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 ~~mega~~ deltas are highly productive regions, they are vulnerable
12 to 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 ~~mega~~ deltas. On a local scale, demand for aquaculture and
17 alternative crops, urban expansion, dike development, sand mining and groundwater extraction decreases rice
18 production in the two ~~mega~~ deltas. Regionally, upstream dam construction impacts rice production in the two
19 ~~mega~~ deltas despite being distally situated. Separately, the localized natural hazards that have adversely
20 affected rice production include droughts, floods and typhoons. Outbreaks of pests and diseases are also
21 common. Climate change induced sea level rise is a global phenomenon that will affect agricultural
22 productivity. Notably, anthropogenic developments meant to improve agricultural productivity or increase
23 economic growth can create many unwanted environmental consequences such as an increase in flooding,
24 saltwater intrusion and land subsidence, which in turn decreases rice production and quality. In addition,
25 natural hazards may amplify the problems created by human activities. Our meta-analysis highlights the ways
26 in which a systems-thinking approach can yield more nuanced perspectives to tackle "wicked" and interrelated
27 environmental challenges. Given that ~~mega~~ deltas worldwide are globally significant for food production and
28 are highly stressed and degraded, a systems-thinking approach can be applied to provide a holistic and
29 contextualized overview of the threats faced in each location.

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

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1. Introduction

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

In this paper, we focus on the Red River Delta (RRD) and the Mekong River Delta (MRD) ~~in~~ in Vietnam as these two ~~mega~~ deltas are highly populated hubs of agricultural production that are highly vulnerable to environmental hazards. We use a systems-thinking approach to illustrate some of the "wicked problems" present in the two ~~mega~~ deltas in Vietnam and the implications of these anthropogenic and natural hazard drivers on rice agriculture. Although a variety of crops is cultivated in Vietnam, we focus on rice as it is a staple food for the Vietnamese (Nguyen et al., 2019b; USDA, 2012) and it is also a key export crop. In 2019~~7~~, Vietnam exported US$1.4~~6~~ billion of rice and was the fourth~~ifth~~ largest rice exporter in the world contributing 6.6~~7.5~~% of the world's total rice exports (Workman, 2020~~18~~).

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

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

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

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

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

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

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

2. Methods

2.1. Study sites

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

Soils in the MRD are highly variable with alluvial, acid sulphate and saline soils dominant. Most of the rice grows on the highly fertile alluvial soils which are found in only 30% of the delta (GRSP, 2013). Conversely, soils

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

thick quaternary accumulation with loose and alternating sediment beds which are mostly organic in nature. In general, the Quaternary is divided into two sequences: the upper part consists of fine sediment clay, sandy clay and fine sand; and the lower part contains gravel with cobbles and coarse sand. The Quarternary sediments are underlain by a >400 m thick layer of Neogene sedimentary rocks that are made up of conglomerate sandstone, clay and siltstone (Berg et al., 2007).

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

and the RRD have a tropical monsoon climate with an average annual rainfall of 1800 mm/year. Due to their latitudinal differences, there are differences in the average summer temperatures - the MRD has an average temperature of 27-30°C while the RRD has a slightly lower temperature of 20-25°C. In the RRD, temperatures are lower in winter at 16-21°C (Li et al., 2006; Ritzema et al., 2008). The two deltas also experience rainy and dry seasons differently. The rainy season in the MRD is between June/July and November/December, while the rainy season in the RRD is between May and October. The dry season in the MRD falls between December and May, while that of the RRD falls between November and April. Both deltas are low-lying with elevations ranging from 0.7 to 1.2 m above sea level (Binh et al., 2017, Luu et al., 2010).

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

2.2. Literature review and causal loop diagrams

We conducted an online search on Scopus, Web of Science, Google, Google Scholar and individual journal databases to find articles related to the effects of anthropogenic land-use change and natural hazards on rice agricultural systems in the RRD and/or MRD. Articles related to the environmental impacts of these anthropogenic interventions and natural hazards were included as these tend to explain the environmental

176 processes in detail. A range of literature sources including peer-reviewed journal articles, book chapters and
177 scientific reports from non-governmental organizations were included. In addition, we reviewed the
178 bibliographies of our articles to follow up with any other relevant literature that was not listed in our search.
179 Since sea level rise would affect the viability of the two deltas as major rice producing regions (Mainuddin et
180 al., 2006), we also included relevant articles on sea level rise.

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

186 We first developed causal links which describe how an anthropogenic driver would influence rice productivity
187 either directly or through an environmental process. We also documented if each driver had an increasing or
188 decreasing effect on an environmental process that could influence rice productivity by affecting rice growing
189 area, rice yield or rice quality. This relationship is represented by an arrow which indicates the direction of
190 influence, from cause to effect. The polarity of the arrows (plus or minus) indicates whether the effect is
191 increasing or decreasing (Lim et al., 2017). A plus sign indicates that a link has "positive polarity" and a minus
192 sign indicates "negative polarity." The polarity of the causal link between A and B is said to be positive when an
193 increase/decrease in A causes B to increase/decrease. A causal link is negative when an increase/decrease in A
194 causes B to decrease/increase (Newell and Watson, 2002). We constructed two flow diagrams - the first flow
195 diagram describes how anthropogenic land-use drivers affect rice growing area, rice yield per hectare and rice
196 quality in the MRD and RRD (Figure 4), while the second causal flow diagram describes how natural hazards in
197 the MRD and RRD affect rice growing area, rice yield per hectare and rice quality (Figure 65). The references
198 we used are found in the Supplementary Materials.

199 **3. Results**

200 **3.1. Local anthropogenic drivers**

201 **3.1.1. Aquaculture and alternative crops**
202 Both mega deltas face widespread salinity intrusion that threatens rice production. In the Mekong
203 Delta, salinity intrusion is a naturally occurring phenomenon during the dry season. Tides from the South China
204 Sea and the Gulf of Thailand bring saltwater inland and salinity intrudes up to 70-90 km inland as the length of
205 sea dikes is limited. There are 1,500 km of sea and estuary dikes in RRD versus 450 km of sea dikes in the MRD
206 (Le et al., 2018; Preston et al., 2003; Pilarcyzk and Nguyen, 2005). Thus, salinity intrusion extends up to 20 km
207 from the main river in the RRD (Ca et al., 1994). As rice plants are unable to thrive in soils with soil salinities
208 exceeding 4 g/L (Pham et al., 2018b), affected farmers have converted their paddy fields into aquaculture
209 ponds to cultivate shrimp and fish instead. Other farmers have turned to planting salinity tolerant crops such
210 as coconut, mango and sugarcane. In some cases, farmers have opted for a rice-aquaculture system whereby
211 rice is planted in the wet season and fish/shrimp is cultivated in the dry season when soil salinities are high
212 (Nguyen and Vo, 2017; Pham et al., 2017).

213 Besides environmental factors, the greater profitability of fruits, vegetables, fish and shrimp also incentivise
214 farmers to plant more non-rice crops. The income per hectare of rice was USD 146 compared to pomelo (USD
215 16,844) and coconut (USD 1,484) (Hoang and Tran, 2019). Meanwhile, farmers who practise shrimp-rice
216 rotational systems earned 50% more than those who had two rice crops (Morton, 2020; Schneider and Asch,
217 2020). In addition, high demand for fruits and vegetables for export and from growing urban populations with
218 greater affluence and knowledge about nutrition, also encouraged farmers to diversify from rice monoculture
219 leading to possible declines in the overall rice growing area (Hai, 2019; Nguyen and Vo, 2017; Figure 4).

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

3.1.2. Urban expansion

229 Rapid urbanization is accelerating the loss of agricultural land in both the Red River Delta and Mekong
230 River Delta. In Hanoi, a major city in the Red River Delta, 1,420 ha of agricultural land was lost per year from
231 2000-2007, equivalent to a yearly loss of 3%. By 2025, up to 450,000 ha of agricultural land are expected to be
232 converted to urban land. Most of this land use conversion occurs in peri-urban areas 5-15 km from the city
233 centre. The same peri-urban land is often used to grow food, flowers and livestock to supply food for the
234 urban population in Hanoi. However, this land is considered by local authorities to be land reserve for urban
235 planning, instead of resources for food supply (Drebold, 2017; Pham et al., 2015). Most of this peri-urban
236 agricultural land is often forcibly obtained with minimal compensation given to farmers and then sold to
237 foreign developers (Drebold, 2017). Similar urban expansion is also occurring in Can Tho city in the Mekong
238 Delta with corresponding losses of agricultural land (cf. Garschagen et al., 2011; Pham et al., 2010). A decline
239 in agricultural land means a decline in rice growing areas as well (Figure 4).

240 High land prices and a shrinking availability of arable land have forced farmers to to practicepractise
241 agricultural intensification. In the RRD, rice production grew more than 25% from 2000-2011 without
242 corresponding increases in rice growing areas due to intensified cropping practices involving the use of new
243 high yielding rice varieties, irrigation during dry season and high inputs of agrochemicals (Drebold, 2017;
244 Morton, 2020). The high pesticide use was reflected in a study in Nam Dinh province in the RRD where 8 out of
245 12 target pesticides were found in agricultural soils. In this study, frequently detected pesticides include
246 isoprothiolane, chlorpyrifos and propiconazole and besides polluting the environment, the presence of high
247 concentrations of pesticide residues also lowers the quality of rice sold for consumption (Braun et al., 2018;
248 Figure 4).

249 In general, pests such as the brown planthopper are naturally occurring and are not a threat at low densities.
250 However, intensive rice production with high seeding densities and the use of susceptible varieties creates a
251 constant supply of food which allows their numbers to balloon. This is exacerbated by the asynchronous
252 planting which creates a continuous supply of rice plants throughout the year in the Mekong Delta. In addition,
253 the over-use of nitrogen fertilizers increase the pests' reproductive potential. Thirdly, the excessive use of
254 pesticides also kills the natural enemies of pests such as spiders, ants, bees, beetles, dragonflies, frogs, lady
255 bugs and wasps. Besides killing the natural predators of rice pests, the pests targeted by the pesticides may
256 also become resistant to the pesticide. As a result, higher doses of the pesticide may be needed to kill them in
257 future. For example, killing plant hoppers now requires a pesticide dose 500 times more than was needed in
258 the past (Normile, 2013). The overuse of pesticide is due to a combination of factors such as insufficient
259 knowledge of its proper use as well as aggressive marketing by agrochemical companies (Bottrell and Schoenly,
260 2012; Normile, 2013; Sebesvari et al., 2011). The hashed lines in Figure 4 show that pesticide use may not
261 necessarily reduce the incidence of pests and diseases if excessive volumes were applied.

3.1.3. Dikes

263 Wet season flooding is a naturally occurring phenomenon in the two d-mega-Deltas of Vietnam (Chan
264 et al., 2012; 2015). To facilitate the planting of rice during the wet season, flood prevention dikes were
265 constructed to keep floodwaters out (Figure 5). The MRD has more than 13,000 km of flood prevention dikes;

266 of which 8,000 km are low dikes below two meters tall. These low dikes were mostly constructed before 2000
267 to delay the entry of floodwaters at the start of the monsoon season to allow two rice crops to be grown. A
268 severe flood in 2000 provided the impetus for river dikes to be heightened to 3.5 m to completely keep
269 floodwaters out. These high dikes have facilitated triple cropping in the MRD, particularly in Dong Thap and An
270 Giang provinces (Chapman et al, 2016; Howie, 2005; Le et al., 2018; Triet et al., 2017). However, the presence
271 of high dikes in the MRD has reduced the supply of fertile alluvium, increasing the need for artificial fertilizers
272 and pesticides to maintain yields (Chapman et al., 2017; Figure 4).

273 A study comparing sediment deposition in areas of high and low dikes in An Giang Province found that double
274 cropping farmers who cultivate their crops in areas with low dikes have an average of 2.5 cm of sediment
275 deposition. This deposition by floodwaters improved their average annual input efficiency by 0.3 tons of yield
276 per ton of fertilizer. Conversely, triple cropping farmers had very little deposition, averaging 0.5 cm as the high
277 dikes kept floodwaters out. Some deposition was found only if there had been a dike breach which also caused
278 crop damage (Chapman et al., 2016). The value of flood deposits is reiterated by Manh et al. (2015)'s study
279 which estimated that the annual deposition of sediment bound nutrient can naturally supply over half of the
280 fertilizers needed for a season of rice crop. The provision of "free" fertilizers by the encroaching flood waters
281 benefits the less economically endowed farmers who must purchase artificial fertilizers to maintain yields
282 (Chapman et al., 2017; Kondolf et al., 2018; Figure 4).

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

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

3.1.4. Sand mining
297 Sand mining is carried out on a large scale in the Mekong (Kondolf et al., 2018). Fueled by demand
298 from reclamation, export and construction, 55.2 million tons of sediment wereas extracted from the Mekong
299 main stem in Laos, Thailand, Cambodia and Vietnam from 2011 to 2012 (Bravard and Gaillot, 2013; Robert,
300 2017). A more recent analysis of bathymetric maps and the local refilling processes by Jordan et al. (2019) put
301 the amount of sand extracted from the Mekong Delta in 2018 at 17.77 Mm^3.

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

310 Aggressive sand mining also disrupts natural flooding. A recent study of riverine mining on flood frequency in
311 the Long Xuyen Quadrangle (LXQ) in the Mekong Delta found that flood frequency had dropped by 7.8% from

312 2005-2015. Water levels at local gauge stations also showed an overall decreasing trend indicating that the
313 lowering of the riverbed hads reduced the frequency of flooding. Disrupted flood regimes result in reduced
314 volumes of water and sediments for agricultural production. In addition, floodwaters typically deposit fertile
315 sediments while flushing the pesticides and fertilizers accumulated from intensive agricultural production.
316 When the flood frequency decreases, the frequency at which farmlands benefit from these natural soil quality
317 enhancement decreases. Consequently, soil fertility may decrease over time and lead to declines in rice yields
318 unless artificial fertilizers are added (Park et al., 2020; Figure 4).

319 While there are several studies on the diffuse, yet insidious nature of sand mining in the Mekong (cf. Bravard
320 and Gaillot, 2013; Bruiner et al., 2014; Jordan et al., 2019; Kondolf et al., 2018; Park et al., 2020; Robert, 2017;
321 Schmitt et al., 2017), the extent of sand mining in the Red River Delta is unclear as there is almost no research
322 on this issue. We did however come across an article in a Vietnamese newspaper about rampant sand mining
323 in the Red River and how mining operations have caused erosion in nearby villages (Chinh, 2018). Similar to
324 the situation in the MRD, the authorities have turned a blind eye to this illegal business (Bravard and Gaillot,
325 2013; Chinh, 2018).

3.1.5. Groundwater extraction

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

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

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

358 Lastly, although high As concentrations in groundwater is common in in the RRD (cf. Berg et al., 2007; Luu,
359 2019; Pham et al., 2018a; Winkel et al., 2011), there is no research on (groundwater induced) land subsidence
360 in the Red River Delta. Thus, the magnitude of land subsidence in the delta is uncertain and should be an area
361 for future research.

3.2. Regional anthropogenic drivers

3.2.1. Upstream dams

364 The Mekong River originates in the Tibetean Plateau and flows through China, Myanmar, Laos,
365 Thailand, Cambodia and southern Vietnam. To meet growing demands for electricity, many small and large
366 scale hydropower projects have been commissioned in each country to take advantage of this supposedly
367 green and clean source of energy (Nhan and Cao, 2019; Manh et al., 2015). A total of 241 dams have been
368 completed in the entire Mekong Basin with another 29 ~~are~~ under construction. A further 91 is currently being
369 planned. These 361 dams consist of 176 hydropower dams and~~,~~ 185 irrigation dams. Of the 364 dams in the
370 Mekong, 20 are in Vietnamese territory (WLE Mekong CGIAR, 2020a). Conversely, the Red River originates in
371 Yunnan province in China and flows towards northern Vietnam. It is less heavily dammed with a total of 105
372 dams in China and Vietnam. There are 25 hydropower dams, 3 multi-purpose dams and 9 irrigation dams in
373 the Red River Basin in Vietnam (Vinh et al., 2014; WLE Mekong CGIAR, 2020b). While there are no dams in the
374 Mekong River Delta or the Red River Delta due to its relatively flat elevation, upstream dam development
375 influences downstream regions in many ways with the environmental impacts extending far beyond the dam
376 itself (Kondolf et al., 2014).

377 Firstly, a substantial amount of coarse sand, gravel and suspended sediment is impounded in reservoirs behind
378 the dams instead of being transported downstream. This diminished sediment load may aggravate erosion
379 downstream from the dam (Nhan and Cao, 2019; Figure 4). Using a network model, under a "definitive future"
380 scenario of 38 new dams, the cumulative sediment reduction in the Mekong Delta would be 51%. Conversely,
381 under full build-up of 133 new dams, only 4% of the pre-dam sediment load will reach the Delta (Kondolf et al.,
382 2014). Manh et al. (2015) also reached similar conclusions with a quasi-2D hydrodynamic model of suspended
383 sediment dynamics. Floodplain sedimentation would decrease by about 21 to 96% while sediment load
384 supplied to the sea at the river will diminish by 14 to 95% with the extreme values representing full dam build-
385 up. Even if dam construction was limited to the river tributaries instead of the main stem, the cumulative
386 sediment trapped could be as high as 68% meaning that only about 32% of the sediment load would reach the
387 Mekong River delta (Kondolf et al., 2014).

388 Indeed, Binh et al. (2020) found that the suspended sediment loads in the MRD ha~~ds~~ decreased by 74.1% in
389 2012-2015 primarily due to six mainstream dams in the Lancang cascade in China. In particular, the Manwan
390 and Dachaoshan dams contributed to 32% of the reduction. In addition, from 2014-2017, the average incision
391 rate of the Tien River in the MRD was three times higher than the previously recorded value. Sand mining was
392 responsible for a max of 14.8% of the annual riverbed incision while the remainder was caused by hydropower
393 dams upstream.

394 The deleterious impacts of dams on sediment loads can also be found in the Red River Delta in spite of the
395 smaller number of dams. While the Hoa Binh dam is located on a tributary of the Red River in Vietnam, its
396 large size has influenced suspended sediment distribution in the lower Red River Basin. For example, an
397 analysis of the suspended sediment concentration over a 50 year period from 1960 to 2010 showed that yearly
398 suspended sediment flux had dropped by 61% at Son Tay near Hanoi (Vinh et al., 2014). Similarly, Duc et al.
399 (2012) calculated that the suspended sediment budget at Son Tay and Hanoi Hydrological monitoring stations
400 was reduced by 56% after the Hoa Binh Dam became operational in 1989. The reduction in sediment loads at
401 the Red River Delta would likewise have a similar impact on delta size and rice growing areas.

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

3.3. Local natural hazard drivers

3.3.1. Drought

415 Droughts do not result solely from a lack of rainfall; theyit can also result from changes in the arrival of rains
416 and the length of the wet season (Adamson and Bird, 2010; Lassa et al., 2016). Vietnam was affected by
417 droughts in 1997-1998, 2002-2003, 2009-2010 and most recently in 2015-2016. The 2015-2016 drought was
418 the most severe in 90 years (Grosjean et al., 2016). All thirteen provinces in the Mekong Delta were affected
419 by the 2015 drought. Besides a lack of water for irrigation, the drought caused saltwater to intrude intrusion of
420 up to 70 km inland. Cumulatively, the drought and accompanying saltwater intrusion damaged 400,000 ha of
421 rice crops including 50,000 ha of paddy in Kieng Giang and Ca Mau provinces in the MRD (Grosjean et al., 2016;
422 Nguyen, 2017). Although there is no research on how droughts and salinity intrusion haves affected rice
423 quality in Vietnam, research from elsewhere has shown that water shortages and salt stress induces
424 physiochemical alterations which affect the rice grains produced (Pandey et al., 2014; Razzaq et al., 2019;
425 Figure 65).

426 Compared to the MRD, there is not much research or reports on droughts in the Red River Delta. The UNW-
427 DPC (2014) reported that the RRD experienced droughts from the end of 1998 to April 1999 which affected
428 86,140 ha of rice. Another drought occurred from January to February 2004 with the water level of the Red
429 River at the lowest in 40 years. Low water levels were also reported in 2010, however drought conditions and
430 saltwater intrusion wereas more severe in the MRD (Overland, 2010). The effect of droughts on rice
431 agriculture –reduced yields from a lack of water and salinity intrusion would also be similar in the RRD.

3.3.2. Freshwater flooding

433 Ranked as the second most severe natural hazard after typhoons, freshwater floods are caused by
434 overflowing rivers, heavy monsoonal rains or associated with heavy rain from typhoons (Chan et al., 2012;
435 2015; Hung et al., 2012; McElwee et al., 2017). Theoretically, flooding reduces rice growing areas but it is
436 simplistic to assume that flooded fields result in immediate loss of rice crops. A study by Kotera et al. (2005) in
437 the RRD showed that the type of rice, stage of rice growth, lengths and depths of submergence were factors
438 that influence the survival rates of rice crops. For example, the local variety Moc Tuyen was less resilient to
439 submergence than the two other genetically improvedmodified high yielding varieties. In terms of growth
440 stage, rice plants at the tillering stage are more likely to succumb to submergence than those at the vegetative
441 stage. Plants fully submerged for short durations (two days) also had lower chances of survival than those that
442 were partially submerged in floodwaters for longer durations (up to eight days). As such the effect of flooding
443 on rice growing areas is uncertain as other factors that affect crop mortality include the type of rice grown, the
444 stage of rice growth as well as the depth and length of submergence in floodwaters (Figure 65).

445 Although severe flooding can disrupt agricultural activities, moderate levels of freshwater flooding bring
446 benefits to (rural) farmers (EEPSEA, 2011). Floodwaters from rivers improve agricultural productivity by
447 depositing nutrient rich flood sediments on agricultural soils (Chapman et al., 2016). In addition, floods wash

448 away contaminants, purify and recharge aquifers, kill pests and mitigate saltwater intrusion (EEPSEA, 2011;
449 Hoang et al., 2018; Figure 65). Aquatic resources such as fish, crabs and snails also come in with the
450 floodwaters which local farmers can collect to supplement their incomes. Besides growing rice, it is also
451 possible to cultivate vegetables, fish, prawns and ducks in the flooded fields (Nguyen and James, 2013).
452 Towards the end of the flooding season and the start of the rice cultivation season, floodwaters provide the
453 water needed to start growing rice (Hoa et al., 2008).

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

3.3.3. Typhoons

463 Typhoons are the most severe natural hazard that affects Vietnam. When a typhoon occurs, affected
464 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
465 Vietnam coincides with the typhoon season, widespread flooding can be expected from heavy rain and
466 overflowing rivers (CCFSC, 2005; Mai et al., 2009; Nguyen et al., 2019a). Storm surges can also occur when high
467 winds pushing on the ocean's surface is combined with the effect of low pressure in the center of a typhoon
468 (Takagi et al., 2013). Imamura and Dang (1997)'s study of typhoon disasters in Vietnam since 1950 found that
469 half of the 450 typhoons recorded during the study period were accompanied by a storm surge of over 1 m
470 and 11% were over 2.5 m high. In the Red River Delta, Quynh et al. (1998) found that the maximum storm
471 surge is usually between 1 to 1.5 m above mean sea level. In short, rice production will be adversely affected
472 by strong winds and widespread flooding from heavy precipitation and storm surges in the event of a typhoon.
473 Saltwater flooding may reduce the rice growing areas as rice is not adapted to withstand prolonged
474 submergence and/or saline conditions. Additionally, strong winds damage rice plants with both effects
475 contributing to a reduction in rice yields (Figure 65).

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

484 An average of five to six typhoons affects Vietnam between June and November every year (Larson et al., 2014;
485 Nguyen et al., 2007). Typhoon activity shifts from the north to the South as the year progresses. Therefore,
486 peak activity in the north and southern part of Vietnam is in August and November respectively (Imamura and
487 Dang, 1997). We reviewed the Digital Typhoon Database and found 303 typhoons that came within 500 km of
488 Vietnam's coastline from 1995 to 2018. 29 cyclones made theirits initial landfall in the Red River Delta while
489 only four cyclones made landfall in the Mekong Delta during the study period – one each in 1973, 1996, 1997
490 and 2006 (Unpublished results). Although the MRD is less prone to typhoons, the two of the most recent
491 typhoons caused significant damage despite each being classified as a tropical storm upon landfall. Typhoon
492 Linda (1997) caused some 349,232 ha of rice to be submerged while Typhoon Durian (2006) damaged 6,978 ha

493 of agricultural land (International Federation of Red Cross and Red Crescent Societies, 2006; UN Department of
494 Humanitarian Affairs, 1997).

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

505 **3.3.4. Pests and diseases**
506 Examples of pests that occur in rice fields of Vietnam include the brown planthopper (BPH,
507 *Nilaparvata Lugens* Stål), white backed planthopper (WBPH, *Sogatella furcifera* Horvath) and small brown
508 planthopper (SBPH, *Laodelphax striatellus* Fallen). These planthoppers not only damage plants by ingesting its
509 sap, they also transmit pathogenic viruses that kill the plants. The BPH is a vector for the rice grassy stunt virus
510 (RGSV) and the rice ragged stunt virus (RRSV); the WBH transmits the southern rice black streak dwarf virus
511 while the SBH vectors the rice stripe virus (RSV) and the rice black streaked dwarf virus (RBSDV) (Bottrell and
512 Schoenly, 2012; Matsukawa-Nakata et al., 2019). Other pests that affect rice include parasitic worms called
513 nematodes. Root nematodes that affect deepwater and irrigated rice fields in the MRD include
514 *Hirschmanniella oryzae* (rice root nematode), *Hirschmanniella murcronata* and *Meloidogyne graminicola* (rice
515 root knot nematode). Stem nematodes like the *Ditylenchus angustus* infect floating, deepwater and rainfed
516 lowland rice in the MRD (Nguyen and Prot, 1995). Other significant pests of rice in Vietnam include rice leaf
517 folders, rice thrips and stem borers (Sebesvari et al., 2011). Meanwhile, common rice diseases include bacterial
518 leaf blight, bakanae, black rot of grain, brown spot, leaf yellowing disease, neck blast, rice blast disease, root
519 rot, sheath blight, sheath rot and stem rot (Pinnschmid et al., 1995; Sebesvari et al., 2011; Trung et al., 1995;
520 Kim et al., 1995).

521 Between 2005 and 2008, rice production in the Mekong Delta was severely reduced by outbreaks of brown
522 planthopper and the associated virulent diseases. The problem was particularly severe in An Giang, Dong Thap
523 and Tien Giang provinces with more than 50% of the cultivated areas affected (Berg and Tam, 2012). In 2009,
524 the Southern rice black streaked dwarf virus affected 19 provinces in North Vietnam including those in the Red
525 River Delta. More than 80% of the rice fields in Nam Dinh, Nghe An, Quang Ninh and Thai Binh provinces
526 wereas infested and yield was non-existent (Hoang et al., 2011). In short, an increase in pest and/or disease
527 outbreaks will likely cause a reduction in rice yield (Figure 65).

528 **3.4. Global natural hazard driver**

529 **3.4.1. Sea level rise (SLR)**
530 Besides creating new environmental challenges, pre-existing threats to rice production and food
531 security will be exacerbated by climate change. One of the effects of climate change includes rising sea levels.
532 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
533 10 mm/year or more by 2010 (Church et al., 2013). This may result in a 0.98 m increase in sea level by 2100
534 (Lassa et al., 2016). To quantify sea level rise locally, observations at tide gauges across Vietnam have recorded
535 an average yearly increase of 3.3 mm from 1993-2014 (Hens et al., 2018). SLR may also increase the risk of
536 storm surges (Hanh and Furukawa, 2007). In the Red River Delta, Neumann et al. (2015) found that sea level
537 rise through 2050 could reduce the recurrence interval of the current 100 year storm surge with a 5 m height
538 to once every 49 years. Inadequately constructed and poorly maintained dikes and embankments may be

539 breached resulting in saltwater flooding which will damage rice growing areas and other properties (Hanh and
540 Furukawa, 2007; Figure 65).

541 Rising sea levels coupled with accelerated coastal subsidence caused by excessive groundwater extraction will
542 cause large portions of the low lying RRD and MRD to be inundated and flooded (Allison et al., 2017). This
543 facilitates the infiltration of saltwater into groundwater aquifers and this may increase salinity gradients in the
544 MRD and RRD. In particular, salinity intrusion will worsen during the dry season. Approximately 1.8 million ha
545 in the MRD are already affected by dry season salinity of which 1.3 million ha are affected by salinity levels
546 above 5 g/L (Lassa et al., 2016). This area is predicted to increase to 2.2 million ha with rising sea levels.
547 Meanwhile, in the northeast part of the RRD, the 1% salinity contour has migrated landwards by 4 to 10 km
548 (Hanh and Furukawa, 2007). Increased soil salinization leads to a loss of land available for rice production
549 (Figure 65). Though there are already sea dikes and saline water intrusion slices in both the MRD and RRD to
550 reduce incursions of seawater (Braun et al., 2018; Tuong et al, 2003), they may be inadequate if they are not
551 well maintained and upgraded.

552 **4. Discussion**

553 **4.1. Untangling complexity**
554 Relevant information on the different drivers and environmental processes affecting rice production
555 in Vietnam are fragmented in a range of academic and non-academic sources (Bosch et al., 2007) making it
556 difficult for policymakers and managers to have a good overview of the reinforcing and interdependent
557 processes and issues affecting food security in Vietnam. Using a systems-thinking approach, we amalgamated
558 the various drivers and created flow diagrams to consider how rice productivity can be positively or negatively
559 impacted by the various drivers and environmental processes (Figures 4, 65). Rice growing areas are negatively
560 affected by the expansion of aquaculture and alternative crops and urban expansion. But with agricultural
561 intensification, facilitated by high agrochemical inputs, it was possible to maximize rice yields in spite of a
562 smaller growing area. However excessive agrochemical use affects rice quality and may have an opposite
563 effect on the prevalence of pests and diseases. Next, anthropogenic developments meant to improve
564 agricultural productivity or increase economic growth can create many unwanted environmental
565 consequences. Dikes keep floodwaters and salt intrusion out but there is a reduction in fertile silt deposits.
566 Sand mining increases channel erosion and reduce the frequency of natural freshwater flooding. Similar to
567 sand mining, upstream dams affect sediment accumulation as sediments are trapped in reservoirs upstream
568 but the impacts of upstream dams extend over a larger geographical area. Lastly, groundwater extraction
569 causes land subsidence, saltwater intrusion and arsenic contamination with negative feedbacks on rice
570 growing areas and the quality of rice produced.

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

580 The use of flow diagrams provides a visual overview of the key anthropogenic drivers and natural hazards that
581 affect rice production but we caution that Red River Delta and the Mekong River Delta are vast and diverse
582 regions and there are differences in the ways each delta is affected by natural hazards and anthropogenic
583 drivers. For example, high dikes and the associated problem of sediment exclusion are a problem unique to the

584 Mekong Delta (Chapman et al., 2017). Next, compared to the Mekong, the Red River has substantially fewer
585 dams (361 vs 105). In addition, typhoons are less common in the Mekong Delta and droughts occur less
586 frequently in the Red River Delta.

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

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

611 **4.2. Adaptation and soft solutions**
612 Recognizing the environmental challenges limiting agricultural production, farmers in both mega
613 deltas have adapted and improvised. Instead of accepting their fate, farmers overcome high soil salinities by
614 implementing measures such as replacing rice with salinity tolerant crops, transiting to shrimp aquaculture, or
615 turning to rice-shrimp farming whereby rice is grown in the wet season and shrimp is cultivated in the dry
616 season. For those unable to switch from rice monoculture, farmers have sought to grow rice on higher ground,
617 shift crop calendars or dig additional ditches to drain saltwater and store freshwater. In addition, to prevent
618 water storage ponds from becoming contaminated with saltwater, canvas sheets are placed on the soil surface
619 to create a protective barrier (Tran et al., 2019; Nguyen et al., 2012). Similarly, farmers in peri-urban areas who
620 are faced with shrinking agricultural lands have turned to practicing agricultural intensification and/or
621 switched to planting high value crops such as fruits and vegetables (Morton, 2020; van den Berg et al., 2003).
622 In short, farmers are constantly experimenting, learning and sharing knowledge and experiences with other
623 farmers to come up with solutions for overcoming environmental limitations (Tran et al., 2019; Nguyen et al.,
624 2012).

625 Unfortunately, adaptations are not successful all the time. For example, the widespread conversion of paddy
626 fields to shrimp ponds will increase soil salinity and reduce the availability of freshwater. Over time, neighbors
627 who have not switched to aquaculture may be unable to plant rice and would have to seek alternative
628 livelihoods (Nguyen et al., 2012). In addition, rice-shrimp systems are not problems free as well. Leigh et al.
629 (2017) found that environmental conditions in rice-shrimp systems were suboptimal and contributed to low

630   yields and survival. Water temperature and salinity tended to be too high in the dry season and dissolved
631   oxygen too low, causing most shrimps to die. For rice, the high soil salinity caused by having the aquaculture
632   pond was a major limitation – in their study, only three out of 18 ponds produced a harvestable rice crop.

633   Apart from farmer-led initiatives related to crop and land use change, integrated pest management (IPM)
634   should also be adopted to reduce the use of pesticides to rid pests. Farmers ~~who~~that practise IPM use a
635   combination of pest resistant cultivars, fertilizer management and agronomic practices to increase the effects
636   of predators and other naturally occurring biological control agents. For example, farmers can grow flowers,
637   okra and beans along their paddy fields to attract bees and wasps that infest planthopper pests' eggs. With
638   more natural predators around, pesticides are only used when necessary (Bottrell and Schoenly, 2012; Normile,
639   2013). Alternatively, rice-fish farming and duck-rice systems can also be implemented to provide a more
640   economically and ecologically sustainable alternative to intensive rice monoculture (Berg and Tam, 2012; Men
641   et al., 2002).

642   In rice-fish farming, farmers use minimal pesticide as it kills the fish and the natural predators of rice pests.
643   Instead, fish help to control pests and fish droppings keep the soil fertile. Upon maturity, the fish can be sold
644   to increase the farmer's income by up to 30% (Berg et al., 2017; Bosma et al., 2012). Ducks can also be reared
645   in immature rice fields. Besides providing food, the ducks serve as biological controls for insects and weeds.
646   Their droppings fertilize the soils and their movement aerates the water to benefit the rice plants (Men et al.,
647   1999; 2002). Men et al. (2002) showed that a duck-rice system in Can Tho province in the Mekong eliminated
648   the use of pesticides, halved the use of fertilizers and the additional income from the sale of ducks increased
649   farmers' incomes by 50 to 150%. Overall, the higher incomes and ecosystem services provided by the fish or
650   ducks, coupled with reduced agrochemical use benefit farmers.

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

663   To mitigate "wicked" environmental challenges, there is a need for holistic land use planning and soft
664   measures (eg. implementing crop and land use change) on top of hard engineering structures. Previously,
665   management options to increase agricultural productivity and mitigate the threats posed by natural hazards
666   were largely characterized by hard options such as the construction of dikes, sea walls and sluice gates. These
667   were typically top-down projects spearheaded by the local government (Neumann et al., 2015; Smajgl et al.,
668   2015). While highly visible engineering structures are easily constructed and generally effective, unwanted side
669   effects may be created. For example, flooding and sediment exclusion were some problems that were
670   inadvertently created due to the presence of high dikes. In the long term, (costly) maintenance is needed to
671   maintain the functionality of engineered structures (Hoang et al., 2018; Neumann et al., 2015). In addition,
672   during the pre-construction phase, natural vegetation may be cleared (Geist and Lambin, 2002). Adopting a
673   systems-thinking approach would allow policymakers and managers to situate the range of mitigation
674   measures within broader environmental processes. In doing so, a clearer view of the possibilities and
675   challenges present in an era of widespread anthropogenic development and changing climates is provided.

5. Conclusions

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

A key finding is that demand for aquaculture and alternative crops and urban expansion ha~~ve~~s diminished rice growing areas. The problem of shrinking agricultural land is ameliorated by agricultural intensification which has increased land efficiency. However, widespread agrochemical use causes land and water pollution and reduces crop quality. In addition, anthropogenic developments such as dike construction can improve agricultural productivity but also create unintended environmental problems. Even human activities that are unrelated to agriculture such as sand mining, groundwater extraction and dam construction can reduce rice productivity. In addition, natural hazards not only affect rice quality and quantity but may also amplify some of the problems created by human activities – for instance, typhoons and sea level rise may induce saltwater flooding and worsen salinity intrusion. In the future, climate change may exacerbate the effects of natural hazards by increasing the frequency and severity of natural disasters. Therefore, the problems associated with some of the natural hazards such as excessive saltwater flooding and saltwater intrusion may be more frequent and possibly worse. In sum, the processes and issues affecting food security are multidimensional and interdependent and we used a systems-thinking approach to develop a visual representation of the ways in which anthropogenic land-use factors and natural hazards can affect rice quantity and quality in the MRD and the RRD in Vietnam. We have also sought to define whether the anthropogenic or natural hazard driver was a local, regional or global driver to highlight the scale at which each driver operates.

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

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

Acknowledgements

This project was funded by EOS grant M4430263.B50.706022. We thank Khoi Dang Kim, ~~Montesclaros~~ Jose Ma Luis Pangalangan Montesclaros and Nghiem Thi Phuong Le for their advice.

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1299 **Table**
1300 **Table 1.** Rice planting, growing and harvesting periods in the Mekong River Delta and the Red River Delta in
1301 Vietnam.

	Planting			Harvesting			
Mekong River Delta	**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

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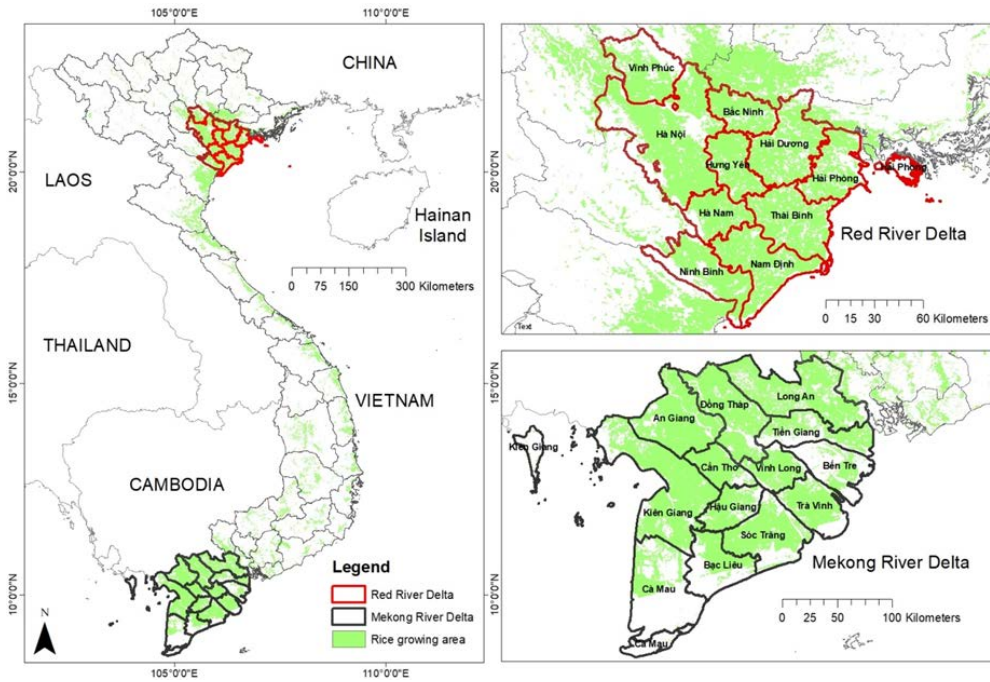
1303 **Figures**

1304

1305 Figure 1. Distribution of rice growing areas in the Red River Delta (RRD) in northern Vietnam and the Mekong
1306 River Delta (MRD) in southern Vietnam. Rice growing extents were obtained from Nelson and Gumma (2015).

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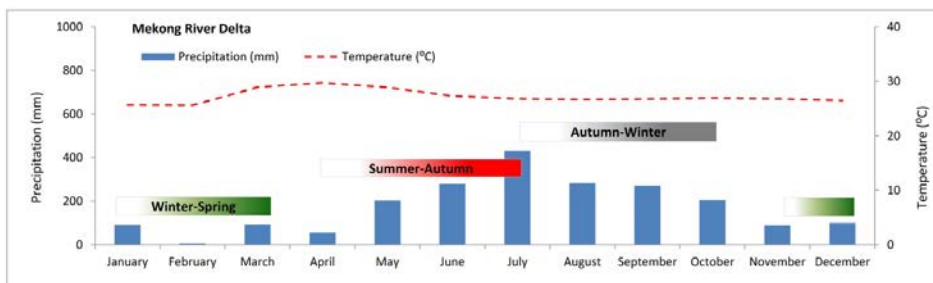
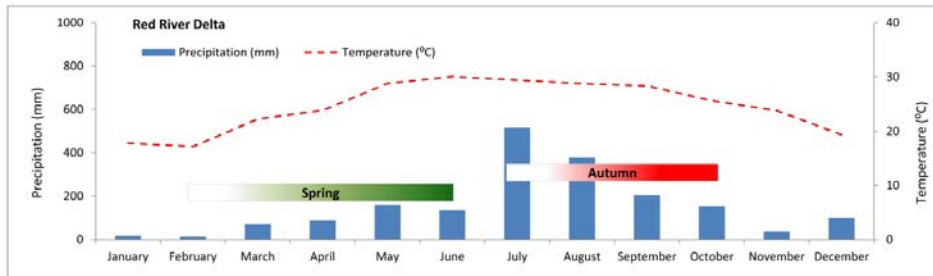
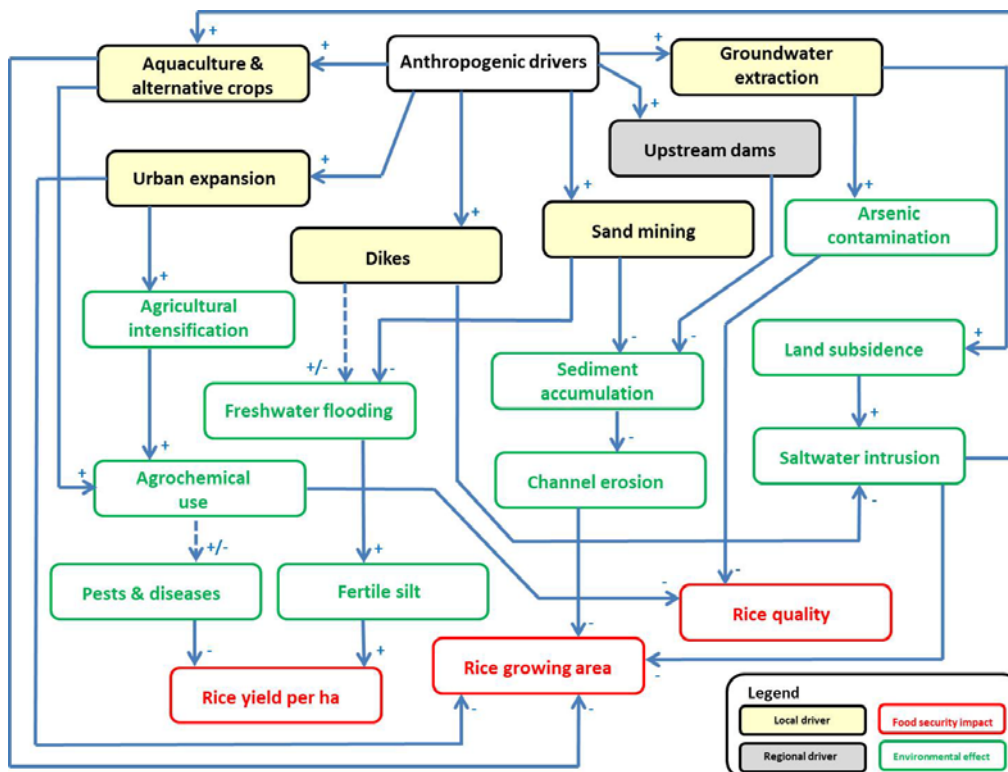

1310

1311 Figure 2. Climograph for the Mekong River Delta annotated with the winter-spring, summer-autumn and
1312 autumn-winter growing seasons. The colour gradient (from faded to dark) represents planting, growing and

 harvesting times for each crop. Precipitation and temperature data were taken from the Statistical Yearbook of
 Vietnam 2018 (General Statistics Office, 2018).

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

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

1327 incidence of pests and diseases but the over-use of chemicals can lead to pesticide resistance which may
1328 increase outbreaks of pests and diseases.

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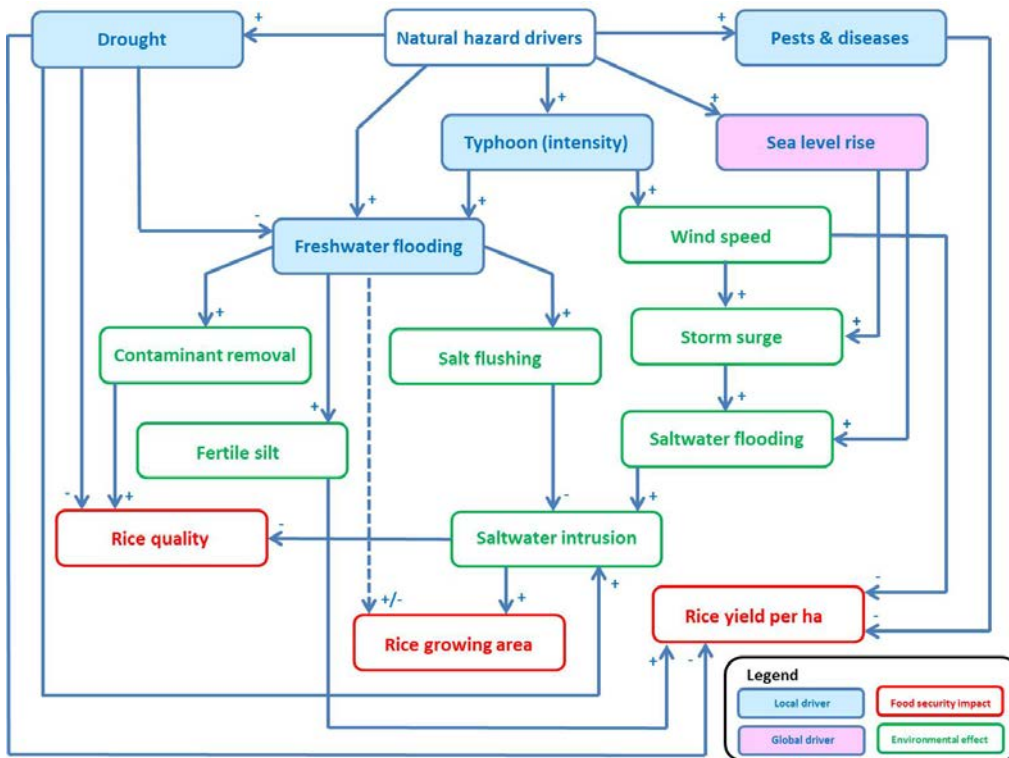
1339 Figure 5. Example of a river dike for flood control in Nam Dinh province in the Red River Delta.

1340

1341 Figure 65. Flow diagram showing the natural hazards that affect rice production in the two mega-deltas of
1342 Vietnam. Local drivers refer to natural hazards that occur within the two mega-deltas. Although sea level rise
1343 has implications on a local scale, it is considered a global driver as it occurs on a global scale. The effect of
1344 flooding on rice growing areas is uncertain as other factors that affect crop mortality include the type of rice
1345 grown, the stage of rice growth as well as the depth and length of submergence in floodwaters.