journal of Science, Technology and Engineering*, 60, 93-96, 2017.  
1035

1036 Nguyen, Q. H., and Vo, H. T.: Paper 3: Ensuring a sustainable tropical fruit industry in the midst of climate  
1037 change: The Vietnam story. 2017 International Symposium on Tropical Fruits., 2017.  
1038

1039 Nguyen, T. T. C., and Prot, J. C.: Nematode parasites of deepwater and irrigated rice in the Mekong River Delta.  
1040 Vietnam and IRRI: A partnership in rice research. Proceedings of a conference held in Hanoi, Vietnam, 4-7 May  
1041 1994, 1995, 251-260.  
1042

1043 Nguyen, V. K., Tran, A. T., Tran, V. H., Vo, D. T., Le, T., Tran, X., and Nguyen, V.: Climate change: Local  
1044 perception, impacts and adaptation of agrarian communities in the coastal provinces of the Mekong River  
1045 Delta, Vietnam, *Water and Climate: Policy Implementation Challenges; Proceedings of the 2nd Practical  
1046 Responses to Climate Change Conference*, 2012, 430.  
1047

1048 Nguyen, Y. T. B., Kamoshita, A., Dinh, V. T. H., Matsuda, H., and Kurokura, H.: Salinity intrusion and rice  
1049 production in Red River Delta under changing climate conditions, *Paddy and Water Environment*, 15, 37-48,  
1050 10.1007/s10333-016-0526-2, 2017.  
1051  
1052 Nhân Dân: Typhoon Kalmaegi claimed 12 lives in northern region:  
1053 <http://en.nhandan.com.vn/society/item/2802302-typhoon-kalmaegi-claimed-12-lives-in-northern-region.html>,  
1054 access: 20 Nov 2018, 2014.  
1055  
1056 Nhan, N. H., and Cao, N. B.: Chapter 19 - Damming the Mekong: Impacts in Vietnam and solutions, in: *Coasts  
1057 and Estuaries*, edited by: Wolanski, E., Day, J. W., Elliott, M., and Ramachandran, R., Elsevier, 321-340, 2019.  
1058  
1059 Nikula, J.: Is harm and destruction all that floods bring?, *Modern myths of the Mekong-a critical review of  
1060 water and development concepts, principles and policies: Water & Development Publications-Helsinki  
1061 University of Technology*. Finland, 27-38, 2008.  
1062  
1063 Normile, D.: Vietnam turns back a 'tsunami of pesticides', *Science*, 341, 737-738,  
1064 10.1126/science.341.6147.737, 2013.  
1065  
1066 Overland, M. A.: Vietnam feels the heat of a 100 year drought:  
1067 <http://content.time.com/time/world/article/0,8599,1969630,00.html>, access: 20 Nov 2018, 2010.  
1068  
1069 Pandey, A., Kumar, A., Pandey, D., and Thongbam, P.: Rice quality under water stress, *Indian Journal of  
1070 Advances in Plant Research*, 1, 23-26, 2014.  
  
1071 Park, E., Ho, H. L., Tran, D. D., Yang, X., Alcantara, E., Merino, E., and Son, V. H.: Dramatic decrease of flood  
1072 frequency in the Mekong Delta due to river-bed mining and dyke construction, *Science of The Total  
1073 Environment*, 723, 138066, <https://doi.org/10.1016/j.scitotenv.2020.138066>, 2020.  
1074  
1075 Pham, H. V., Pham, T. K. T., and Dao, V. N.: Arsenic contamination in groundwater in the Red river delta,  
1076 Vietnam - a review, *Vietnam Journal of Science, Technology and Engineering*, 60, 5, 2018a.  
1077  
1078 Pham, T. M. T., Raghavan, V., and Pawar, N. J.: Urban expansion of Can Tho city, Vietnam: A study based on  
1079 multi-temporal satellite images, *Geoinformatics*, 21, 147-160, 10.6010/geoinformatics.21.147, 2010.  
1080  
1081 Pham, V. C., Pham, T.-T.-H., Tong, T. H. A., Nguyen, T. T. H., and Pham, N. H.: The conversion of agricultural  
1082 land in the peri-urban areas of Hanoi (Vietnam): patterns in space and time, *Journal of Land Use Science*, 10,  
1083 224-242, 10.1080/1747423X.2014.884643, 2015.  
1084  
1085 Pham, V. H. T., Febriamansyah, R., Afrizal, A., and Anh Tran, T.: Impact of saline intrusion on social and  
1086 economic livelihoods of farmers in the Vietnam Mekong Delta, *International Journal of Agricultural Sciences*, 1,  
1087 75-84, van kien 1, 10, 10.25077/ijasc.1.2.%p.2017, 2017.  
1088  
1089 Pham, V. H. T., Febriamansyah, R., and Thong, T. A.: Government intervention and farmers' adaptation to  
1090 saline intrusion: A case study in the Vietnamese Mekong Delta, *International Journal on Advanced Science,  
1091 Engineering and Information Technology*, 8, 2142-2148, <http://dx.doi.org/10.18517/ijaseit.8.5.7090>, 2018b.  
1092  
1093 Phuong, T. D., Chuong, P. V., Khiem, D. T., and Kokot, S.: Elemental content of Vietnamese rice Part 1. Sampling,  
1094 analysis and comparison with previous studies, *Analyst*, 124, 553-560, 10.1039/A808796B, 1999.  
1095  
1096 Pilarczyk, K. W., and Nguyen, S. N.: Experience and practices on flood control in Vietnam, *Water International*,  
1097 30, 114-122, 10.1080/02508060508691843, 2005.  
1098  
1099 Pinnschmidt, H. O., Long, N. D., Viet, T. T., Don, L. D., and Teng, P. S.: Characterization of pests, pest losses, and  
1100 production patterns in a rainfed lowland rice of the Mekong River Delta. Vietnam and IRR: A partnership in  
1101 rice research. Proceedings of a conference held in Hanoi, Vietnam, 4-7 May 1994, 1995, 223-240.  
1102

1103 Preston, N., Brennan, D., and Clayton, H.: An overview of the project research, in: Rice–shrimp farming in the  
1104 Mekong Delta: Biophysical and socioeconomic issues. ACIAR Technical Reports No. 52e, edited by: Preston, N.,  
1105 and Clayton, H., 2003.  
1106

1107 Quynh, D. N., Ninh, P. V., M, M. V., and V, L. N. T.: The typhoon surges in Vietnam: the regime characteristics  
1108 and prediction. Proceedings of the Fifth Asian Science and Technology Week, Hanoi., 1998.  
1109

1110 Rahman, M. A., and Hasegawa, H.: High levels of inorganic arsenic in rice in areas where arsenic-contaminated  
1111 water is used for irrigation and cooking, *Science of The Total Environment*, 409, 4645-4655,  
1112 <https://doi.org/10.1016/j.scitotenv.2011.07.068>, 2011.  
1113

1114 Razzaq, A., Ali, A., Safdar, L. B., Zafar, M. M., Rui, Y., Shakeel, A., Shaukat, A., Ashraf, M., Gong, W., and Yuan, Y.:  
1115 Salt stress induces physiochemical alterations in rice grain composition and quality, *Journal of Food Science*, 85,  
1116 14-20, <https://doi.org/10.1111/1750-3841.14983>, 2020.  
1117

1118 Rittel, H. W. J., and Webber, M. M.: Dilemmas in a general theory of planning, *Policy Sciences*, 4, 155-169,  
1119 10.1007/BF01405730, 1973.  
1120

1121 Robert, A.: A river in peril: Human activities and environmental impacts on the Lower Mekong River and its  
1122 Delta, *Environment: Science and Policy for Sustainable Development*, 59, 30-40,  
1123 10.1080/00139157.2017.1374794, 2017.  
1124

1125 Rubin, Z. K., Kondolf, G. M., and Carling, P. A.: Anticipated geomorphic impacts from Mekong basin dam  
1126 construction, *International Journal of River Basin Management*, 13, 105-121, 10.1080/15715124.2014.981193,  
1127 2015.  
1128

1129 Schmitt, R. J. P., Rubin, Z., and Kondolf, G. M.: Losing ground - scenarios of land loss as consequence of shifting  
1130 sediment budgets in the Mekong Delta, *Geomorphology*, 294, 58-69,  
1131 <https://doi.org/10.1016/j.geomorph.2017.04.029>, 2017.  
1132

1133 Schneider, P., and Asch, F.: Rice production and food security in Asian Mega deltas—A review on  
1134 characteristics, vulnerabilities and agricultural adaptation options to cope with climate change, *Journal of*  
1135 *Agronomy and Crop Science*, 206, 491-503, <https://doi.org/10.1111/jac.12415>, 2020.  
1136

1137 Sebesvari, Z., Le, T. T. H., and Renaud, F. G.: Climate change adaptation and agrichemicals in the Mekong Delta,  
1138 Vietnam, in: *Environmental change and agricultural sustainability in the Mekong Delta*, edited by: Stewart, M.  
1139 A., and Coclanis, P. A., Springer Netherlands, Dordrecht, 219-239, 2011.  
1140

1141 Seto, K. C.: Exploring the dynamics of migration to mega-delta cities in Asia and Africa: Contemporary drivers  
1142 and future scenarios, *Global Environmental Change*, 21, S94-S107,  
1143 <https://doi.org/10.1016/j.gloenvcha.2011.08.005>, 2011.  
1144

1145 Smajgl, A., Toan, T. Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., Tri, V. P. D., and Vu, P. T.: Responding to  
1146 rising sea levels in the Mekong Delta, *Nature Climate Change*, 5, 167, 10.1038/nclimate2469, 2015.  
1147

1148 Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J.,  
1149 Vörösmarty, C., Saito, Y., Giosan, L., and Nicholls, R. J.: Sinking deltas due to human activities, *Nature*  
1150 *Geoscience*, 2, 681-686, 10.1038/ngeo629, 2009.  
1151

1152 Syvitski, J. P. M., and Saito, Y.: Morphodynamics of deltas under the influence of humans, *Global and Planetary*  
1153 *Change*, 57, 261-282, <https://doi.org/10.1016/j.gloplacha.2006.12.001>, 2007.  
1154

1155 Takagi, H., Nguyen, D. T., Esteban, M., Tran, T. T., Knaepen, H. L., Mikami, T., and Yamamoto, L.: Coastal  
1156 disaster risk in Southern Vietnam—the problems of coastal development and the need for better coastal  
1157 planning. Background paper prepared for the Global Assessment Report on Disaster Risk Reduction 2013,  
1158 Geneva, 2013.  
1159

1160 Terry, J. P., Winspear, N., and Cuong, T. Q.: The ‘terrific Tongking typhoon’ of October 1881 – implications for  
1161 the Red River Delta (northern Vietnam) in modern times, *Weather*, 67, 72-75,  
1162 <https://doi.org/10.1002/wea.882>, 2012.  
1163

1164 Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., and Fofoula-  
1165 Georgiou, E.: Profiling risk and sustainability in coastal deltas of the world, *Science*, 349, 638,  
1166 10.1126/science.aab3574, 2015.  
1167

1168 Tong, Y. D.: Rice intensive cropping and balanced cropping in the Mekong Delta, Vietnam — economic and  
1169 ecological considerations, *Ecological Economics*, 132, 205-212,  
1170 <https://doi.org/10.1016/j.ecolecon.2016.10.013>, 2017.  
1171

1172 Tran, D. D., van Halsema, G., Hellegers, P. J. G. J., Phi Hoang, L., Quang Tran, T., Kumm, M., and Ludwig, F.:  
1173 Assessing impacts of dike construction on the flood dynamics of the Mekong Delta, *Hydrology and Earth  
1174 System Science*, 22, 1875-1896, 10.5194/hess-22-1875-2018, 2018.  
1175

1176 Tran, D. D., and Weger, J.: Barriers to implementing irrigation and drainage policies in An Giang province,  
1177 Mekong Delta, Vietnam, *Irrigation and Drainage*, 67, 81-95, <https://doi.org/10.1002/ird.2172>, 2018.  
1178

1179 Tran, T. A., Nguyen, T. H., and Vo, T. T.: Adaptation to flood and salinity environments in the Vietnamese  
1180 Mekong Delta: Empirical analysis of farmer-led innovations, *Agricultural Water Management*, 216, 89-97,  
1181 <https://doi.org/10.1016/j.agwat.2019.01.020>, 2019.  
1182

1183 Triet, N. V. K., Dung, N. V., Fujii, H., Kumm, M., Merz, B., and Apel, H.: Has dyke development in the  
1184 Vietnamese Mekong Delta shifted flood hazard downstream?, *Hydrology and Earth System Sciences*, 21, 3991-  
1185 4010, 10.5194/hess-21-3991-2017, 2017.  
1186

1187 Trung, H. M., Vien, N. V., Thanh, D. T., Thuy, N. T., Thanh, H. M., Cassman, K. G., Mew, T. W., Teng, P. S., and Cu,  
1188 R. M.: Relationships between rice intensification, plant nutrition, and diseases in the Red River Delta. Vietnam  
1189 and IRRI: A partnership in rice research. Proceedings of a conference held in Hanoi, Vietnam, 4-7 May 1994,  
1190 1995, 200-210.  
1191

1192 Tuong, T. P., Kam, S. P., Hoanh, C. T., Dung, L. C., Khiem, N. T., Barr, J., and Ben, D. C.: Impact of seawater  
1193 intrusion control on the environment, land use and household incomes in a coastal area, *Paddy and Water  
1194 Environment*, 1, 65-73, 10.1007/s10333-003-0015-2, 2003.  
1195

1196 UN Department of Humanitarian Affairs: Vietnam typhoon situation report no.4:  
1197 <https://reliefweb.int/report/viet-nam/vietnam-typhoon-linda-situation-report-no4>, access: 20 Nov 2018, 1997.  
1198

1199 United Nations Vietnam: Viet Nam: Tropical storm Mirinae situation update no. 1 (as of 2 August 2016):  
1200 [http://www.un.org.vn/en/publications/doc\\_details/516-viet-nam-tropical-storm-mirinae-situation-update-no-  
1201 1-as-of-2-august-2016.html](http://www.un.org.vn/en/publications/doc_details/516-viet-nam-tropical-storm-mirinae-situation-update-no-1-as-of-2-august-2016.html), access: 20 Nov 2018, 2016.  
1202

1203 UNW-DPC: Drought situation and management in Vietnam:  
1204 [http://www.droughtmanagement.info/literature/UNW\\_DPC\\_NDMP\\_Country\\_Report\\_Vietnam\\_2014.pdf](http://www.droughtmanagement.info/literature/UNW_DPC_NDMP_Country_Report_Vietnam_2014.pdf),  
1205 access: 20 Nov 2018, 2014.  
1206

1207 USDA: Vietnam: Record rice production forecast on surge in planting in Mekong Delta:  
1208 <https://ipad.fas.usda.gov/highlights/2012/12/Vietnam/>, access: 16 Nov 2018, 2012.  
1209

1210 van den Berg, L. M., van Wijk, M. S., and van Hoi, P.: The transformation of agriculture and rural life  
1211 downstream of Hanoi, *Environment and Urbanization*, 15, 35-52, 10.1177/095624780301500122, 2003.  
1212

1213 Van Kien, N., Han, N. H., and Cramb, R.: Trends in rice-based farming systems in the Mekong Delta, in: *White  
1214 gold: The commercialisation of rice farming in the Lower Mekong Basin*, Palgrave Macmillan, Singapore, 347-  
1215 373, 2020.  
1216

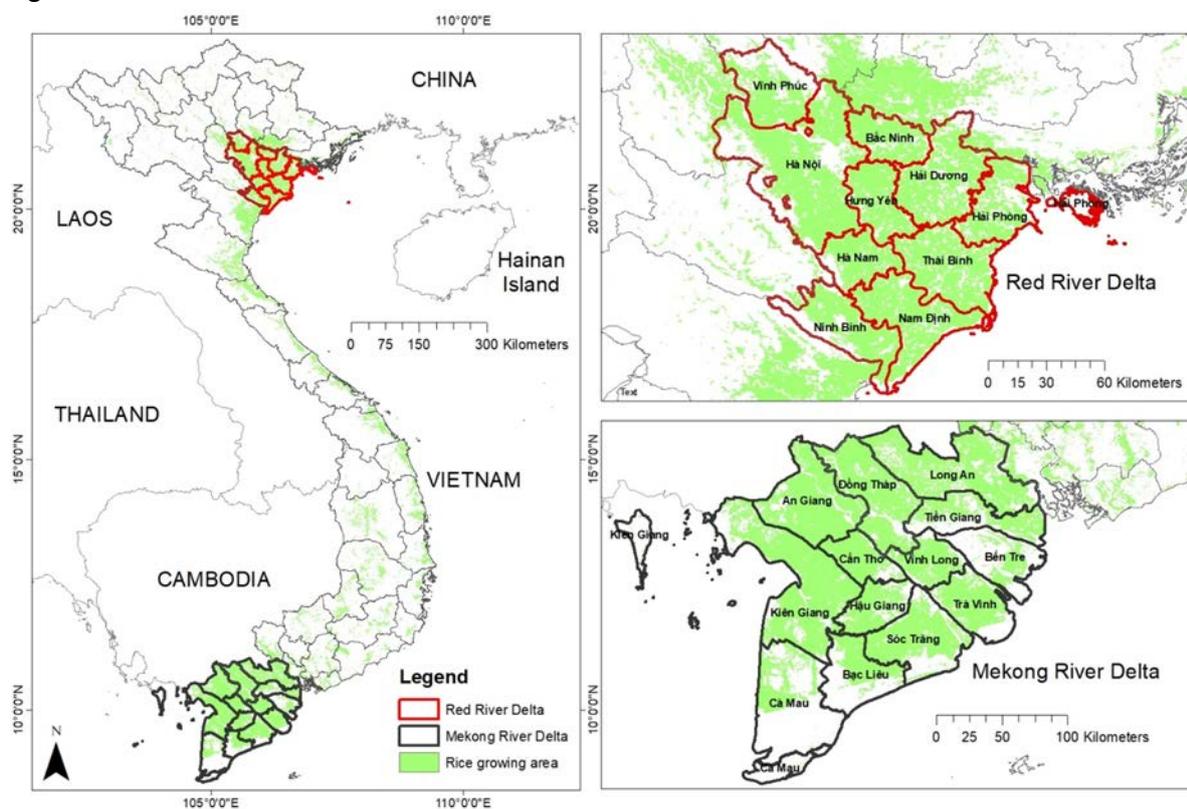
1217 Viêt Nam News: Typhoon Nesat wrecks havoc in coastal areas:  
1218 [https://vietnamnews.vn/Miscellany/216044/Typhoon-Nesat-wrecks-havoc-in-coastal-](https://vietnamnews.vn/Miscellany/216044/Typhoon-Nesat-wrecks-havoc-in-coastal-areas.html#LxRMtk4clvxbUTz.97)  
1219 [areas.html#LxRMtk4clvxbUTz.97](https://vietnamnews.vn/Miscellany/216044/Typhoon-Nesat-wrecks-havoc-in-coastal-areas.html#LxRMtk4clvxbUTz.97), access: 20 Nov 2018, 2011.  
1220  
1221 Vinh, V. D., Ouillon, S., Thanh, T. D., and Chu, L. V.: Impact of the Hoa Binh dam (Vietnam) on water and  
1222 sediment budgets in the Red River basin and delta, *Hydrology and Earth System Sciences*, 18, 3987-4005,  
1223 10.5194/hess-18-3987-2014, 2014.  
1224  
1225 VNA: Downpours, flooding wreak havoc in northern localities: [https://en.vietnamplus.vn/downpours-flooding-](https://en.vietnamplus.vn/downpours-flooding-wreak-havoc-in-northern-localities/135075.vnp)  
1226 [wreak-havoc-in-northern-localities/135075.vnp](https://en.vietnamplus.vn/downpours-flooding-wreak-havoc-in-northern-localities/135075.vnp), access: 20 Nov 2018, 2018a.  
1227  
1228 VNA: Floods damage 2,000 ha of rice in Mekong Delta: [https://en.vietnamplus.vn/floods-damage-2000ha-of-](https://en.vietnamplus.vn/floods-damage-2000ha-of-rice-in-mekong-delta/140921.vnp)  
1229 [rice-in-mekong-delta/140921.vnp](https://en.vietnamplus.vn/floods-damage-2000ha-of-rice-in-mekong-delta/140921.vnp), access: 20 Nov 2018, 2018b.  
1230  
1231 Winkel, L. H. E., Trang, P. T. K., Lan, V. M., Stengel, C., Amini, M., Ha, N. T., Viet, P. H., and Berg, M.: Arsenic  
1232 pollution of groundwater in Vietnam exacerbated by deep aquifer exploitation for more than a century,  
1233 *Proceedings of the National Academy of Sciences*, 10.1073/pnas.1011915108, 2011.  
1234  
1235 WLE Mekong CGIAR: Mapping the dams of the Mekong: [https://wle-mekong.cgiar.org/changes/where-we-](https://wle-mekong.cgiar.org/changes/where-we-work/red-river)  
1236 [work/red-river](https://wle-mekong.cgiar.org/changes/where-we-work/red-river)  
1237 [basin/#:~:text=A%20development%20river&text=In%20China%2C%20there%20are%2041,immense%20reserv](https://wle-mekong.cgiar.org/changes/where-we-work/red-river)  
1238 [oirs%20in%20the%20Basin.](https://wle-mekong.cgiar.org/changes/where-we-work/red-river), access: 9 Jan 2021, 2020a.  
1239 WLE Mekong CGIAR: Red River basin: <https://wle-mekong.cgiar.org/wp-content/uploads/unnamed-11.jpg>,  
1240 [access: 9 Jan 2021, 2020b.](https://wle-mekong.cgiar.org/wp-content/uploads/unnamed-11.jpg)  
1241 Workman, D.: Rice exports by country: <http://www.worldstopexports.com/rice-exports-country/>, access: 19  
1242 Nov 2020, 2020.  
1243  
1244 Ziegler, A. D., Echaubard, P., Lee, Y. T., Chuah, C. J., Wilcox, B. A., Grundy-Warr, C., Sithithaworn, P., Petney, T.  
1245 N., Laithevewat, L., Ong, X., Andrews, R. H., Ismail, T., Sripan, B., Khuntikeo, N., Poonpon, K., Tungtang, P., and  
1246 Tuamsuk, K.: Untangling the complexity of liver fluke infection and cholangiocarcinoma in NE Thailand through  
1247 transdisciplinary learning, *EcoHealth*, 13, 316-327, 10.1007/s10393-015-1087-3, 2016.  
1248  
1249  
1250  
1251  
1252  
1253  
1254  
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1256  
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1259 **Table**  
 1260 **Table 1.** Rice planting, growing and harvesting periods in the Mekong River Delta and the Red River Delta in  
 1261 Vietnam.

Mekong River Delta	Planting			Harvesting			
	Onset	Peak	End	Onset	Peak	End	Growing period
Winter-spring	1 Nov	30 Nov	30 Dec	15 Feb	25 Mar	30 Apr	115 – 120 days
Summer-autumn	15 Mar	15 Apr	15 May	20 Jun	20 Jul	25 Aug	95 – 100 days
Autumn-winter	30 Jun	20 Jul	20 Aug	5 Oct	25 Oct	30 Nov	95- 100 days
Red River Delta	Onset	Peak	End	Onset	Peak	End	Growing period
Spring	25 Jan	10 Feb	25 Feb	5 Jun	15 Jun	25 Jun	115 - 130 days
Autumn	15 Jun	1 Jul	20 Jul	5 Oct	25 Oct	10 Nov	105 - 110 days

1262

1263 **Figures**

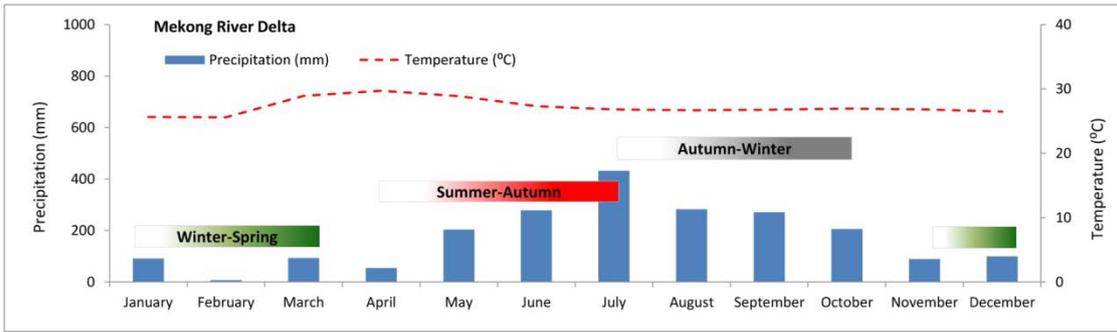


1264  
 1265 Figure 1. Distribution of rice growing areas in the Red River Delta (RRD) in northern Vietnam and the Mekong  
 1266 River Delta (MRD) in southern Vietnam. Rice growing extents were obtained from Nelson and Gumma (2015).

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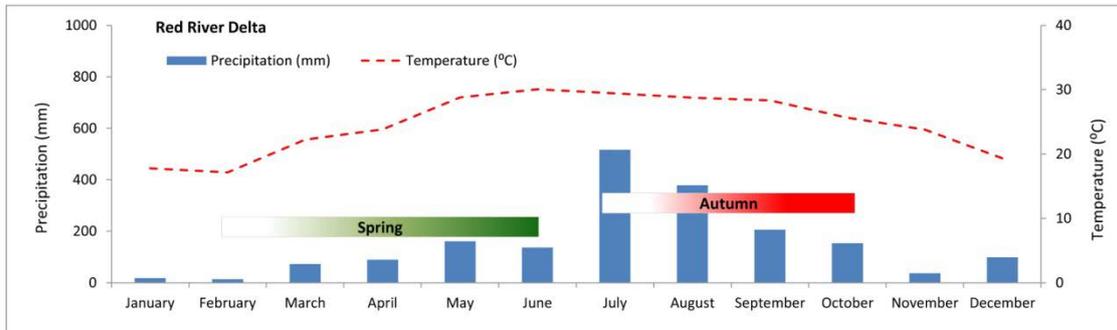
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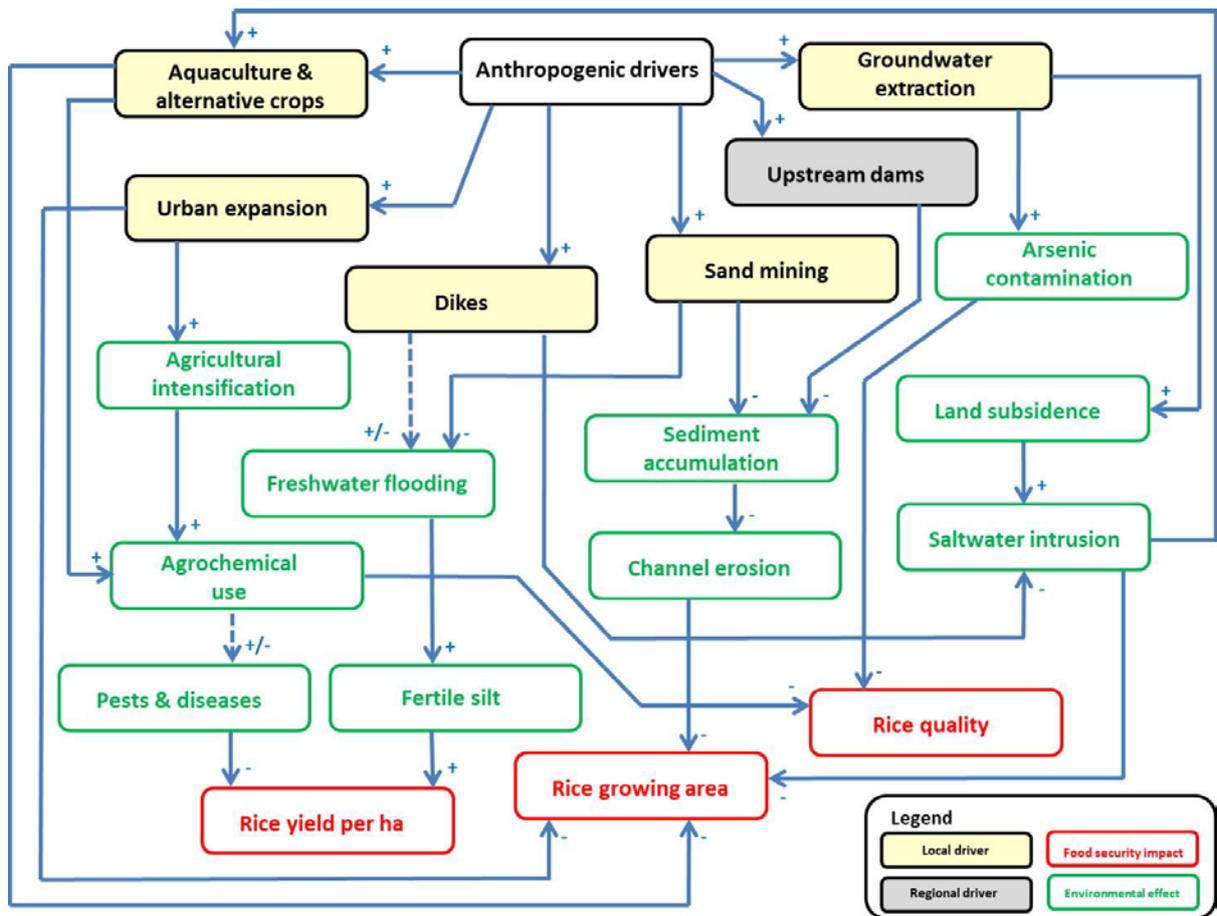
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1271 Figure 2. Climograph for the Mekong River Delta annotated with the winter-spring, summer-autumn and  
 1272 autumn-winter growing seasons. The colour gradient (from faded to dark) represents planting, growing and  
 1273 harvesting times for each crop. Precipitation and temperature data were taken from the Statistical Yearbook of  
 1274 Vietnam 2018 (General Statistics Office, 2018).



1275

1276 Figure 3. Climograph for the Red River Delta annotated with the spring and autumn growing seasons. The  
 1277 colour gradient represents planting, growing and harvesting times for each crop. Precipitation and  
 1278 temperature data were taken from the Statistical Yearbook of Vietnam 2018 (General Statistics Office, 2018).



1279

1280 Figure 4. Flow diagram showing the key anthropogenic drivers that affect rice production in the two mega-  
 1281 deltas of Vietnam. The drivers are classified as a local driver if it occurs in the two mega-deltas. Regional  
 1282 drivers are those that occur further away from the two mega-deltas, but within the Asian region. A plus (+) sign  
 1283 indicates that an increase/decrease in A causes B to increase/decrease. A negative (-) sign indicates an  
 1284 increase/decrease in A causes B to decrease/increase. Hashed lines with "+/-" are used when outcomes are  
 1285 unclear. For example, dikes reduce flooding but poorly maintained or planned dikes increase flooding instead.  
 1286 In additions, dikes may potentially cause flooding in unprotected areas. Agrochemical use may reduce the  
 1287 incidence of pests and diseases but the over-use of chemicals can lead to pesticide resistance which may  
 1288 increase outbreaks of pests and diseases.

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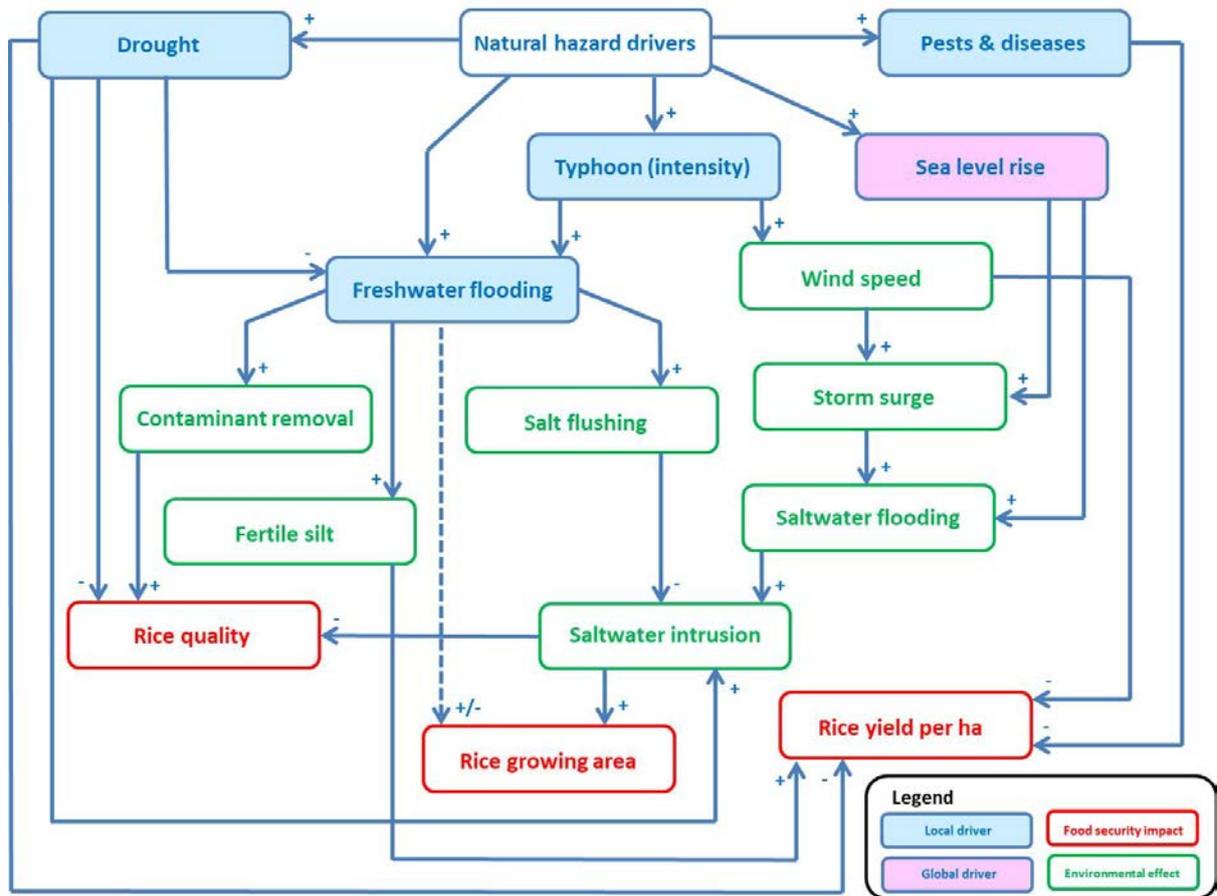
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1298

1299 Figure 5. Example of a river dike for flood control in Nam Dinh province in the Red River Delta.



1300

1301 Figure 6. Flow diagram showing the natural hazards that affect rice production in the two mega-deltas of  
 1302 Vietnam. Local drivers refer to natural hazards that occur within the two mega-deltas. Although sea level rise  
 1303 has implications on a local scale, it is considered a global driver as it occurs on a global scale. The effect of  
 1304 flooding on rice growing areas is uncertain as other factors that affect crop mortality include the type of rice  
 1305 grown, the stage of rice growth as well as the depth and length of submergence in floodwaters.