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Socio-hydrological trade-offs arising from triple cropping in the Vietnamese Mekong Delta: Revisiting environmental impacts and adaptation pathways

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ABSTRACT

Trade-offs between socio-economic growth and environmental protection have remained a critical issue of sustainable development, especially in the Global South. In the floodplains of the Vietnamese Mekong Delta (VMD), the development of high-dike polders for intensive rice production has degraded ecosystems and changed socio-economic patterns. Sustainable development pathways must be considered during policy formulations to keep pace with such transformations. In this study, the interwoven socio-economic development and rice-based agricultural production processes were assessed based on mixed data sources, including 550 interviews with farmers in two major delta floodplain provinces — An Giang and Dong Thap. It highlights the pros and cons of the triple-rice farming systems under high-dike protections compared to low-dike farming systems. Results showed that the environmental degradation due to the overuse of agrochemicals (e.g., fertilizer and pesticides) costs approximately US $565 per hectare per crop season, resulting in the lower marginal benefits for the triple-rice production compared to the double-rice production pattern. This includes higher costs borne by local farmers/communities, given the adverse effects of agrochemicals on their health. The study urgently calls for local governments to consider relevant drivers of environmental degradation in agricultural production, especially in rice cultivation. Future policy needs to consider whether the intensification in agriculture, such as triple-rice production, would be an appropriate development pathway for the rural economy. Our study conveys to central and local governments and associated stakeholders that the agriculture-driven development policies would not be a sustainable development pathway under new environmental complexities in the delta.

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1. Introduction

Agricultural activities in deltas are major contributors to both national and regional economy in food production, and play an important role in improving populations' living standards and reducing poverty (Suy et al., 2018), particularly in rural regions. However, at the same time, urbanization and rural economic development, have also placed a greater pressure on farmers (Yuan et al., 2018) and often brings about undesirable environmental consequences (Chau et al., 2015; Ekman, 2017), especially in densely populated deltas (Tran et al., 2019; Zhang et al., 2020). Intensive agricultural production patterns have caused environmental pollution in rural areas, where agrochemical use have directly affected water sources (Berg et al., 2017; Nguyen et al., 2018). Pesticides and fertilizers are heavily utilized in intensive farming systems (two or three crops per year) that seeks to increase yields and safeguard national food security (Berg et al., 2017). However, combined with less seasonal flushing of residues from agricultural fields, this has resulted in severe contamination of water and surrounding environments (Berg et al., 2017; Chau et al., 2015). In a 2015 study by Chau et al. all investigated water sources which rural populations depend on for their daily essentials, including surface water, groundwater, water at public pumping stations, surface water chemically treated at household level, harvested rainwater, and bottled water, were found to be contaminated by pesticides. As such, while development affords perceived opportunities for large agricultural enterprises to gain more benefits from markets, it is necessary to consider how these processes truly shape environment-development landscapes in rural, densely-populated agricultural areas. Various adaptive measures have been recommended to curb with the situation, including intercropping (Martin-Guay et al., 2018), ecological landscape approaches (Rockström et al., 2017) and nature-based solutions (i.e., floodwater-based restorations, mangrove forest protection) that are defined as actions or measures based in nature addressing societal challenges (Hanson et al., 2020).

The upper floodplains of the Vietnamese Mekong Delta (VMD) stand at the forefront of these environment-development complexities of intensive-agriculture induced degradation and socio-economic development policy. This is due to two main reasons. Firstly, the dike development (low[1]- and high-dike[2]) in VMD floodplains over the last three decades, following rapid agricultural expansion and intensification, has led to significant expansion of rice cultivation (Dung et al., 2018c; Park et al., 2022; Tran et al., 2019). Between 1986 and 2014, a total of 91,000 km of dikes was built (Manh et al., 2015), substantially increasing areas for rice production in the delta where it now contributes to 50% of the national food productivity (Triet et al., 2020). Meanwhile, evidence suggests that construction of these dikes has altered flood regimes occurring within the floodplains and beyond (Park et al., 2020; Thanh et al., 2020; Vu et al., 2021). Extensive high-dike development for triple-rice production in the floodplains has also caused land degradation, making the livelihoods of rice farmers unstable (Dung et al., 2018b,a). Secondly, while the VMD floodplains is also experiencing a multitude of environmental challenges exacerbated by extensive dike development and climate change, health risk impact on farmer's livelihood remains unclear. In the coming years, it is expected that the triple-rice production in the VMD floodplain provinces will be gradually replaced by more sustainable crops with nature-based practices[3] (Hoang et al., 2019; Triet et al., 2020); however, the pathway is not clear. In that context, it is still unknown the trade-offs between low- and high-dike development for double- and triple-rice production, farmers' costs and benefits and the associated health risk exposed to farmers due to agrochemical use for both farming systems.

This study investigates the trade-offs between intensive rice production and environmental protection in the floodplains from a sustainable livelihood perspective. A two-step approach is used. First, we explore how the environmental consequences from low- and high-dike development for rice protection in the VMD floodplains exacerbate agro-environmental systems and minimize rural livelihoods' sustainability focusing on assessing the use of fertilizer and pesticide of farmers in both farming systems. Second, we examine how the rice production systems under low- and high-dike development overtime put farmers' health at risk. Intensive literature reviews on rice farmers' livelihoods in the floodplains and rice production costs under high-dike protection were carried out. Socio-economic data analysis was implemented to present trade-offs between dikes and rural livelihoods and interview data from farmers were analyzed to examine costs and profits of double- and triple-rice farming systems, and to risks to rice farmers' health. In terms of the potential adaptation strategies, we hypothesize that high-dike protection has undermined farmers' livelihoods and nature-based practices such as floating crops under no-dike and low-dike protection will be able to sustainably accomplish and re-establish ecosystems in the VMD floodplains due to their harmless to the environment, thus benefitting farmers more than the environmental costs incurred by intensive rice production (Faivre et al., 2017; Pauleit et al., 2017). While engaging in nature-based practices, farmers would obtain more sustainable livelihood outcomes due to low investments and minimal interventions to nature. We tested these hypotheses by analyzing empirical data collected in An Giang and Dong Thap Provinces in the VMD (Fig. 1).

[1] Low-dikes are used to protect two rice crops each year to ensure the second crop (Summer–Autumn from April to July) can be harvested before floodwaters enter the fields in August.

[2] High-dikes fully protect rice fields against floodwater year-round to allow for triple-rice cultivation annually.

[3] Nature-based practices include crops that grow in land or river and mostly get fertile nutrients from floodwater.

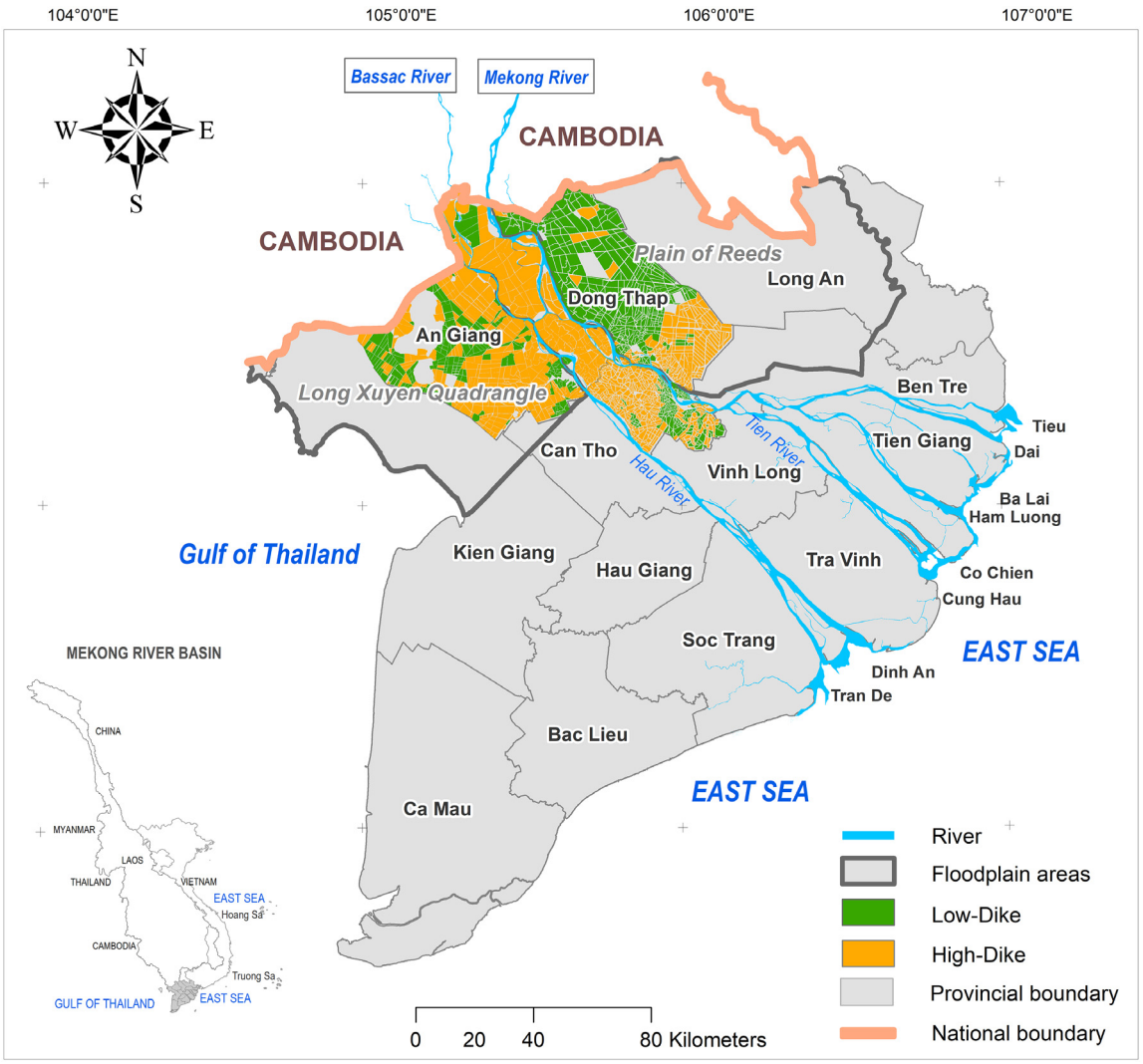

Fig. 1. An Giang and Dong Thap Provinces in the Vietnamese Mekong Delta and the occupation of low- and high-dike systems in the 2015 condition.

2. Research methods

2.1. Study area

The VMD comprises of 13 provinces (Fig. 1). Amongst them, An Giang and Dong Thap are located in the delta floodplains. We selected these two provinces as a case study because they have the highest proportion of land areas devoted to triple-rice production under high-dike protection (Dung et al., 2018a). Specifically, the triple-rice production areas in Dong Thap and An Giang were 90,000 and 150,000 ha in 2015, respectively (AGGSO, 2015; DTGSO, 2015). After this year, the areas for triple-rice mostly remained constant due to the national policy (Fig. A.1 in the Appendix) but these areas are still highest among provinces of the VMD. In addition, intensive rice production in these provinces have degraded land and polluted water conditions in many areas over the last two decades.

Two upper floodwater retention areas in the floodplains known as the Long Xuyen Quadrangle (LXQ) and the Plain of Reeds (PoR) have areas of 600,000 and 697,000 ha, respectively. An Giang and Dong Thap Provinces cover a large proportion of the LXQ (59%) and the PoR (46%). These floodplains retain floodwater upstream mostly from the main rivers of Mekong and Bassac during the annual flood season from July to November (Duc Tran et al., 2018). During flood events before 2000, when high-dike polders were not constructed for flood protection, the floodplains were exposed to inundation of 1.5 to 4 m, lasting from 3 to 5 months (Mekong Delta Plan, 2013). The LXQ floodplain retained 16×10^9 m^3 of floodwater in its natural state (Dung et al., 2018b). Together with the PoR in connection to the Cambodian floodplain,

the two floodplains perform the dual functions of retaining and regulating floodwater for the whole VMD (Kummu et al., 2014; Lyon et al., 2017).

The two floodplain provinces are physically characterized by dominant alluvial soils attributed to sediment transport by annual floodwaters (Mekong Delta Plan, 2013), providing fertile land for growing high-yielding rice varieties (Xuan and Matsui, 1998). Rice production has intensified since the late 1980s, spurred by the *Doi Moi* economic policy reforms in 1986 and successive campaigns for achieving national food security objectives (Käkönen, 2008; Netherlands, 2011; Veerman, 2013). Importantly, this period has witnessed a dramatic shift from the double-crop rice cultivation under low-dike protection to the triple-crop rice pattern supported by high-dike systems (Huu, 2011).

Today, the floodplains are densely occupied by low- and high-dike polders. In An Giang Province for instance, 90% of its agricultural land areas are protected by high-dikes, whereas a lower level of high-dike protection (about 30%) is found in Dong Thap (Thanh et al., 2020; Hui et al., 2022). The expansion of cultivated lands under high-dike protection in An Giang Province has accelerated since 1998 (see Fig. A.1 in the Appendix). At present, 91% of the agricultural area in the province is devoted to paddy rice production, and the remaining 9% is to the production of vegetables, fruit trees, and aquaculture. Over the past two decades, the floodplains have seen widespread land degradation and water pollution, especially in An Giang Province (Dung et al., 2018a; Tran et al., 2019). Much of the problem was largely attributed to intensive rice farming with a preference of quantity over quality, leading to substantial degradation of floodplains' ecosystems and threatening the sustainable development goal of the delta (Tran and James, 2019; Tran and Tuan, 2020).

2.2. Methods for data collection and analysis

Applied desk study and field data were carried out to explore the trade-offs between intensive rice production and environmental, economic losses (Fig. 2). In particular, we conducted literature reviews and analyzed interview data to determine the costs and benefits of the double- and triple-rice production under dike protection and assessed health risks associated with farmers' on-field activities (use of agrochemicals for rice production) in the selected study areas.

Data used in this study are derived from various sources and integrated for descriptive statistical analysis (Table 1). These sources provided salient evidence of the issues under study and complemented the insufficient data extracted from a single source. For example, analysis of the costs of agrochemicals use in double- and triple-rice production systems in the VMD upper floodplains was based on the data from Joep (2015), IUCN (2015), and Dung et al. (2018a) containing relevant field survey data from 2014 to 2016. This analysis also involved data from researchers at An Giang University, consisting of rice farmers' health risk assessments (120 interviews with farmers carried out in 2014 and 2017 in An Phu and Thoai Son Districts, in both low- and high-dike areas). These data were used to quantify the health risk exposure contributed by intensive rice production (see Table 1 for the detailed description), evident from declining health conditions of farming households living within the dike areas such as acute and chronic symptoms (e.g., vision, nerve system, digestive system, respiratory system and excretory system/skin), and signs/symptoms* (i.e., hand tremor, fever and itchy rash, and dizziness/blurred vision etc.) due to exposure to pesticides. In all field surveys, a stratified random sampling method was applied to select farmers for interviews. Questionnaires and the cost–benefit analysis method could be found from our previous publication of Dung et al. (2018a).

The health indicators were selected from literature-based evidence and experts' experience. The indicators include body exposure to pesticides relevant to vision, nerve system, digestive system, respiratory system and excretory system/skin, and signs/symptoms (i.e., hand tremor, fever and itchy rash, and dizziness/blurred vision etc.). A number of studies have applied these indicators to evaluate health-risk associated with poisoning with pesticides (Dassanayake et al., 2021; Kumari and John, 2018). Here, pesticide poisoning takes two forms: chronic and acute. Chronic symptoms are manifested by small and long-term exposure that slowly damage health, while acute symptoms refer to immediate exposure to high volumes of pesticides. Acute poisoning can lead to death, while chronic poisoning causes long-term health damage (Pain et al., 2019). Acute poisoning will not be fatal under timely intervention, but it will cause long-term aftershocks (Azab et al., 2016).

Finally, adaptation pathways were explored as a planning approach addressing the uncertainty and challenges from a shock and changes due to environmental consequences, based on cost and benefit analysis data and systematic literature reviews, to reduce the costs to farmers and increase their long-term benefits. This involved in-depth examination of adaptive measures undertaken by local farmers to ensure sustainable intensive agriculture production practices (e.g., triple-rice production) that could reduce environmental consequences.

3. Results and discussion

3.1. Socio-hydrological and environmental impacts: a tradeoff from the high-dike development

Low-dike systems have been rapidly transformed into high-dike systems in the upper part of the VMD (Fig. 1), making it possible to practice a third rice crop and allow for the diversification of permanent land-use types. Here, the high-dike systems bring several social benefits for local farmers, such as land diversification and protection, transport system, and safety from annual floods. However, this has caused declining yields (by more than 40%) because high dikes prevent the entry of alluvium and organic matter onto the field (Howie, 2011). The expansion of high dikes across the floodplains

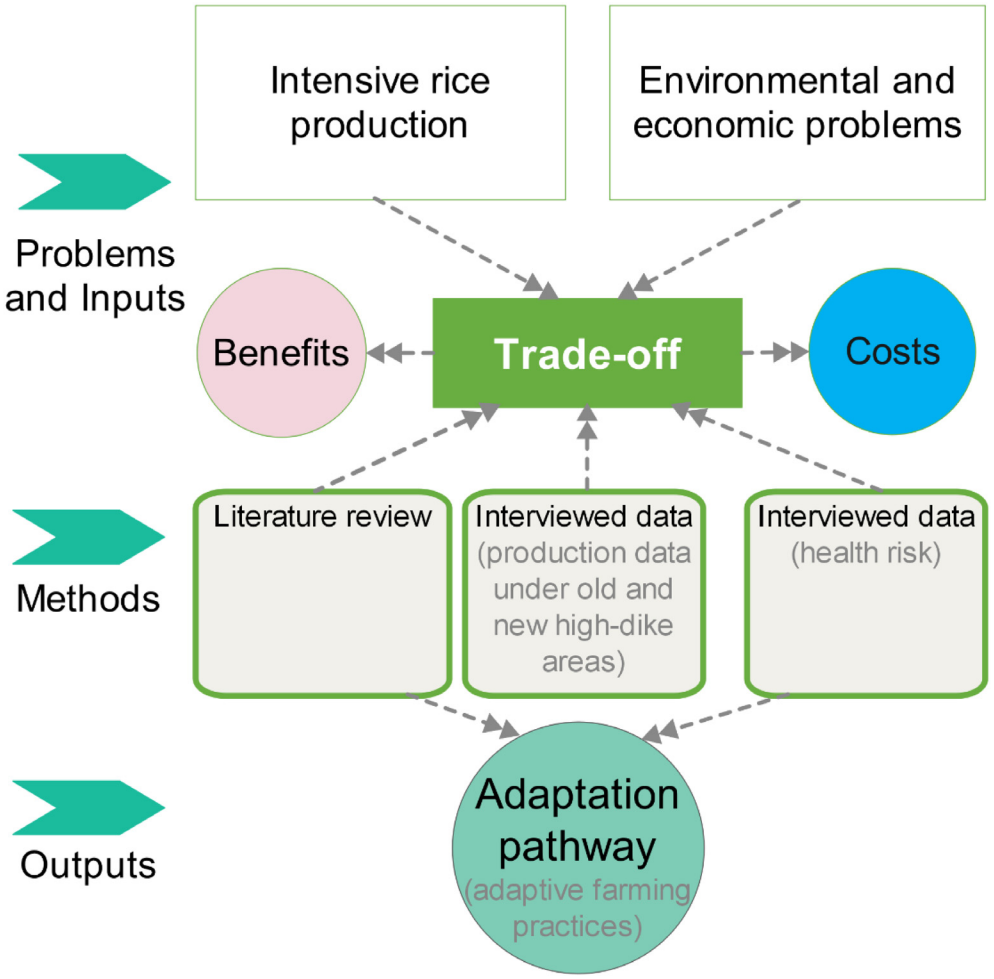

Fig. 2. Methodological flowchart.

has narrowed down the room for flood retention areas, causing in situ flooding effects (high flooding levels), as observed in the Mekong River (Tien River) and increased intensity of flood flows in the middle/coastal VMD (Dung et al., 2018c; Triet et al., 2020). Other dike-driven effects include the substantial decline in fish, water pollution and an increased in production costs incurred by rice farmers (Chapman et al., 2016; Kondolf et al., 2018; Lu et al., 2014).

Narratives of high-dike development in the floodplains speak directly to unexpected land-use and flood consequences, both locally and at the Mekong basin scale. Hydrological regimes in the VMD have evidently become abnormal, with little or no floodwater from the upstream stretches due to combined impacts from climate change, upstream developments, and internal dynamics of water infrastructure systems (Hoang et al., 2019; Lauri et al., 2012; Tran et al., 2022). These have prompted the adoption of innovative water management practices that allow local farmers to better adapt to change (Tran et al., 2021). That being the case, the livelihood of most rice-based farmers remains unstable with studies demonstrating the unsuccessful government-mandated flood-controlled strategy exercised on the ground (Tran and Weger, 2017; Tran, 2019; Tran et al., 2020a).

3.2. Cost-benefit tradeoffs from rice production overtime under the low and high-dike systems

Fig. 4 presents the increase in agrochemical use in intensive rice production areas under old high-dikes (>15 construction years) compared with those in new high-dike (<5 construction years) and low-dike systems (Dung et al., 2018a). Compared to the low-dike farming system, the mean pesticide use is 4–12 bottles/ha per crop (5%) higher in the new high-dike system, and 16–25 bottles/ha per crop (39%) higher in the old high-dike farming system. This indicates a significantly higher pesticide use in the high-dike farming systems (79–95 bottles/ha/year to 141–192 bottles/ha/year) than low-dike farming systems. The higher use of pesticide maybe from the increase in harmful insects from the year-round mono-rice crops as a favored living environment under high-dike protections (Dung et al., 2018a). Furthermore,

Table 1
Data availability and descriptions (see Fig. 3 for interview locations).

Data availability	Location	Collection year	Description	Sources
28 questionnaire-based interviews with farmers	Low-dike area (14 in Phu An Commune) and high-dike area (14 in Phu Binh Commune) in An Giang Province (see Fig. 3)	2014	The interviews were conducted by Joep Hagenvoort, a Dutch student for his master thesis, aimed at evaluating the costs and benefits of rice production under high-dike compared to low-dike protection in a typical upper floodplain of the VMD	Joep (2015) and Dung et al. (2018a)
120 questionnaire-based interviews with farmers in 2015 for health risk assessment 105 interviews with triple-rice farmers in 2014 105 interviews with rice-based farmers in 2017	Low- and high-dike areas in An Phu District, An Giang Province In the high-dike areas of Chau Thanh, Thoai Son and Cho Moi Districts of An Giang Province In the high-dike areas of Thoai Son of An Giang Province	2014, 2015, and 2017	Field studies were undertaken in 7 communes, including Chau Phong, Vinh Hoi, Vinh Binh, Vinh Loc, Vinh Phuoc, Vinh Trung, Vinh Truong. The study aimed at assessing the health risk of rice farmers under pesticide impacts. Indicators were used to examine acute and chronic symptoms of the human body exposed to pesticides (e.g., vision, nerve system, digestive system, respiratory system and excretory system/skin), and signs/symptoms* (i.e., hand tremor, fever and itchy rash, and dizziness/blurred vision etc.)	An Giang University
140 interviews with farmers	Low-dike area in My Hoa commune, Dong Thap Province	2015	Our colleagues at International Union for Conservation of Nature (IUCN) in Vietnam examined the profit-ability of different farming systems, with 30 interviews with triple-rice farmers and 110 interviews with households that combined rice farming with lotus and vegetable cultivation, or lotus farming with fishing and tourism.	IUCN (2015) and Dung et al. (2018a)
52 interviews with rice farmers	Low-dike area (15 interviews in Tan My commune in Dong Thap Province, 12 in Binh Phu, An Giang Province) and high-dike area (13 interviews in Thanh My Tay and 12 in O Long Vy communes in An Giang)	2016	Based on the data of Joep (2015), this study, based on two forms of semi-structured questionnaire, elaborated the costs and benefits associated with farming in the "old" high-dike areas of O Long Vy commune (>15 construction years) and in the "new" high-dike areas of Thanh My Tay and Tan My (<5 construction years). Interviews in Binh Phu commune explored low-dike farming systems.	Dung et al. (2018a)
Total: 550 interviews				

* Symptoms include: vision (eye): dizziness, blurred vision, narrow pupils; nerve system: dizziness, head function, convulsions, arm restlessness, irregular heartbeat, and trouble sleeping/insomnia; digestive system: excessive drooling nausea, vomiting/vomiting, diarrhea; respiratory system: difficulty breathing; excretory system/skin: skin blistering, sweating above normal (Sharma and Singhvi, 2017).

evidence also suggests greater fertilizer use, amounting to 100–200 kg/ha per crop, in old high-dike farming systems than new-dike farming systems (30% higher on average in the new high-dike farming system), with an additional of almost 90% of fertilizer. Over the past 15 years, fertilizer use could be 133% to 234% higher in some areas with high-dike systems compared to the low-dike counterparts. Our findings of the accelerating rates of agrochemical application over time in the high-dike farming systems, compared to those in low-dike ones, corresponds to studies by Howie (2011), Kien and Van (2014), and Tong (2017).

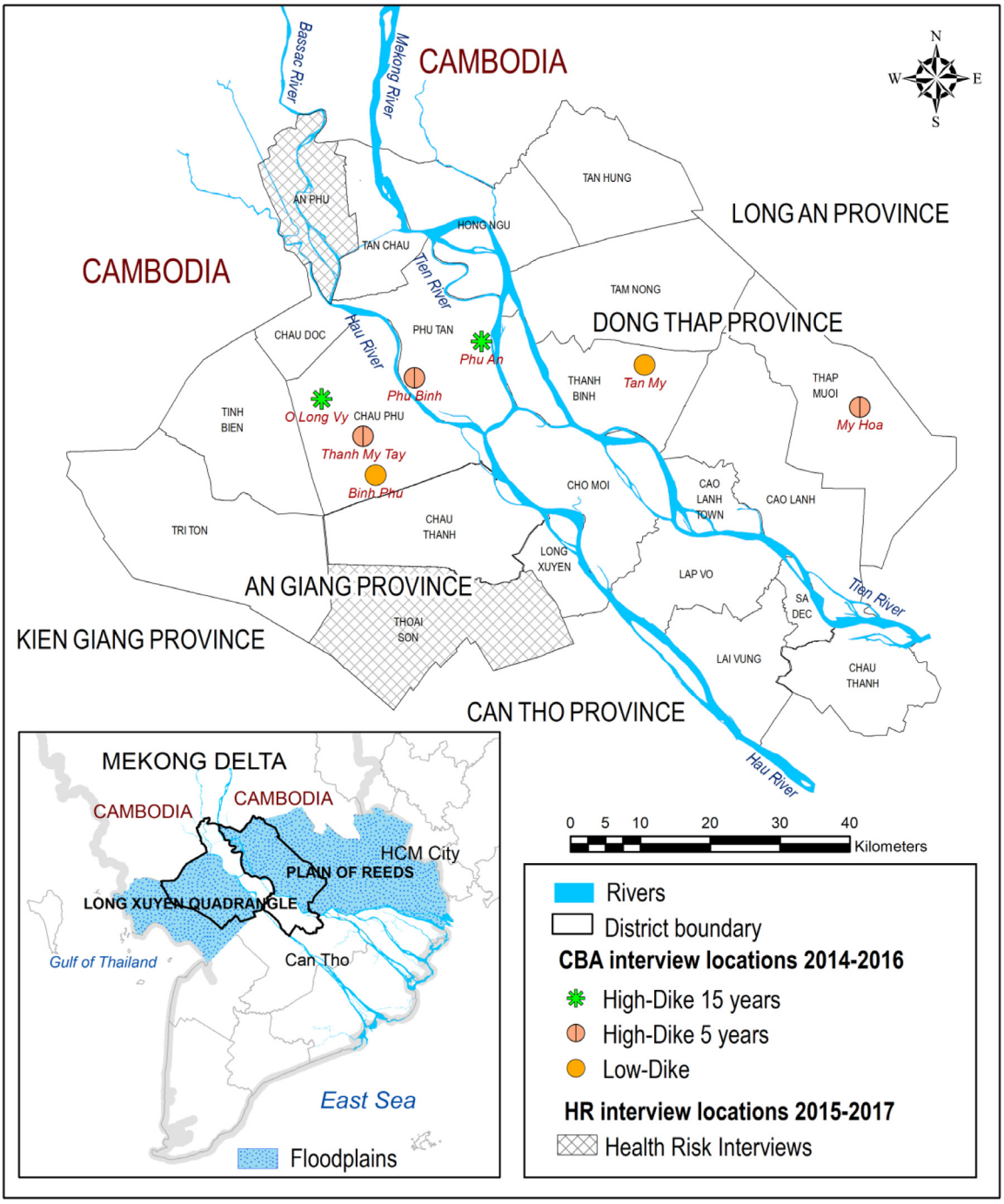

Fig. 3. An Giang and Dong Thap Provinces (lower) and the surveyed locations (upper) with base maps adopted from Dung et al. (2018a). Interviews on health risk (HR) assessment were conducted in 2015–2017 in An Phu District of An Giang Province.

Fertilizer and pesticide use has increased over the years in the triple-rice farming system. This meant that production costs have also risen in tandem. As shown in Fig. 5, the production costs for the triple-rice farming system include fertilizer and pesticides application, pumping, land preparation, seeds, harvesting, and labor. Here, farmers' labor and expenses for health treatment due to pesticide effects were not factored into the total production cost. This study, therefore, asserts that the actual production costs should be higher, and the consequent accumulative costs in the triple-rice model in the delta floodplains will also be much higher. Based on the findings by Dung et al. (2018a), the costs for triple-rice production

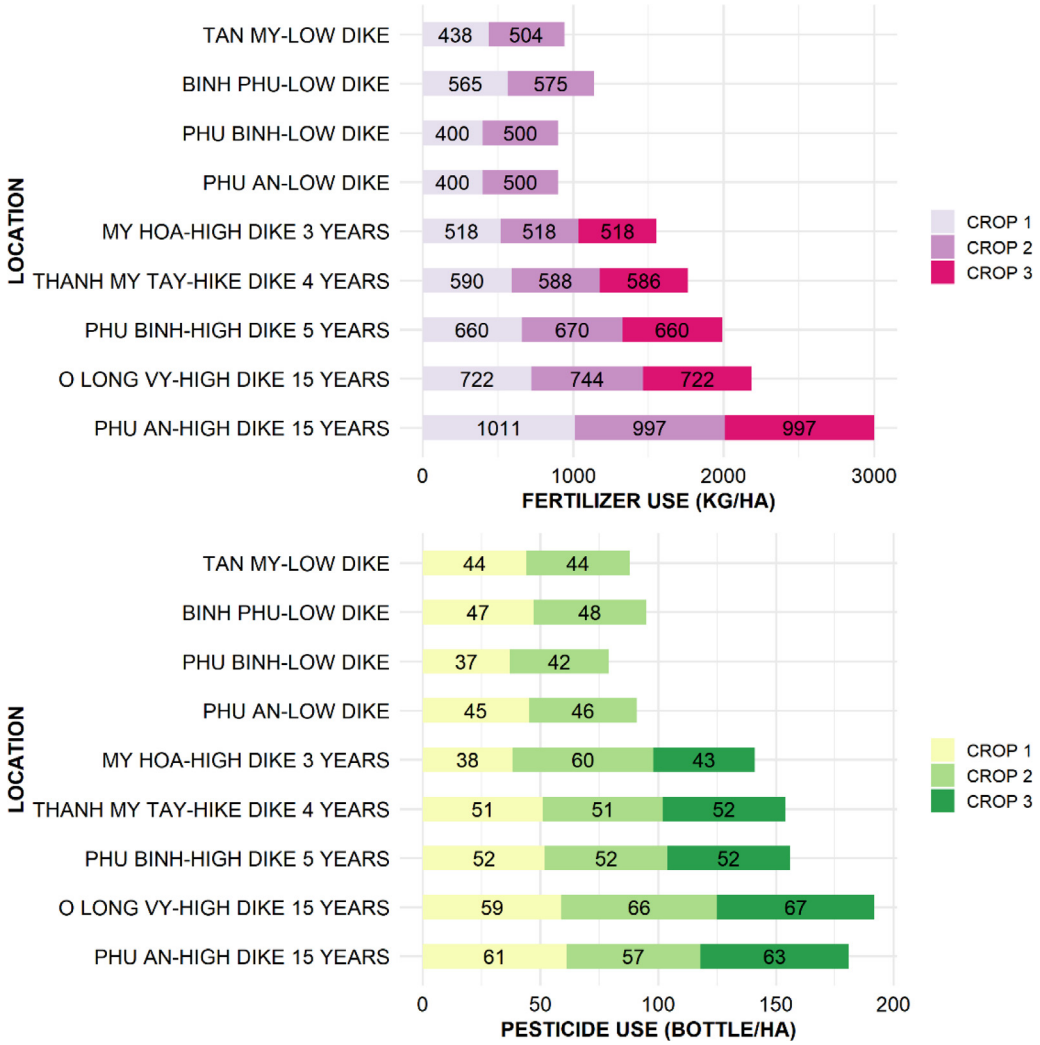

Fig. 4. Presentation of fertilizer and pesticides used for rice production in low- and new- and old high-dike areas in An Giang and Dong Thap Provinces. Data sourced from Dung et al. (2018a) defined that a new and old high-dike system is under 5 and over 15 construction years respectively.

averaged at US $240 per hectare per crop season for pesticides, and US $325 per hectare per crop season for fertilizer (Fig. 5). These amount to about 19% to 34% higher costs than those used in the double-rice production. As a result, the annual rice production profit was decreased up to 45% from some old high-dike compartments compared to those in the low-dike areas. Hence, the production cost for one hectare triple-rice farm is higher and the annual profit is lower if the health treatment cost is included. Although there exist social benefits, including more jobs, and less social evils (i.e., festive gathering of male farmers in drinking or playing cards) during the third crop season, their impacts are usually intangible, thus difficult to be considered.

3.3. Health risk of farmers under dike protections

A study conducted by Climate Change Institute, An Giang University in 2015 revealed the effects of pesticides exposure to farmers working on the farm. Most interviewed farmers (43.3%) informed that they experienced disruptive nerve effects during rice production activities, whereas only 6.7% of farmers reported digestive problems (Fig. 6). Of those main types of body exposure, pesticide effects on the respiratory system, excretory system, and vision were reported to have a smaller effect (28.3%, 21.7%, and 16.7%, respectively).

Regarding the 15 pesticide symptoms, excessive sweating/difficult breathing, dizziness and blurred vision, headache, and skin rashes had high effects on farmers, accounting for 28.1%, 25.6%, 21.5%, and 15.7% respectively (Fig. 7). Lesser than those four, 7.4%, 6.6%, 5%, and 5% of interviewed farmers responded that they experienced anxiety disorder/staggering, excessive salivation, nausea, excessive sweating, and hand tremor.

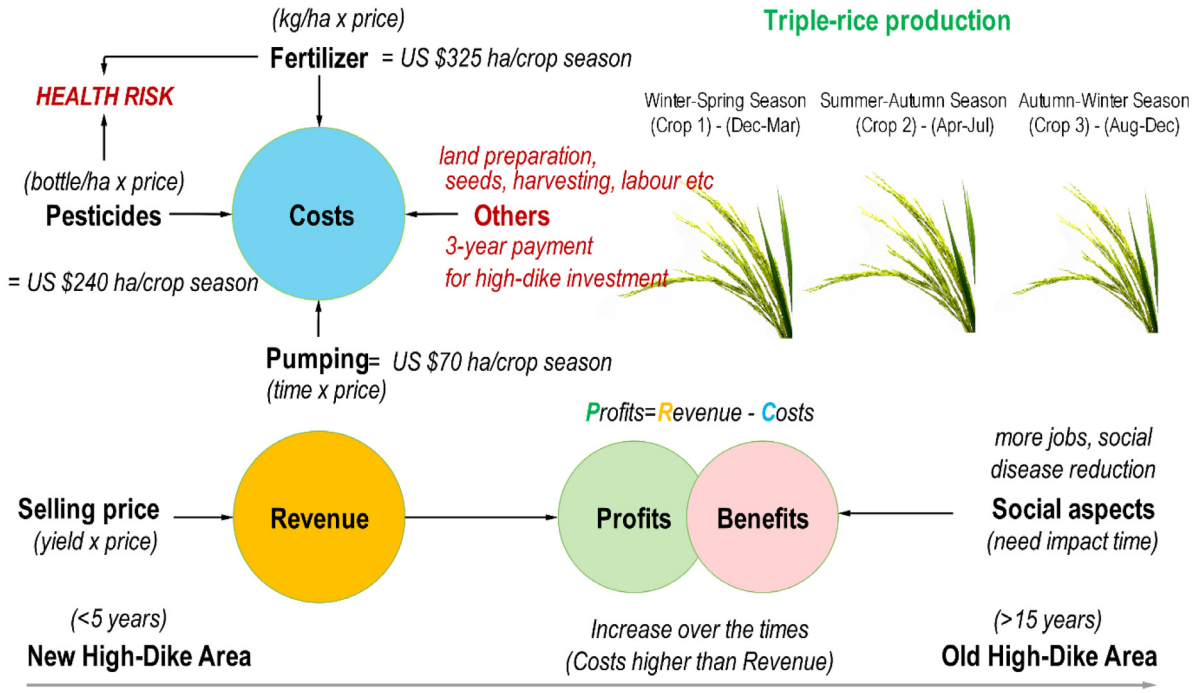

Fig. 5. Production costs and benefits between triple- and double-rice farming systems in relation to health risk assessment.

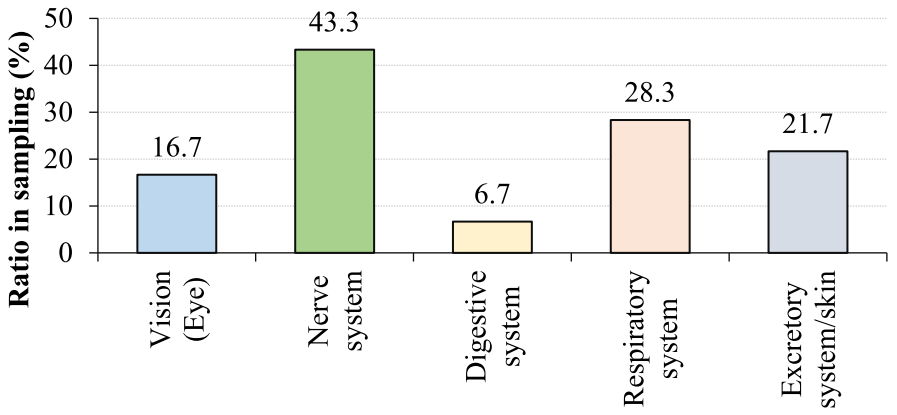

Fig. 6. The proportion of An Phu farmers exposed to pesticides.

The poisoning rate of those exposed to pesticides in Thoai Son District was lower than in An Phu District (see Figs. 8 and 1). Specifically, the study on rice farmers in An Giang (2014) showed that 9.5% was exposed to pesticides while working in the field (Fig. 8). According to a study conducted in An Phu in 2015, 18.2% of interviewees (22 out of 120 interviews) said they experienced pesticide poisoning. However, this rate was much lower (only 2.9%) as reported by a study in Thoai Son in 2017. This could be attributed to rice farmers in Thoai Son using personal protective equipment while farmers in An Phu rarely followed this while spraying pesticides. This differences is likely due to the higher level of education of Thoai Son farmers than An Phu farmers. These aggregated data suggest a mean of 10.2% of rice farmers was exposed to pesticide poisoning at least once during their crop production. Among the 22 farmers who reported being poisoned by pesticides in An Phu, we found 18 common chronic symptoms, including easy fatigue, cough, blurred vision, muscle pain, anorexia, shortness of breath, fever, dizziness, and dizziness. Our results also revealed that the increased use of pesticides in high-dike areas was closely related to farmers' increased health problems, especially those involved in directly spraying pesticides.

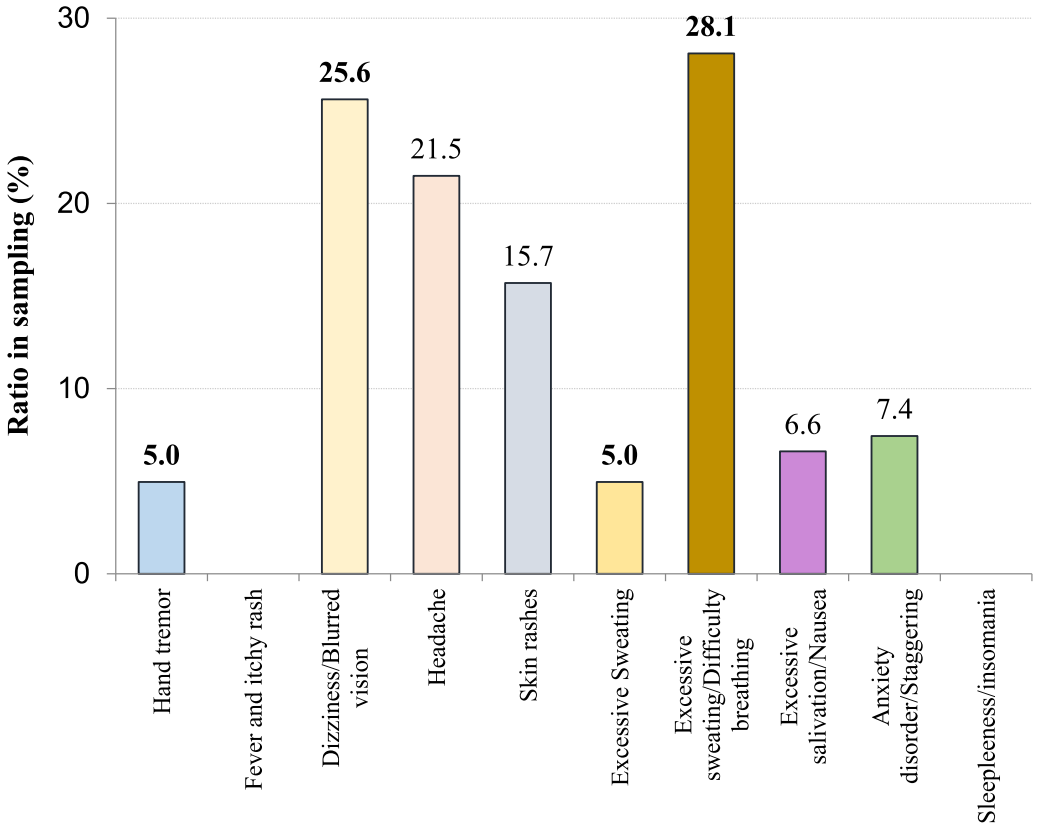

Fig. 7. Main pesticide symptoms reported by An Phu farmers.

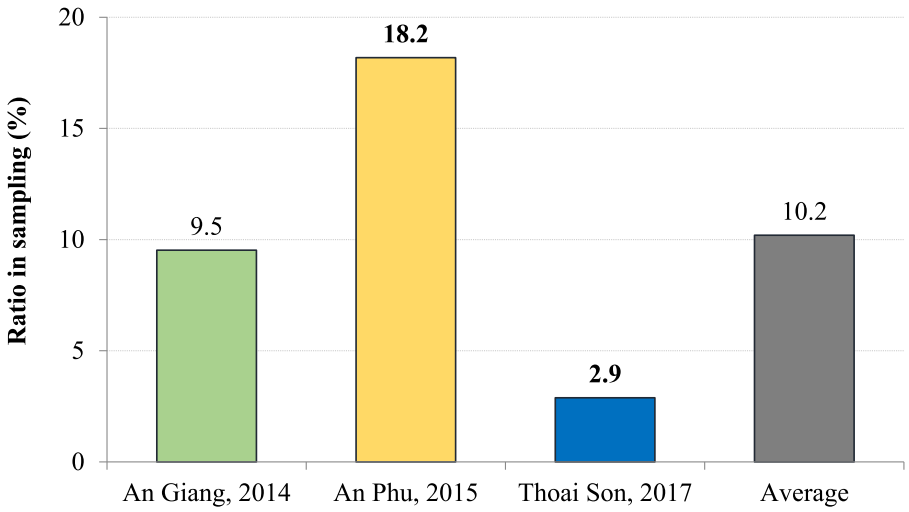

Fig. 8. The proportion of farmers exposed to pesticides from on-field practices.

3.4. Adaptation measures towards a sustainable adaptation pathway in rice farming

Secondary research on current prevention measures presents 17 most relevant case studies to our study on the relationships between intensified crop production and environmental and economic costs incurred. They were categorized according to (i) specific objectives, (ii) methods, and (iii) measures and outputs. The reviewed studies were synthesized chronologically by publication year and presented in Table 2.

Table 2
Potential adaptation measures for environmental protection of intensive rice production in the VMD floodplains.

Name of case study and reference	Objective/Context	Method	Output/Measures
1. Cost and benefit analysis for intensive rice production (Dung et al., 2018a; Tong, 2017; Tran et al., 2019) and impacts of rice intensification on rural households in the Mekong Delta (Nguyen et al., 2018)	Determining costs and benefits of double and triple rice production under low- and new, old high-dike protection and exploring alternatives for more sustainable farms in the floodplains at different scales of the VMD	Cost and benefit analysis across delta scales using literature review, secondary data, and interviews with farmers	Double-rice crop as "balanced cropping" better than triple-rice crop in taking advantages of the flood's benefit; flood-based farming systems such as intensive lotus crop with tourism, water lily, or floating rice combined with vegetables that could gain "common pool resources" from floodwater and reduce the use of fertilizer and pesticide
2. Sustainable intensification of agriculture (Rockström et al., 2017)	Proposing a paradigm for sustainable intensification that can be defined and translated into an operational framework for agricultural development	Literature review and discussion then suggestion of adding a new dimension to sustainable agricultural development, namely managing natural capital for long-term productivity and social–ecological resilience at field, watershed, and regional scales, in agricultural systems	The challenge of improving the health and livelihoods of farmers needs to be addressed, and it is essential to apply "*nature-based solutions for sustainable intensification of agriculture to build prosperity and resilience*".
3. Health risks from agricultural intensification (Lam et al., 2017)	Examining and synthesizing the evidence for human health risks of agricultural intensification in Southeast Asia	A systematic review of 73 peer-reviewed articles published between the years of 2000 and 2015	The knowledge on health risks appears to be limited. Agricultural intensification shows expansive impacts on communities; however, studies mainly concentrated on the occupational and consumer exposure to pesticides, without specifying the actual health risk
4. Agricultural intensification and damages to human health (Elahi et al., 2019)	Application of artificial intelligence to assess damages to human health in relation to agrochemicals for agricultural intensification	Statistical data analysis with 360 rice growers collected in 2017 from 9 districts of Punjab, Pakistan, using a multistage sampling technique	Pesticide application caused skin irritation, eye irritation, cough, dizziness, nausea, and diarrhea. The study recommended using bio-chemicals for agricultural sustainability and human health protection
5. System of rice intensification (Taylor and Bhasme, 2019)	Assessment of the potential of the system of rice intensification (SRI) for smallholder farmers.	Semi-structured interviews with over 50 farmers, agricultural laborers, extension officers, agricultural scientists, and NGO staff in Mahabubnagar, Telangana state, southern India	Although the SRI applies a reduction in water use and external inputs, a political ecology framework is required.
6. Ecological sustainability and environmental risks of agricultural intensification (Djagba et al., 2019)	Assessment of ecological sustainability and environmental risks of agricultural intensification in inland valleys in Benin	"Driving Force–Pressure–State–Impact–Response" approach in four agro-ecological zones of Benin	Activities and policies monitoring chemical inputs and farming practices in inland valleys to reduce negative impacts on the environment and human health
7. The use of pesticides in agricultural activities and potential health risk (Elfikrie et al., 2020)	Identifying the occurrence of pesticides in surface water and pesticides removal efficiency due to leach from the irrigation of mostly rice cultivation in Tanjung Karang, Selangor, Malaysia	Thirty river water samples and eighteen water samples were collected from a conventional drinking water treatment plant	Advanced water treatment processes such as activated carbon can increase pesticide removal efficiencies in drinking water treatment plant
8. Pesticides applied in rice fields in developing countries (Wong and Brown, 2021)	Evaluating methods and outcomes of previous studies to quantify pesticide exposure amongst rice growers in developing countries	Critical literature review	Dermal exposures much more than inhalation exposures The use of active pesticide substances in developing countries that have been banned in many developed countries.

(*continued on next page*)

From the studies, nature-based practices were considered of vital significance to agricultural production that could reduce the costs to farmers and increase their long-term benefits, under the perceived detrimental effects of intensive

Table 2 (*continued*).

9. Risk assessment of heavy metal contamination of paddy soil and rice (Ihedioha et al., 2019)	Evaluating the concentration and bioavailability of Pb, Cd, Zn, Cr and Fe metals in soil from rice fields in Abakaliki, Nigeria, and their human health risk on consumers	Samplings were conducted, including 40 soil samples and 40 rice grain samples from farm A and farm B, making a total of 80 samples	No adverse health effects from heavy metal ingestion through consumption of rice grown in the region; however, the warnings exist and seriously consider the use of fertilizer.
10. Risks of pesticide use (Rahaman et al., 2018)	Examining the level of knowledge and awareness of environmental pollution of farmers in Bangladesh due to unsafe use of pesticides for controlling rice pests and exploring ways of reducing their usage	Interviews with 120 rice farmers	Many farmers have understood the harmful effects of pesticides on the health of humans and animals, beneficial species, fish, insect resistance, soil, and food. Measures include timely removal of weeds, appropriate timing for pesticide application, balanced doses of fertilizers, pest monitoring, the correct dose of appropriate pesticides, pest tolerant varieties, increasing technical knowledge and skills and creating social awareness of environmental pollution among farmers.
11. Pathway for intensive pesticide degradation in rice and environment (Ma et al., 2021)	Investigating a novel epigenetic mechanism responsible for the degradation of the pesticide atrazine in rice crops in Korea	Rice genotypes (Oryza sativa) Nipponbare (wide type, WT1), Dong Jing (DJ, WT2), Kitaake (KT, WT3), and Hwayoung (HY, WT4) were used for experiments and analyzed	A novel regulatory mechanism implicated in the defense linked to the epigenetic modification and jasmonate signaling pathway and provides a modus operandi that can be used for metabolic engineering of rice to minimize amounts of atrazine in the crop and environment
12. Use and avoidance of pesticides in the rice ecosystem (Horgan and Kudavidanage, 2020)	Investigate farmers' decisions in southern Sri Lanka of applying or avoiding pesticides on rice farms	Interviews with 275 farmers	Certification of 'pesticide-free' and 'insecticide-free' cultivation is important
13. Decreased use of pesticides for increased yields of rice (Berg and Tam, 2018)	Assessment of the use of pesticides and the attitude to pest management strategies among rice and rice-fish farmers in the Can Tho and Tien Giang Provinces in Vietnam	Interviews with 80 rice-fish farmers	85% and 75% of interviewed farmers had experienced health effects and a decrease in fish yields mainly due to pesticides Rice fish is a good farming system with high yields and fewer pesticides use
14. Human health and pesticide use (Sheahan et al., 2017)	Exploring the relationship between pesticide use and the value of crop output and identifying human health outcomes in four Sub-Saharan African countries	Based on nationally representative panel survey data from four Sub-Saharan African countries	Pesticide use is strongly correlated with an increased value of harvest and higher costs associated with human illness, such as increased health expenditures and time lost from work due to sickness
15. Sustainability performance indicators for assessing rice crop management practices in the Vietnamese Mekong Delta (Stuart et al., 2018)	Assessing the sustainability performance of "One Must Do, Five Reductions" rule and the three different management approaches for rice production over two rice cropping seasons in the VMD's study area, using eight farm-level Sustainable Rice Platform (SRP) performance indicators	This study conducted a household survey (155 farmers in three communes) of GAP (VietGAP and GlobalGAP), "Small Farmer Large Field" and conventional farmers in Can Tho Province in the VMD and established replicated production-scale field trials of "One Must Do, Five Reductions" rule in rice production, with an emphasis on further reducing seed and pesticide inputs	Mean total production cost per season fell by 23% (203 USD ha^{-1}), and mean net income increased by 19% (175 USD ha^{-1}), resulting in a 28% increase in the benefit: cost ratio and five of eight farm-level SRP indicators showed an improvement in sustainability performance

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agricultural practices in the VMD (Nguyen et al., 2018; Rockström et al., 2017; Tran et al., 2019). These nature-based practices which include floating rice, water crops like water lily are encouraged to grow in nodike or low-dike areas in the flood season to replace triple-rice production under high-dikes to gain natural benefits from floodwaters such as fertile sediment and wild fish. Under intensive farming systems, the overuse of fertilizer and pesticides has significantly degraded the living environment, diminished ecosystems, and negatively impacted human health (i.e., Chau et al., 2015; Djagba

Table 2 (*continued*).

16. Pesticide pollution of multiple drinking water sources in the Vietnamese Mekong Delta (Chau et al., 2015)	Exploring potential exposure sources to pesticides from agricultural-based cultivations in rural areas of the VMD	A survey of the use of different drinking water sources and the pollution with pesticides, including interviews with 104 households living along the canals of four study sites and 260 grab water samples collected.	Concentrations were highest in canal waters among the studied water resources; however, pesticide concentrations varied with cropping season but did not diminish through the year. No clean water source was found in the Mekong Delta with respect to pesticide pollution, and studies on drinking water-related health risk issues was recommended.
17. Fairtrade, agrochemical input use, and effects on human health and the Environment (Sellare et al., 2020)	Influences of Fairtrade certification on fertilizer, pesticide use and human health and the environment were analyzed	Data from farmers and rural workers in 50 cooperatives (25 Fairtrade certified and 25 non-certified cooperatives) in Cote d'Ivoire were analyzed	Fairtrade reduces the incidence of pesticide-related acute health symptoms among farmers and workers

et al., 2019; Elahi et al., 2019). Hence, sustainable intensification in agriculture is required in agroecosystems, where bio-fertilizer and biochemical pesticides are utilized instead. This approach should be ruled by an ecological framework that acquires a trict consideration of ecological protection for systems of rice intensification (Taylor and Bhasme, 2019) or Global Good Agriculture Practice (GAP) or Viet GAP (Stuart et al., 2018). Furthermore, assessment approach such as "Driving Force–Pressure–State–Impact–Response" framework should also be more readily applied to monitor chemical inputs in agricultural activities to reduce negative impacts on the environment and human health (Djagba et al., 2019). In Can Tho Province and many other places in the VMD, "One Must Do, Five Reductions" has been an effective rule used to reduce fertilizer and pesticide use in rice production because agrochemical use is considered as a requirement for crop growth and cannot be avoided (Stuart et al., 2018). Of those, Thi et al. (2013) explained that "One must" recommends that farmers must use certified seeds; "Five Reductions" include reducing seed rate (use from 80–100 kg seeds/ha, use drum seeder), reducing fertilizer (reduce nitrogen fertilizer, apply fertilizer by using leaf color chart), reducing pesticide (only use pesticide when necessary by following the guidance of technical staffs), reducing water (reduce water amount in irrigation and number of water pumping), and reducing post harvest loss (reduce grain loss in and post harvest, use combine harvester to harvest rice and rice dryer to dry rice).

While much effort has been made in shifting adaptation pathways in the VMD floodplains evidenced by the flexibility of decision-making and adaptive planning processes in the agricultural production sector (Gajjar et al., 2019), our study suggests that the existing triple-rice farming system would not bring a sustainable pathway for sustainable development to the delta floodplains, particularly in terms of environmental and economic dimensions. It proposed that achieving sustainable development goals in the VMD should not go hand in hand with the triple-rice farming practice which could not completely stopped and takes times for nature-based alternative farming system. Instead, nature-based adaptation practices or one season off should be adopted in the high-dike areas to enhance the functionality and performance of local ecosystem services. In the context of the floodplains, implementation of such adaptive measures requires an empirical understanding of the wide-ranging social-ecological context in decision making across governance scales, i.e., how the triple-rice farming practice supports the national adaption policy for food security (Colloff et al., 2016). In addition, market stability is one of the most important factors for triple-rice farmers to transform their rice crop which has been considered as a traditional crop and its market is quite stable ensured by national food security policy for many years. These also a need to consider uncertainties relevant to the coupled environment and dynamics in the VMD (Bhave et al., 2018).

3.5. Limitations and future outlooks

Although this study has revealed the important social-hydrological trade-offs from triple-rice farming in the VMD floodplains, we acknowledge that the findings are limited in two aspects. Firstly, the assessment could be expanded with the integration of soil and water quality measurements in the studied low- and high-dike polders to more accurately determine environmental consequences of the farming system. Secondly, a longitudinal study where interviews with farmers were conducted over continuous years, could provide a better estimation of health risk for comparison between the low- and new and old high-dike farming systems. This can allow for better monitoring of farmers' agricultural practices over a longer time period, with better records of the signs and symptoms of pesticide poisoning. Overall, future studies should be expanded to larger geographical scales while also considering longer-term environmental and health implications of intensive agricultural practices in the VMD.

Future sustainable adaptation strategy in the VMD should also incorporate the impacts of external drivers (i.e., climate change, hydropower development upstream the Mekong river and across the Mekong countries) and internal drivers (i.e., local intensive crops supported by irrigation systems with mainly pumps and dike polders). At the institutional level, local governments in adaptation should be made responsible, with the current adaptation policies reframed to accommodate the "nature-based" practices stipulated in central and local government policy documents (Lupp et al.,

2021). It is also beneficial to formulate a concrete mechanism to mobilize local governments' support that allows farmers to maximize their capacity to adapt to change via effective policies and resources considering the environmental changes in both internal and external dimensions. At the farm level, the role of farmers in adaptation is important; therefore, the diffusion of empirical and experimental knowledge of adaptation (farming initiatives) should be promoted among farmer groups, which together contributes to creating epistemic communities in adapting to changes such as climate change and environmental challenges (Dang et al., 2020; Tran et al., 2020b).

4. Conclusions

This study assesses the trade-offs between socio-economic growth and the environmental and social consequences of overused agrochemicals in the VMD's upper floodplains under the dike protection context. Our study demonstrated the social and health challenges farmers experience due to the increased use of agrochemicals in rice production. We contend that the overuse of agrochemicals from triple-rice production systems is akin to increased costs, estimating about US $565 per hectare per crop season, thus lowering its marginal benefits, compared to double-rice production system. In addition, rice farmers were directly exposed to pesticide impacts. Therefore, to support policy and decision making processes for the sustainable development of the VMD, we proposed three critical considerations:

First, better engagement in coupled environment-development systems by harmonizing costs (production costs such as pesticide and fertilizer use and health risk) and benefits (income and national food security) of agricultural-based development and upscaling nature-based adaptation approaches in the delta's farming systems. While sustainable adaptation approaches exist in agricultural production, the shift to this paradigm is not easy as. farmers' decisions to change existing farming patterns are impeded by the availability of high-dike systems.

Second, serious consideration in limiting and removing the reliance on fertilizer and pesticides despite their central role in agricultural productivity and pests control. The adverse impacts on human health should not be underestimated and sustainable agricultural production policies in the VMD should also include education of farmers to comply with technical advice (e.g. wearing personal protective equipment) in applying pesticides on the field.

Finally, the need to mainstream the environmental consequences from triple-rice production, into the broader understanding of the floodplains' contemporary environment and development complexities, where farmers are direct victims. In the support for economic development and food demand and, the environmental issues associated with land degradation and water quality pollution have cumulative impacts on farmers' costs. Small-holder farmers are particularly vulnerable as they depend heavily on these natural resources for living. Yet, rural policy and practices continue to treat these communities as marginalized groups. These considerations are essential for the survival and sustainability of the delta in the future.

CRediT authorship contribution statement

Dung Duc Tran: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Edward Park:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Thong Anh Tran:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Thang Tat Vo:** Resources, Data curation, Writing – review & editing. **Phong Thanh Le:** Resources, Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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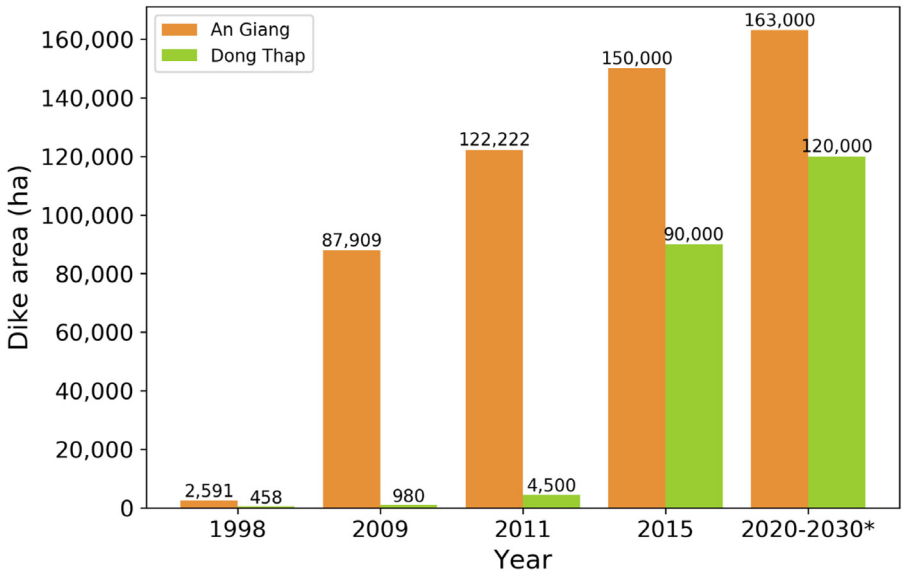

Fig. A.1. Progress of building high-dikes in An Giang and Dong Thap provinces.

Appendix

See Fig. A.1.

References

AGGSO, 2015. Statistical Yearbook of An Giang Province 2015. An Giang Statistics Office, An Giang Province, Vietnam.

Azab, S.M.S., Hirshon, J.M., Hayes, B.D., El-Setouhy, M., Smith, G.S., Sakr, M.L., Tawfik, H., Klein-Schwartz, W., 2016. Epidemiology of acute poisoning in children presenting to the poisoning treatment center at Ain Shams University in Cairo, Egypt, 2009–2013. Clin. Toxicol. 54, 20–26. http://dx.doi.org/10.3109/15563650.2015.1112014.

Berg, H., Ekman Söderholm, A., Söderström, A.-S., Tam, N.T., 2017. Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. Sustain. Sci. 12, 137–154. http://dx.doi.org/10.1007/s11625-016-0409-x.

Berg, H., Tam, N.T., 2018. Decreased use of pesticides for increased yields of rice and fish-options for sustainable food production in the Mekong Delta. Sci. Total Environ. 619–620, 319–327. http://dx.doi.org/10.1016/j.scitotenv.2017.11.062.

Bhave, A.G., Conway, D., Dessai, S., Stainforth, D.A., 2018. Water resource planning under future climate and socioeconomic uncertainty in the cauvery river basin in Karnataka, India. Water Resour. Res. 54, 708–728. http://dx.doi.org/10.1002/2017WR020970.

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

Chau, N.D.G., Sebesvari, Z., Amelung, W., Renaud, F.G., 2015. Pesticide pollution of multiple drinking water sources in the Mekong Delta, Vietnam: evidence from two provinces. Environ. Sci. Pollut. Res. 22, 9042–9058. http://dx.doi.org/10.1007/s11356-014-4034-x.

Colloff, M.J., Doherty, M.D., Lavorel, S., Dunlop, M., Wise, R.M., Prober, S.M., 2016. Adaptation services and pathways for the management of temperate montane forests under transformational climate change. Clim. Change 138, 267–282. http://dx.doi.org/10.1007/s10584-016-1724-z.

Dang, V.H., Tran, D.D., Cham, D.D., Hang, P.T., Nguyen, H.T., Truong, H.V., Tran, P.H., Duong, M.B., Nguyen, N.T., Le, K.V., Pham, T.B., Nguyen, A.H., 2020. Assessment of rainfall distributions and characteristics in coastal provinces of the Vietnamese Mekong Delta under climate change and ENSO processes. Water http://dx.doi.org/10.3390/w12061555.

Dassanayake, T.L., Weerasinghe, V.S., Gawarammana, I., Buckley, N.A., 2021. Subacute and chronic neuropsychological sequalae of acute organophosphate pesticide self-poisoning: a prospective cohort study from Sri Lanka. Clin. Toxicol. 59, 118–130. http://dx.doi.org/10.1080/15563650.2020.1778719.

Djagba, J.F., Zwart, S.J., Houssou, C.S., Tenté, B.H.A., Kiepe, P., 2019. Ecological sustainability and environmental risks of agricultural intensification in inland valleys in Benin. Environ. Dev. Sustain. 21, 1869–1890. http://dx.doi.org/10.1007/s10668-018-0107-1.

DTGSO, 2015. Statistical Yearbook of Dong Thap Province 2015. Dong Thap Statistics Office, Dong Thap Province, Vietnam.

Duc Tran, D., van Halsema, G., Hellegers, P.J.G.J., Phi Hoang, L., Quang Tran, T., Kummu, M., Ludwig, F., 2018. Assessing impacts of dike construction on the flood dynamics of the Mekong Delta. Hydrol. Earth Syst. Sci. 22, 1875–1896. http://dx.doi.org/10.5194/hess-22-1875-2018.

Dung, D.T., Gerardo, V.H., Petra, J.G.J.H., Fulco, L., Wyatt, A., 2018a. Questioning triple rice intensification on the Vietnamese Mekong Delta floodplains: An environmental and economic analysis of current land-use trends and alternatives. Environ. Water Manage. http://dx.doi.org/10.1016/j.jenvman.2018.03.116.

Dung, D.T., Gerardo, V.H., Petra, J.G.J.H., Ludwig, F., Chris, S., 2018b. Stakeholders assessment of alternative flood-based farming systems from a sustainable livelihood perspective in An Giang province. Agric. Water Manage. 206, 187–199.

Dung, D.T., van Halsema, G., Hellegers, P.J.G.J., Phi Hoang, L., Quang Tran, T., Kummu, M., Ludwig, F., 2018c. Assessing impacts of dike construction on the flood dynamics in the Mekong Delta. Hydrol. Earth Syst. Sci. 22, 1875–1896. http://dx.doi.org/10.5194/hess-22-1875-2018.

Ekman, A., 2017. Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta. Vietnam 13, 7–154. http://dx.doi.org/10.1007/s11625-016-0409-x.

Elahi, E., Weijun, C., Zhang, H., Nazeer, M., 2019. Agricultural intensification and damages to human health in relation to agrochemicals: Application of artificial intelligence. Land Use Policy 83, 461–474. http://dx.doi.org/10.1016/j.landusepol.2019.02.023.
Elfikrie, N., Ho, Y., Bin, Zaidon, S.Z., Juahir, H., Tan, E.S.S., 2020. Occurrence of pesticides in surface water, pesticides removal efficiency in drinking water treatment plant and potential health risk to consumers in Tengi River Basin, Malaysia. Sci. Total Environ. 712, 136540. http://dx.doi.org/10.1016/j.scitotenv.2020.136540.
Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., Vandewoestijne, S., 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environ. Res. 159, 509–518. http://dx.doi.org/10.1016/j.envres.2017.08.032.
Gajjar, S.P., Singh, C., Deshpande, T., 2019. Tracing back to move ahead: a review of development pathways that constrain adaptation futures. Clim. Dev. 11, 223–237. http://dx.doi.org/10.1080/17565529.2018.1442793.
Hanson, H.I., Wickenberg, B., Alkan Olsson, J., 2020. Working on the boundaries—How do science use and interpret the nature-based solution concept? Land Use Policy 90, 104302. http://dx.doi.org/10.1016/j.landusepol.2019.104302.
Hoang, L.P., van Vliet, M.T.H., Kummu, M., Lauri, H., Koponen, J., Supit, I., Leemans, R., Kabat, P., Ludwig, F., 2019. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes. Sci. Total Environ. 649, 601–609. http://dx.doi.org/10.1016/j.scitotenv.2018.08.160.
Horgan, F.G., Kudavidanage, E.P., 2020. Use and avoidance of pesticides as responses by farmers to change impacts in rice ecosystems of southern Sri Lanka. Environ. Manage. 65, 787–803. http://dx.doi.org/10.1007/s00267-020-01272-x.
Howie, C., 2011. Co-Operation and Contestation: Farmer-State Relations in Agricultural Transformation, an Giang Province, Vietnam. University of London, England.
Hui, T.R., Park, E., Loc, H.H., Tien, P.D., 2022. Long-term hydrological alterations and the agricultural landscapes in the Mekong Delta: Insights from remote sensing and national statistics. Environ. Challenges 7, 100454. http://dx.doi.org/10.1016/J.ENVC.2022.100454.
Huu, P.C., 2011. Planning and Implementation of the Dyke Systems in the Mekong Delta, Vietnam. Bonn University, Germany.
Ihedioha, J.N., Ogili, E.O., Ekere, N.R., Ezeofor, C.C., 2019. Risk assessment of heavy metal contamination of paddy soil and rice (Oryza sativa) from Abakaliki, Nigeria. Environ. Monit. Assess. 191, 350. http://dx.doi.org/10.1007/s10661-019-7491-3.
IUCN, 2015. Flood retention livelihood demonstration design study. In: International Union for Conservation of Nature in Ho Chi Minh City. Vietnam.
Joep, H., 2015. Flood Control in the Vietnamese Mekong Delta. Wageningen University, Wageningen.
Käkönen, M., 2008. Mekong Delta at the crossroads: More control or adaptation? Ambio http://dx.doi.org/10.1579/0044-7447(2008)37[205:MDATCM]2.0.CO;2.
Kien, N., Van, 2014. An Economic Evaluation of Flood Dike Construction in the Mekong Delta. LAP LAMBERT Academic Publishing, Germany.
Kondolf, G.M., Schmitt, R.J.P., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A., Cochrane, T.A., Gibson, S., Kummu, M., Oeurng, C., Rubin, Z., Wild, T., 2018. Changing sediment budget of the Mekong : Cumulative threats and management strategies for a large river basin. Sci. Total Environ. 625, 114–134. http://dx.doi.org/10.1016/j.scitotenv.2017.11.361.
Kumari, D., John, S., 2018. In: Siddiqui, N.A., Tauseef, S.M., Bansal, K. (Eds.), Safety and Occupational Health Hazards of Agricultural Workers HandLing Pesticides: A Case Study BT - Advances in Health and Environment Safety. Springer Singapore, Singapore, pp. 75–82.
Kummu, M., Tes, S., Yin, S., Adamson, P., Józsa, J., Koponen, J., Richey, J., Sarkkula, J., 2014. Water balance analysis for the Tonle Sap Lake–floodplain system. Hydrol. Process 28, 1722–1733. http://dx.doi.org/10.1002/hyp.9718.
Lam, S., Pham, G., Nguyen-Viet, H., 2017. Emerging health risks from agricultural intensification in Southeast Asia: a systematic review. Int. J. Occup. Environ. Health 23, 250–260. http://dx.doi.org/10.1080/10773525.2018.1450923.
Lauri, H., de Moel, P.J., Räsänen, T.A., Keskinen, M., Kummu, M., 2012. Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge. Hydrol. Earth Syst. Sci. 16, 4603–4619. http://dx.doi.org/10.5194/hess-16-4603-2012.
Lu, X., Kummu, M., Oeurng, C., 2014. Reappraisal of sediment dynamics in the Lower Mekong River, Cambodia. Earth Surf. Process. Landf. 39, 1855–1865. http://dx.doi.org/10.1002/esp.3573.
Lupp, G., Zingraff-Hamed, A., Huang, J.J., Oen, A., Pauleit, S., 2021. Living Labs—A concept for co-designing nature-based solutions. Sustainability (13), http://dx.doi.org/10.3390/su13010188.
Lyon, S.W., King, K., Polpanich, O., Lacombe, G., 2017. Assessing hydrologic changes across the Lower Mekong Basin. J. Hydrol. Reg. Stud. 12, 303–314. http://dx.doi.org/10.1016/j.ejrh.2017.06.007.
Ma, L.Y., Zhai, X.Y., Qiao, Y.X., Zhang, A.P., Zhang, N., Liu, J., Yang, H., 2021. Identification of a novel function of a component in the jasmonate signaling pathway for intensive pesticide degradation in rice and environment through an epigenetic mechanism. Environ. Poll. 268, 115802. http://dx.doi.org/10.1016/j.envpol.2020.115802.
Manh, N., Van, Dung, N.V., Hung, N.N., Kummu, M., Merz, B., Apel, H., 2015. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. Glob. Planet. Change 127, 22–33. http://dx.doi.org/10.1016/j.gloplacha.2015.01.001.
Martin-Guay, M.-O., Paquette, A., Dupras, J., Rivest, D., 2018. The new Green Revolution: Sustainable intensification of agriculture by intercropping. Sci. Total Environ. 615, 767–772. http://dx.doi.org/10.1016/j.scitotenv.2017.10.024.
Mekong Delta Plan, 2013. Kingdom of the netherlands & the socialist Republic of Vietnam.
Netherlands, K., 2011. Towards a Mekong Delta Plan. Vietnam-Netherlands Cooperation, Vietnam.
Nguyen, V.K., Dumaresq, D., Pittock, J., 2018. Impacts of rice intensification on rural households in the Mekong Delta: emerging relationships between agricultural production, wild food supply and food consumption. Food Secur. 10, 1615–1629. http://dx.doi.org/10.1007/s12571-018-0848-6.
Pain, D.J., Mateo, R., Green, R.E., 2019. Effects of lead from ammunition on birds and other wildlife: A review and update. Ambio 48, 935–953. http://dx.doi.org/10.1007/s13280-019-01159-0.
Park, E., Ho, H.L., Tran, D.D., Yang, X., Alcantara, E., Merino, E., Son, V.H., 2020. Dramatic decrease of flood frequency in the Mekong Delta due to river-bed mining and dyke construction. Sci. Total Environ. 723, 138066. http://dx.doi.org/10.1016/j.scitotenv.2020.138066.
Park, E., Loc Ho, H., Van Binh, D., Kantoush, S., Poh, D., Alcantara, E., Try, S., Lin, Y.N., 2022. Impacts of agricultural expansion on floodplain water and sediment budgets in the Mekong River. J. Hydrol. 605, 127296. http://dx.doi.org/10.1016/j.jhydrol.2021.127296.
Pauleit, S., Zölch, T., Hansen, R., Randrup, T.B., Konijnendijk van den Bosch, C., 2017. In: Kabisch, N., Korn, H., Stadler, J., Bonn, A. (Eds.), Nature-Based Solutions and Climate Change – Four Shades of Green BT - Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice. Springer International Publishing, Cham, pp. 29–49. http://dx.doi.org/10.1007/978-3-319-56091-5_3.
Rahaman, M.M., Islam, K.S., Jahan, M., 2018. Rice farmers' knowledge of the risks of pesticide use in Bangladesh. J. Heal. Pollut. 8. http://dx.doi.org/10.5696/2156-9614-8.20.181203.
Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., Smith, J., 2017. Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46, 4–17. http://dx.doi.org/10.1007/s13280-016-0793-6.
Sellare, J., Meemken, E.-M., Qaim, M., 2020. Fairtrade, agrochemical input use, and effects on human health and the environment. Ecol. Econ. 176, 106718. http://dx.doi.org/10.1016/j.ecolecon.2020.106718.
Sharma, N., Singhvi, R., 2017. Effects of chemical fertilizers and pesticides on human health and environment: A review. Int. J. Agric. Environ. Biotechnol. 10, 675–680.

Sheahan, M., Barrett, C.B., Goldvale, C., 2017. Human health and pesticide use in Sub-Saharan Africa. Agric. Econ. 48, 27–41. http://dx.doi.org/10.1111/agec.12384.

Stuart, A.M., Devkota, K.P., Sato, T., Pame, A.R.P., Balingbing, C., My Phung, N.T., Kieu, N.T., Hieu, P.T.M., Long, T.H., Beebout, S., Singleton, G.R., 2018. On-farm assessment of different rice crop management practices in the Mekong Delta, Vietnam, using sustainability performance indicators. F. Crop. Res. 229, 103–114. http://dx.doi.org/10.1016/j.fcr.2018.10.001.

Suy, R., Choun, C., Chhay, L., 2018. Review of agriculture and rural development to poverty reduction in Cambodia: SWOT analysis. Asian Themes Soc. Sci. Res. Asian Themes Soc. Sci. Res. 1.

Taylor, M., Bhasme, S., 2019. The political ecology of rice intensification in south India: Putting SRI in its places. J. Agrar. Change 19, 3–20. http://dx.doi.org/10.1111/joac.12268.

Thanh, V.Q., Roelvink, D., van der Wegen, M., Reyns, J., Kernkamp, H., Van Vinh, G., Linh, V.T.P., 2020. Flooding in the Mekong Delta: the impact of dyke systems on downstream hydrodynamics. Hydrol. Earth Syst. Sci 24, 189–212. http://dx.doi.org/10.5194/hess-24-189-2020.

Thi, T., Chi, N., Anh, T., Tuan, T.Q., Palis, F., Singleton, G., Toan, N.V., 2013. Implementation of 'One must and five reductions' in rice production, in An Giang province.

Tong, Y.D., 2017. Rice intensive cropping and balanced cropping in the Mekong Delta, Vietnam — Economic and ecological considerations. Ecol. Econ. 132, 205–212. http://dx.doi.org/10.1016/j.ecolecon.2016.10.013.

Tran, T.A., 2019. Land use change driven out-migration: Evidence from three flood-prone communities in the Vietnamese Mekong Delta. Land Use Policy 88, 104157. http://dx.doi.org/10.1016/j.landusepol.2019.104157.

Tran, D.D., van Halsema, G., Hellegers, P.J.G.J., Hoang, L.P., Ludwig, F., 2019. Long-term sustainability of the Vietnamese Mekong Delta in question: An economic assessment of water management alternatives. Agric. Water Manage 223, 105703. http://dx.doi.org/10.1016/j.agwat.2019.105703.

Tran, D.D., Huu, L.H., Hoang, L.P., Pham, T.D., Nguyen, A.H., 2021. Sustainability of rice-based livelihoods in the upper floodplains of Vietnamese Mekong Delta: Prospects and challenges. Agric. Water Manage 243, 106495. http://dx.doi.org/10.1016/j.agwat.2020.106495.

Tran, T., James, H., 2019. Changing Livelihood Options as Adaptation: A Comparative Analysis of Three Flood Control Schemes in the Vietnamese Mekong Delta BT - Population, Development, and the Environment: Challenges to Achieving the Sustainable Development Goals in the Asia Pacifi. Springer Singapore, Singapore, pp. 137–154. http://dx.doi.org/10.1007/978-981-13-2101-6_9,

Tran, D.D., Park, E., Tuoi, H.T.N., Thien, N.D., Tu, V.H., Anh Ngoc, P.T., Van, C.T., Kim Long, P., Ho, H.L., Quang, C.N.X., 2022. Climate change impacts on rice-based livelihood vulnerability in the lower Vietnamese Mekong Delta: Empirical evidence from Can Tho City and Tra Vinh Province. Environ. Technol. Innov. 28, 102834. http://dx.doi.org/10.1016/J.ETI.2022.102834.

Tran, T.A., Pittock, J., Tran, D.D., 2020a. Adaptive flood governance in the Vietnamese Mekong Delta: A policy innovation of the North Vam Nao scheme, An Giang Province. Environ. Sci. Policy 108, 45–55. http://dx.doi.org/10.1016/j.envsci.2020.03.004.

Tran, D.D., Quang, C.N., Tien, P.D., Tran, P.G., Kim Long, P., Van Hoa, H., Ngoc Hoang Giang, N., Thi Thu Ha, L., 2020b. Livelihood vulnerability and adaptation capacity of rice farmers under climate change and environmental pressure on the Vietnam Mekong Delta floodplains. Water http://dx.doi.org/10.3390/w12113282.

Tran, T.A., Tuan, L.A., 2020. Policy transfer into flood management in the Vietnamese Mekong Delta: a North Vam Nao study. Int. J. Water Resour. Dev. 36, 106–126. http://dx.doi.org/10.1080/07900627.2019.1568862.

Tran, D.D., Weger, J., 2017. Barriers to implementing irrigation and drainage policies in an giang province, Mekong Delta, Vietnam. In: Irrig. Drain. http://dx.doi.org/10.1002/ird.2172.

Triet, N.V.K., Dung, N.V., Hoang, L.P., Duy, N., Le, Tran, D.D., Anh, T.T., Kummu, M., Merz, B., Apel, H., 2020. Future projections of flood dynamics in the Vietnamese Mekong Delta. Sci. Total Environ. 742, 140596. http://dx.doi.org/10.1016/j.scitotenv.2020.140596.

Veerman, C.M., 2013. Mekong Delta Plan: Long-Term Vision and Strategy for a Safe, Prosperous and Sustainable Delta. Vietnam, p. 126.

Vu, H.T., Trinh, V.C., Tran, D.D., Oberle, P., Hinz, S., Nestmann, F., 2021. Evaluating the impacts of rice-based protection dykes on floodwater dynamics in the Vietnamese Mekong Delta using geographical impact factor (GIF). Water http://dx.doi.org/10.3390/w13091144.

Wong, H.L., Brown, C.D., 2021. Assessment of occupational exposure to pesticides applied in rice fields in developing countries: a critical review. Int. J. Environ. Sci. Technol. 18, 499–520. http://dx.doi.org/10.1007/s13762-020-02834-6.

Xuan, V.T., Matsui, S., 1998. Development of Farming Systems in the Mekong Delta, Vietnam, Vol. 13. Ho Chi Minh City Publ. House, Ho Chi Minh City, Vietnam, p. 314. http://dx.doi.org/10.1002/ldr.494.

Yuan, J., Lu, Y., Ferrier, R.C., Liu, Z., Su, H., Meng, J., Song, S., Jenkins, A., 2018. Urbanization, rural development and environmental health in China. Environ. Dev. 28, 101–110. http://dx.doi.org/10.1016/j.envdev.2018.10.002.

Zhang, S., Wang, D., Hong, L., Ren, H., Feng, C., Liang, Y., Kharrazi, A., Yu, Y., Liang, S., 2020. Co-benefits and trade-offs of environmental pressures: A case study of Zhejiang's socio-economic evolution. J. Clean. Prod. 255, 120365. http://dx.doi.org/10.1016/j.jclepro.2020.120365.