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Interacting effects of land-use change, natural hazards and climate change on rice agriculture in Vietnam

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Abstract
Vietnam is a major rice producer and much of the rice grown is concentrated in the Red River Delta (RRD) and the Mekong River Delta (MRD). While the two mega-deltas are highly productive regions, they are vulnerable to natural hazards and the effects of human related environmental change. The natural hazards that affect Vietnam include typhoons, floods and droughts while the major anthropogenic developments happening in Vietnam include dike development, sand mining, dam construction and groundwater extraction. Outbreaks of pests and diseases are also common. Although there is a substantial volume of work investigating the environmental impacts of these natural hazards and anthropogenic interventions, few studies have examined the implications of these on food security. To show that the processes and issues affecting food security are reinforcing and interdependent, we used a systems thinking approach to represent the ways in which natural hazards, anthropogenic land-use and climate change affect rice production in the two mega-deltas. A key finding is that anthropogenic developments meant to improve agricultural productivity or increase economic development create many unwanted environmental consequences such as an increase in flooding, saltwater intrusion and land subsidence which in turn create other negative feedbacks on rice production and quality. In addition, natural hazards may amplify the problems created by human activities. In future, besides creating new environmental threats, climate change may exacerbate the effects of natural hazards by increasing the frequency and severity of natural disasters. Our meta-analysis highlights the ways in which a systems thinking approach can yield more nuanced perspectives to tackle complex and interrelated environmental challenges. Given that mega-deltas worldwide are globally significant for food production and are highly stressed and degraded landscapes, a systems thinking approach can be applied to provide a holistic and contextualized overview of the threats faced in each location.

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

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1. Introduction

Rice is an indispensable staple crop for the 560 million low and lower-middle income people in Asia (GRSP, 2013). Of the 160 million hectares (ha) of rice harvested globally in 2016, 140 million ha (88%) was harvested in Asia, of which 47 million (29%) came from Southeast Asia (FAO, 2017). In 2017, Vietnam exported US$1.6 billion of rice and was the fifth largest rice exporter in the world contributing 7.5% of the world's total rice exports (Workman, 2018). Besides cultivation for export, rice is also a staple food for the Vietnamese (USDA, 2012). The importance of rice as a key cash crop in Vietnam is reflected in the total area allocated for rice paddy production in 2016 – 4.1 million ha or 15% of the country's 27 million ha of agricultural land (General Statistics Office of Vietnam, 2018).

While Vietnam's rice sector is an important source of revenue and food for the country, it is vulnerable to the effects of natural and human related environmental change which can adversely affect rice productivity and rice growing areas. Rice growing regions in Vietnam are concentrated in low-lying coastal areas, which are susceptible to crop damage from natural hazards such as typhoons, storm surges, flooding and sea-level rise. Approximately 59% of Vietnam's total land area and 71% of its population are susceptible to the impacts of typhoons and floods due to its long coastline and large populations inhabiting low-lying coastal areas (Chau et al., 2014). Typhoons are common in Vietnam with 147 typhoons making landfall in Vietnam from 1949 to 2014, causing deaths and adversely affecting infrastructure, fisheries and agriculture (Huang et al., 2017; Nguyen et al., 2019). 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).

Human related environmental change in the form of anthropogenic land-use activities such as the application of pesticides and land development may not immediately lead to crop damage but could threaten the long-term viability of arable lands for rice production. For example, the use of pesticides in rice fields has led to pesticide resistance. Killing plant hoppers now requires a pesticide dose 500 times more than was needed in the past. In addition, pesticide over-use also leads to the emergence of new strains of rice disease; make it increasingly harder to avoid crop losses (Hoang et al., 2011; Normile, 2013). On the other hand, infrastructure related development such as coastal dikes and hydroelectric dams together with resource extraction activities such as of river bed sand mining and groundwater extraction can lead to a reduction in sediment and water availability which are needed for the long-term productivity of rice agricultural systems (Allison et al, 2017; Robert, 2017; Schmitt et al., 2017).

Many studies have investigated how Vietnam is affected by natural hazards or anthropogenic land-use changes (cf. Howie, 2005; Minderhoud et al., 2018; Nguyen et al., 2019; Vinh et al., 2014) and a number of studies have examined how natural hazards and changes in anthropogenic land-use have affected rice productivity. For example, the construction of high dikes to mitigate flooding in the Mekong Delta has facilitated triple cropping and increased rice yields (Chapman and Darby, 2016). Another example is how saltwater intrusion which is a naturally occurring phenomenon has increased in extent in recent times due to a shrinking delta caused by unsustainable levels of ground water extraction. This 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). However, few studies have attempted to evaluate the overarching picture of how both natural hazards and anthropogenic land-use could influence rice productivity, how these natural and human led drivers could interact in a way that reinforces or diminishes rice production, and how the onset of climate change could create new challenges for food production (Shrestha and Trang, 2015).

Accounting for the multiple effects of natural hazards, anthropogenic land-use and climate change on rice productivity require a systems thinking approach (Bosch et al., 2007). Systems thinking is commonly used to understand natural resource management since many of these issues are considered complex or "wicked" problem situations (DeFries and Nagendra, 2017). Notably, it can be applied at multiple scales to understand what factors drive environmental change at the global to local levels. 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 local landscape scale.

Here, we apply a systems thinking approach to understand how rice productivity in Vietnam responds to multiple natural and human drivers of change, and apply this approach at a regional scale, specifically focusing on the Red River Delta (RRD) in the north and the Mekong River Delta (MRD) in the south. Our aim is to use a literature review to develop causal loop diagrams to represent the major linkages between natural hazards and anthropogenic land-use factors and elaborate on how they interact and influence rice productivity in these two 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.

2. Methods

2.1. Study sites

The Mekong River Delta (MRD) is the world's third largest delta (4 million ha) and the larger of the two mega-deltas in Vietnam (Nguyen et al., 2007; Figure 1). In 2017, 4,188,800 ha of rice were planted in the MRD with 23.6 million tons of rice produced. The delta is also home to 17.7 million people who depend on agriculture for their livelihoods. That 55% 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 and Darby, 2016; Cosslett and Cosslett, 2017; General Statistics Office of Vietnam, 2018). Up north, the Red River Delta (RRD) is the next largest with a floodplain area of 2,105,100 ha (Figure 1; Nguyen et al., 2017). In 2017, 1,029,800 ha of planted rice produced 5.9 million tons of rice, the equivalent of 14% Vietnam's total rice production. Approximately 21.3 million people live on the RRD and rely on agriculture for their livelihoods (General Statistics Office of Vietnam, 2018).

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). Soils in the RRD consist of thick Quaternary accumulation with loose and alternating sediment beds which are mostly organic in nature (Berg et al., 2007). Climatically, the MRD and the RRD have a tropical monsoon climate with an average annual rainfall of ~1800 mm/year. Due to their latitudinal differences, there are slight differences in the average summer temperatures - the MRD have an average temperature of 27-30°C while the RRD have 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 and November, 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 (Berg et al., 2007; 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 has facilitated the production of three rice crops annually: winter-spring, summer-autumn and autumn-winter (Table 1). In 2017, the summer-autumn crop was the largest (13 million tons), the winter-spring crop was the second largest (9.9 million tons), followed by the autumn-winter crop (699,100 tons) (General Statistics Office of Vietnam, 2018). Compared to the MRD, rice is planted bi-annually in the RRD, first, from February to March (spring crop) and a second time in July (summer crop) (Table 1). The chilly winters preclude the cultivation of a third crop of rice. Approximately 3.5 million tons of rice was produced during the spring cropping season while 2.5 million tons was produced during the autumn season in 2017 (General Statistics Office of Vietnam, 2018).

2.2. Literature review and causal loop diagrams

A literature review was conducted to compile a list of relevant articles on the effects of natural hazards and anthropogenic land-use on rice agricultural systems in the RRD or MRD. We used online databases such as Scopus, Web of Science, Google, Google Scholar and individual journal databases and conducted this search from June to October 2018. We included a range of literature sources including peer-reviewed journal articles, book chapters and scientific reports from non-governmental organizations. In addition, we reviewed the bibliographies of our articles to follow up with any other relevant literature that was not listed under our search. Since climate change would affect the viability of the two deltas as a major rice producing region (Mainuddin et al., 2006), we also included relevant articles on climate change and sea level rise.

We obtained 125 articles through our literature search and retained 101 articles which described how rice production was affected by natural hazards and/or anthropogenic land-use. Every article was considered to be a single case study and was read in detail by the lead author. Thereafter, the natural or anthropogenic drivers and/or the environmental process that would lead to a change in rice productivity directly or indirectly were identified. Adopting a systems thinking approach, we constructed causal network diagrams to identify and visualize the interconnections among the drivers of rice productivity in both deltas.

We first developed causal links which describe how a driver, that could either be a natural hazard or an anthropogenic land-use, would influence rice productivity either directly or through an environmental process. We also documented if each driver had an increasing or decreasing effect on an environmental process that could influence rice productivity by affecting rice growing area, rice yield or rice quality. This relationship is represented by an arrow which indicates the direction of influence, from cause to effect. The polarity of the arrows (plus or minus) indicates whether the effect is increasing or decreasing (Lim et al., 2017). A plus sign indicates that a link has "positive polarity" and a minus sign indicates "negative polarity." The polarity of the causal link between A and B is said to be positive when an increase/decrease in A causes B to increase/decrease. A causal link is negative when an increase/decrease in A causes B to decrease/increase (Newell and Watson, 2002). We constructed two causal network diagrams. The first causal network diagram describe how natural hazards and anthropogenic land-use affect rice production in the MRD and RRD (Supplementary Table 1), while the second causal network diagram describe the potential impact of climate change on rice production in the MRD and RRD (Supplementary Table 2). The references we used are found in the Supplementary Materials.

3. Results

3.1. Multifaceted and interrelated challenges from natural hazards and anthropogenic activities

From our review, we found 94 case studies on how rice productivity in the RRD and MRD was affected by natural hazards or by anthropogenic land-use (Supplementary Table 1). The natural hazards that had an effect on rice productivity include tropical cyclones, floods and droughts. 44% (n=41) of our total case studies contained information on the effects of tropical cyclones (n=12 studies), floods (31) and droughts (10). On the other hand, anthropogenic land-use activities such as dike development (28), sand mining (18), dam construction (41) and groundwater extraction (19) were found in 81% (n=76) of our reviewed studies. Outbreaks of pests and diseases were considered an environmental process with 12 relevant studies. 68% (n=64) of the articles we reviewed focused on the Mekong River Delta, while 21% (n=20) focused on the Red River Delta. Studies that covered both deltas made up 11% (n=10).

Our causal loop diagram (Figure 2) shows how the processes and issues affecting rice production in the Mekong River Delta (MRD) and the Red River Delta (RRD) are not one dimensional and linear but reinforcing and interdependent. On one hand, anthropogenic developments such as dikes help enhance yields. On the other, these developments could reduce rice growing areas and productivity over time. For example, flooding caused by heavy monsoonal rains, typhoons or high tides is a naturally occurring phenomenon in the two mega-Deltas of Vietnam (Chan et al., 2012). To avoid crop loss, dikes were constructed to keep floodwaters out. However, the presence of high dikes in the MRD has reduced the supply of fertile alluvium, increasing the need for artificial fertilizers and pesticides to maintain yields (Chapman et al., 2017; Figure 2). In addition, the deposition of fluvial sediments also ensures the long term sustainability of the delta. According to Howie (2005), each

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cubic metre of flood water contains up to half a kilogram of sediment, silt and organic matter which can be a sizeable amount considering that (unprotected) low lying areas can be inundated by two to three metres of water for three or four months every year. Without the high dikes, flood sediments can be used to offset land loss due to land subsidence (Chapman and Darby, 2016) and maintain the delta landform for agricultural activities (Figure 2).

Worst of all, poorly planned and/or maintained dikes are not only functionally ineffective against floodwaters or coastal surges, they become an amplifier of destruction when their presence creates a false sense of security which results in intensive development of low lying areas (Mai et al., 2009; Tran et al., 2018). Areas unprotected by dikes may be more vulnerable to flooding as the excess water has to flow somewhere. Using a GIS-linked numerical model, Le et al. (2007) confirmed that engineering structures in the MRD increased water levels and flow velocities in rivers and canals. This in turn increased the risk of flooding in both non-protected areas and protected areas (due to dike failure) (hashed lines in Figure 2 show that dikes do not necessarily reduce flooding). Lastly, dikes and irrigation canals contribute to the salinity intrusion problem by acting as efficient conduits for saltwater to flow upstream with saltwater seeping under dikes into agricultural land (Nguyen et al., 2017).

Another example of an anthropogenic development creating other interrelated problems is that of groundwater extraction. While groundwater extraction has increased the availability of water for human activities, it has exacerbated land subsidence, which together with sea-level rise, have increased the severity and extent of saltwater intrusion and reduced the suitability of land for rice cultivation. Moreover, rice crops become contaminated with arsenic when arsenic-rich groundwater used for non-agricultural use is discharged into rivers and the river water is used for rice irrigation (Lan and Giao, 2017; Minderhoud et al., 2018). Crop quality is reduced when the aresenic enriched water is deposited on topsoils and absorbed by rice plants during growth (Rahman and Hasegawa, 2011; Figure 2). Notably, natural hazards might also amplify the problems created by human activities. Apart from the flooding and erosion problems that dikes create in unprotected areas, drought could intensify ground water extraction, resulting in increased land subsidence, saltwater intrusion and arsenic contamination (Binh et al., 2017; Erban et al., 2013; Nguyen, 2017).

Worryingly, sand mining and upstream dam construction have caused a substantial decline in fluvial sediment loads with trickle down effects on rice growing areas and rice yields. Dams cause sediments to be impounded in reservoirs behind the dams while sand mining mean that sand and sediment are taken away from where it should naturally occur. The substantial reduction in sediment, coupled with the process of land subsidence and rising seas will reduce the size of the delta and the availability of land for rice cultivation (Figure 2; Kondolf et al., 2014; Kondolf et al., 2018). Although Darby et al. (2016) showed that one-third (32%) of the suspended sediment reaching the delta is delivered by runoff generated by rainfall associated with tropical typhoons (Figure 2), there is a lack of research quantifying sediment mobilization by typhoons. This process of sediment transport has important implications for a delta adversely affected by substantial declines in fluvial sediment loads.

3.2. Climate change

Besides creating new environmental challenges, pre-existing threats to rice production and food security will be exacerbated by climate change. We found 31 articles which documented how climate change could influence natural hazards and how this would lead to an increasing or decreasing effect on rice yield, rice quality or the extent of rice cultivated (Supplementary Table 2). Some of the effects of climate change include increasing temperatures, rising sea levels, variable rainfall as well as an increase in the frequency and severity of natural hazards such as typhoons and droughts (Figure 3; Darby et al., 2016; Grosjean et al., 2016; Mainuddin et al., 2011). In addition, there may be changes to the severity and distribution of pests and diseases (Sebesvari et al., 2011) (Figure 3). Of the 31 case studies, 24 (77%) contained information on sea level rise and flooding, nine (29%) contained information on the effects of climate change and typhoons, five (16%) on droughts and one (3%) on pests and disease incidence. Likewise, most of these studies were focused on the Mekong Delta Region (21), with four case studies (13%) for the Red River Delta and six case studies (19%) that include both deltas.

According to the Fifth Assessment Report by the United Nations Intergovernmental Panel on Climate Change (IPCC), unabated greenhouse gas emissions will cause global temperatures to increase by up to 4.8°C (Stocker et al., 2013). Increases in global temperatures leads to thermal expansion of seawater which accelerates the melting of ice caps and glaciers. Consequently, a rise in sea levels is inevitable (Robert, 2017; Smajgl et al., 2015). The IPCC has projected sea levels to rise from a rate of 3.2 mm/year from 1993 to 2010 to as much as 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 (Lassa et al., 2016). Presently, sea levels in Vietnam have increased by 5 cm in the last 30 years (Nguyen et al., 2007). Rising sea levels coupled with coastal subsidence caused by compaction and groundwater extraction will cause large portions of the low lying RRD and MRD to be inundated and flooded (Allison et al., 2017). This leads to a loss of land available for rice production (Figure 3). Rising sea levels will also increase coastal erosion in both the Mekong and the Red River Delta. Hanh and Furukawa (2007) showed that erosion has occurred along a quarter of the coastline of each delta with a total of 469 km of coastline already eroding at a rate of 5 to 10 mm/year. With climate change, an even greater loss of land is expected at these sites with a significant loss of (arable) land over time (Figure 3).

Sea level rise could also increase the risk of storm surges (Hanh and Furukawa, 2007). In the Red River Delta, Neumann et al. (2015) found that sea level rise through 2050 could reduce the recurrence interval of the current 100 year storm surge of 5 m to once every 49 years. Inadequately constructed and poorly maintained dikes may be breached resulting in flooding which will damage rice growing areas and other properties (Hanh and Furukawa, 2007; Figure 3). Rising seas also facilitate infiltration of saltwater into groundwater aquifers and this may increase salinity gradients in the MRD and RRD. In particular, salinity intrusion will worsen during the dry season. Approximately 1.8 million ha in the MRD is already affected by dry season salinity of which 1.3 million ha is affected by salinity levels above 5 g/L (Lassa et al., 2016). This area is predicted to increase to 2.2 million ha with rising sea levels. In the RRD, the 1% salinity contour has migrated landwards by 4 to 10 km. Apart from making the ground unsuitable for rice cultivation, the contamination of aquifers by saltwater reduces the availability of freshwater for consumption (Hanh and Furukawa, 2007; Figure 3).

Climate change can also cause sea surface temperatures (SST) to increase. Hausfather et al. (2017) found that SST has increased from 0.07°C to 0.12°C per decade from 1997 to 2015. This indicates a higher rate of warming in recent years. An increase in SST could potentially generate more powerful typhoons with higher wind speeds, more rainfall, and higher storm surges that last for a longer duration (Larson et al., 2014). An increase in SST in the higher latitudes of the Pacific Ocean may also result in more typhoons from the Northwest Pacific Ocean. These typhoons may travel eastwards and make landfall or pass close to Vietnam (Nguyen et al., 2007). Using a high resolution climate model system (PRECIS 2.1), Wang et al. (2017) examined the potential changes in typhoon activity in Vietnam posed by climate change. Their key findings include an increase in tropical cyclone activity during winter due to more favourable large scale conditions and a decrease in tropical cyclone activity in summer. This means that the Mekong River Delta could be affected by more tropical cyclones as typhoon activity shift southwards towards the end of the year (Imamura and Dang, 1997). Similarly, Redmond et al. (2015) used PRECIS but concluded that although the number and intensity of tropical cyclones across the South China Sea will likely increase under future climate change, their track locations may shift eastwards and away from Vietnam. Their findings also showed that there would be an increase in the amount of precipitation and frequency of the most intense typhoons. Even though the different scenarios created by climate change were modelled, the consensus amongst scientists is that more frequent and severe disasters can be expected.

In addition, climate change may also cause more frequent drought conditions. Regions previously affected by droughts may see longer and more frequent droughts in future (Grosjean et al., 2016). Droughts do not result solely from a lack of rainfall; it can also result from changes in rainfall patterns (Adamson and Bird, 2010). Changes in the arrival of rains, the length of the wet season as well as the amount of rainfall mean that farmers would be unable to plant and harvest rice based on current crop calendars as certain stages of rice growth that require more water no longer coincide with periods of abundant rainfall (Lassa et al., 2016). For example, no rain fell in the last three months of 2004 and the lack of rain caused a loss of 1.6 million ha of rice. Rainfall during this period is needed for the full development of the rain-fed rice crop during its final stages of growth

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(Adamson and Bird, 2010). In addition, drought conditions and inadequate rainfall exacerbates the salinity intrusion problem (Nguyen et al., 2017) which leads to further reductions in rice yields (Figure 3).

Lastly, although extreme weather such as unusually high or low temperatures, excessive rainfall and prolonged droughts have previously contributed to pest and disease outbreaks, the impacts of climate change on pest and disease outbreak is unpredictable (Sebesvari et al., 2011). Individual pest species do not experience climate change in isolation from other species and changes in environmental factors such as rainfall regimes and temperature ranges will have different effects on the survivability of pests and their natural predators. For example, the attack rates of *Cyrtorhinus lividipennis reuter*, a natural predator that attacks the eggs of the Brown planthopper pest increased when temperatures were between 20 and 32°C. Beyond 35°C, the ability to reduce Brown planthopper populations was curtailed (Song and Heong, 1997). It is also difficult to disentangle the effects of climate change from crop management practices such as the overuse of agrochemicals and the practice of intensive cropping which can influence outbreaks (Bastakoti et al., 2014; Bottrell and Schoenly, 2012; Sebesvari et al., 2011). These factors explain the uncertain effect of climate change on pest and disease outbreaks (Figure 3).

4. Discussion

4.1. Untangling complexity

Relevant information on the different drivers and environmental processes affecting rice production in Vietnam are fragmented in a range of academic and non-academic sources (Bosch et al., 2007) making it difficult for policymakers and managers to have a good overview of the reinforcing and interdependent processes and issues affecting food security in Vietnam. Using a systems thinking approach, we use causal loops to consider how rice productivity can be positively or negatively impacted by the various drivers and environmental processes (Figure 2). In doing so, we highlight how the various natural hazards and anthropogenic land-use activities may interact with one another and lead to unintended consequences such as an increase in flooding, saltwater intrusion and land subsidence. In addition, we show that climate change may exacerbate the effects of natural hazards by increasing the frequency and severity of natural disasters with potential downsides on rice production (Figure 3).

The use of causal loop diagrams (Figure 2) can provide a general overview of the key anthropogenic drivers and natural hazards that affect rice production but we caution that Red River Delta and the Mekong River Delta are vast and diverse regions and there are differences in the ways each delta are affected by natural hazards and anthropogenic drivers. For example, high dikes and the associated problem of sediment exclusion is a problem unique to the Mekong Delta (Chapman et al., 2017). While high dikes are absent in the Red River Delta, a common problem associated with dikes in both deltas is that of poor maintenance and planning which results in dike failures with overtopping of floodwaters (Mai et al., 2009; Hanh and Furukawa, 2007; Pilarcyzk and Nguyen, 2005). Next, compared to the Mekong, the Red River has substantially fewer dams (364 vs 87). In addition, typhoons are less common in the Mekong Delta and droughts occur less frequently in the Red River Delta.

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

One limitation of our study is that it was not possible to include all the problems that can potentially affect rice cultivation in our causal loop diagrams. We acknowledge issues related to industrial pollution, which may reduce rice quality and rice productivity (Khai and Yabe, 2012; 2013; Huong et al., 2008). However pollution seems to be a localized issue rather than a major concern across the deltas (Phuong et al., 2010). In addition, the over-use of chemical fertilizers and pesticides can reduce soil and water quality despite having positive effects on rice yields (Guong and Hoa, 2012; Sebesvari et al., 2012). We are also aware of the conversion of rice growing areas into shrimp ponds or for industrial and urban development which reduces the area of land available for growing rice (Be et al., 1999; Tung and Higano, 2011). Furthermore, the limited research on sand mining and groundwater induced land subsidence in the RRD mean that there is little understanding on the scale of the problem(s) present, if any.

In spite of this, our study presents the major issues that are common in both mega-deltas and describes how the issues and processes affecting rice production are multifaceted and interrelated. Adopting a systems thinking approach has allowed the multitude of drivers and environmental processes affecting rice production to be visualized and mapped in a manner that is easy to understand. As ameliorating problems require policymakers and managers to have a good grasp of the different factors and processes present, a method that considers all the different drivers and possible unintended consequences from the outset can help avoid the risk of oversimplifying a problem and assuming a straightforward solution can be found (DeFries and Nagendra, 2007). For example, to solve the problem of a shrinking delta, the effects of (high) dikes, sand mining, upstream dams and groundwater extraction have to be considered. While typhoons may increase fluvial sediment loads to offset a shrinking delta (Darby et al., 2016), more intense and more frequent typhoons wrought by climate change is not necessarily a good thing especially in vulnerable coastal areas (Figure 3). Additionally, an impending typhoon would mean that precautions against strong winds, heavy rains and flooding must be taken (Figure 2).

4.2. Hard and soft solutions

Presently, management options to increase agricultural productivity and mitigate climate change are largely characterized by hard options such as the construction of dikes, sea walls and sluice gates (Neumann et al., 2015; Smajgl et al., 2015). While these highly visible engineering structures are easily constructed and are generally effective, unwanted side effects may be created, such as those associated with high dikes in the Mekong. Flooding, sediment exclusion and exacerbating land subsidence are some of the problems that were inadvertently created. In the long term, (costly) maintenance is needed to maintain their functionality (Hoang et al., 2018; Neumann et al., 2015). A combination of hard and soft options (e.g., implementing crop and land use change) to respond to environmental threats and climate change is advocated with blanket use of either option inadvisable (Conway, 2015). Smajgl et al. (2015) pointed out that erecting sea dikes in the western parts of the Mekong Delta is likely to reduce the income of thousands of households that have adapted to increasing salinity levels by cultivating shrimp which require saline conditions (a soft option); while hard options for the eastern coastline to protect the land from sea level rise and salinity intrusions is a plausible solution as intensive rice agriculture is still dominant there.

Another soft solution that can be implemented to improve livelihoods includes integrated farming practices such as integrated pest management (IPM). Instead of relying solely on pesticides to rid pests, farmers that practice IPM use a combination of pest resistant cultivars, fertilizer management and agronomic practices to increase the effects of predators and other naturally occurring biological control agents. For example, farmers can grow flowers, okra and beans along their paddy fields to attract bees and wasps that infest planthopper pests' eggs. With more natural predators around, pesticides are only used when necessary (Bottrell and Schoenly, 2012; Normile, 2013). Other options include rice-fish farming and duck-rice systems to provide a more economically and ecologically sustainable alternative to intensive rice monoculture (Berg and Tam, 2012; Men et al., 2002).

In rice-fish farming, farmers use minimal pesticide as it kills the fish and the natural predators of rice pests. Instead, fish helps to control pests and fish droppings keep the soil fertile. Upon maturity, the fish can be sold to increase the farmer's income by up to 30% (Berg et al., 2017; Bosma et al., 2012). Ducks can also be reared in immature rice fields. Besides providing food, the ducks serve as biological controls for insects and weeds. Their droppings fertilize the soils and their movement aerates the water to benefit the rice plants (Men et al., 1999;

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2002). Men et al. (2002) showed that a duck-rice system in Can Tho province in the Mekong eliminated the use of pesticides, halved the use of fertilizers and the additional income from the sale of ducks increased farmers' incomes by 50 to 150%. Overall, the higher incomes and ecosystem services provided by the fish or ducks, coupled with reduced agrochemical use benefits farmers.

Increasingly, there are calls to move away from three to two rice crops a year. Instead of planting a third crop, floodwaters are allowed to enter the fields to replenish soil nutrients, wash away contaminants, kill pests and mitigate salinity intrusion. Fish, crabs and snails that arrive with the floodwaters can be collected for additional income. Triple cropping of rice provides only a single ecosystem service which is marketable rice while the integration of rice cropping with natural flooding creates a series of positive feedbacks mechanisms and ecosystem services such as rice, fish, pest control and nutrient cycling (Nikula, 2018; Tong, 2017).

Looking ahead, the need for holistic land use planning and for soft measures on top of hard engineering structures is something that is applicable in other localities. Although soft measures are not perfect, they are arguably less environmentally damaging. Conversely, engineering structures tend to create unintended consequences post-construction. In addition, during the pre-construction phrase, natural vegetation may need to be cleared (Geist and Lambin,, 2002). The adoption of soft strategies requires political and social acceptance of the measures such as the need for local communities to learn and implement new farming methods and for funding agencies to be willing to equip local farmers with the necessary knowledge and resources. While initially troublesome, there are cost saving benefits to be reaped in the long run. Initial start-up costs to educate and equip local communities is likely to be less than the maintenance costs for hard options which is likely to be incurred repeatedly over many years (Conway, 2015; Smajgl et al., 2015). Adopting a systems thinking approach would allow policymakers and managers to situate the range of mitigation measures within broader environmental processes. In the process, a clearer view of the possibilities and challenges present in an era of widespread anthropogenic development and changing climates is provided.

5. Conclusion

The focus of this paper is on the impacts of natural hazards, land use patterns and climate change 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. In this study, the natural hazards that adversely affect Vietnam include typhoons, floods and droughts. Outbreaks of pests and diseases are also common. Meanwhile, dike development, sand mining, dam construction and groundwater extraction are the main anthropogenic developments that have a major impact on rice production in the two mega-deltas. Few studies have examined the implications of these hazards and drivers on food security as research is largely focused on their broader environmental impacts (e.g., sedimentation, deforestation). As the processes and issues affecting food security are multidimensional and interdependent, we have used a systems thinking approach to develop a visual representation of the ways in which natural hazards, anthropogenic land-use and climate change factors affect rice quantity and quality in the MRD and the RRD in Vietnam.

A key finding is that anthropogenic developments can improve agricultural productivity but also create unintended environmental problems. Even human activities that are unrelated to agriculture such as sand mining and dam construction can have negative effects on rice productivity. In addition, natural hazards may amplify the problems created by human activities. In the long term, besides creating new environmental threats, climate change may exacerbate the effects of natural hazards by increasing the frequency and severity of natural disasters. While the effect of climate change on food productivity is still uncertain, the causal loop diagram allow the multiple, interrelated uncertainties and risks to be illustrated.

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 with a large supporting population. 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; Day et al., 2016; Giosan et al., 2014; Syvitski et al., 2009).

Given that river deltas worldwide are highly stressed and degraded landscapes, a systems thinking approach can provide a holistic overview of the threats 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 activity and climate change have compromised deltaic sustainability.

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Tables

Table 1. Rice planting, growing and harvesting periods in the Mekong River Delta and the Red River Delta in 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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Figures

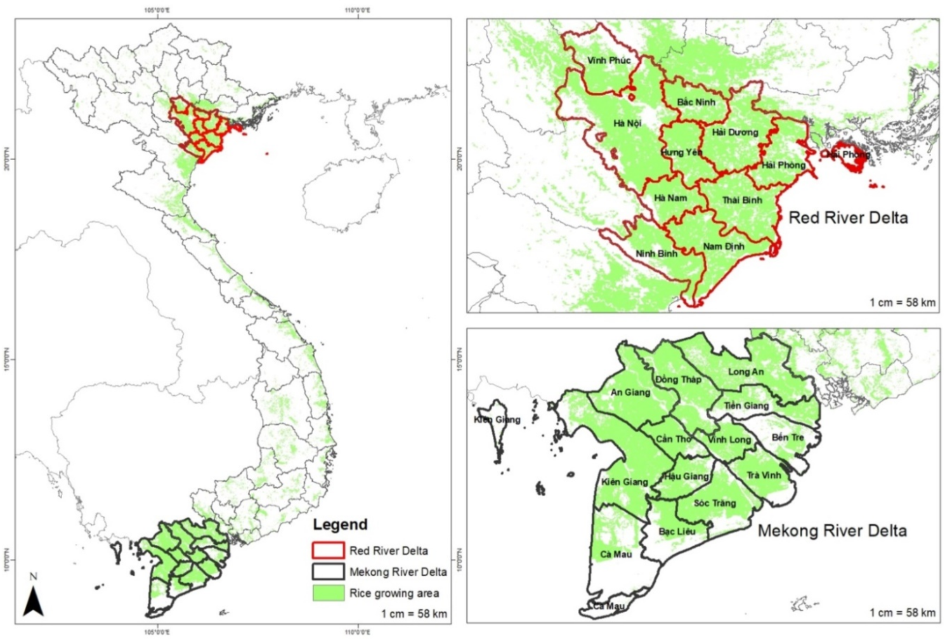

Figure 1. Distribution of rice growing areas in the Red River Delta (RRD) in northern Vietnam and the Mekong River Delta (MRD) in southern Vietnam. The provinces in the RRD include Bac Ninh, Ha Nam, Hai Duong, Hung Yen, Nam Dinh, Ninh Binh, Thai Binh, Ha Tay, Vinh Phuc, Hanoi (municipality) and Hai Phong (municipality). The provinces in the MRD include Dong Thap, An Giang, Bac Lieu, Ben Tre, Ca Mau, Can Tho, Hau Giang, Kieng Giang, Long An, Soc Trang, Tien Giang, Tra Vinh and Vinh Long. Rice growing extents were obtained from Nelson and Gumma (2015).

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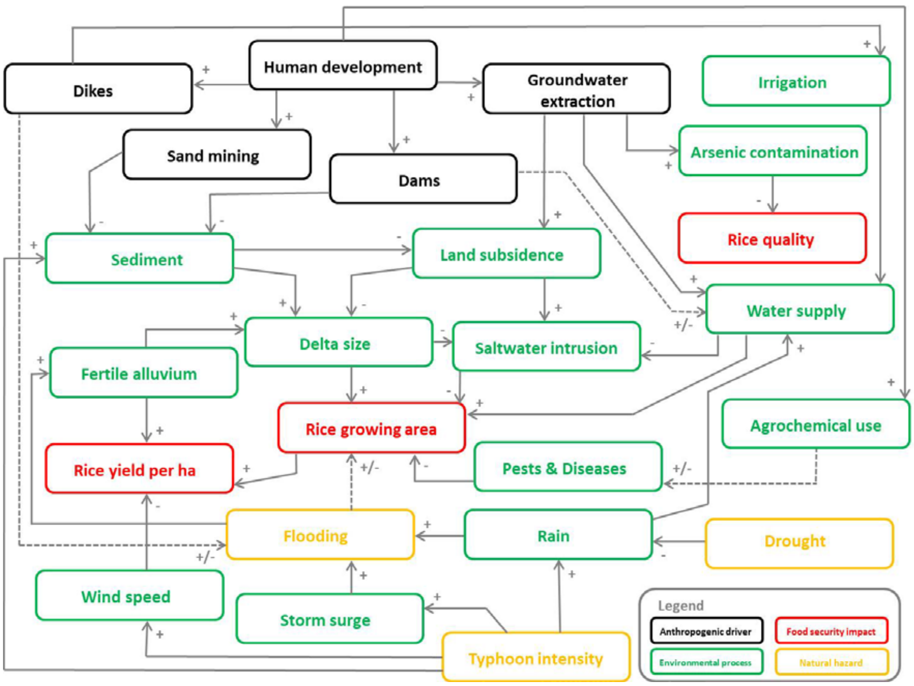

Figure 2. Causal loop diagram showing the key anthropogenic drivers and natural hazards that affect rice production in the two mega-deltas of Vietnam. A plus (+) sign indicates that an increase/decrease in A causes B to increase/decrease. A negative (-) sign indicates an increase/decrease in A causes 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. Dams may increase or decrease water supply as dams can regulate water flow. Similarly, floods are often considered bad but moderate flooding can improve fertility, remove contaminants and kill pests. Lastly, agrochemical use may reduce the incidence of pests and diseases but the over-use of chemicals can lead to pesticide resistance which may increase outbreaks of pests and diseases.

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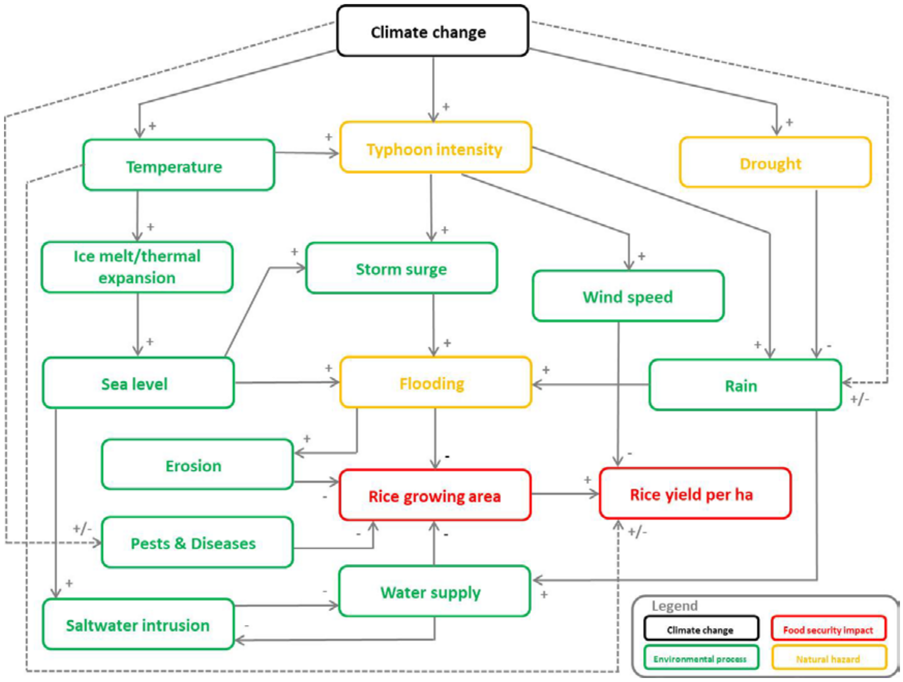

Figure 3. Causal loop diagram showing the potential impacts of climate change on the two mega-deltas of Vietnam. Hashed lines with "+/-" represent instances where the impacts of climate change is unclear, such as the effect of climate change on rainfall patterns or the effects of increasing temperatures on rice yields. The temperature variable refers to air and sea temperatures. The effect of climate change on pest and disease incidence is also not straightforward.