Flooding, soil and food – Interactions between water management and rice production within An Giang province, Vietnam

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A R T I C L E   I N F O

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A B S T R A C T

Rapid intensification of Vietnamese rice production has had a positive effect on the nation’s food production and economy. However, the sustainability of intensive rice production is increasingly being questioned within Vietnam, particularly in major agricultural provinces such as An Giang. The construction of high dykes within this province, which allow for complete regulation of water onto rice fields, has enabled farmers to grow up to three rice crops per year. However, the profitability of producing three crops is rapidly decreasing as farmers increase their use of chemical fertilizer inputs and pesticides. Increased fertilizer inputs are partly used to replace natural flood-borne, nutrient-rich sediment inputs that have been inhibited by the dykes, but farmers believe that despite this, soil health within the dyke system is degrading. However, the effects of the dykes on soil properties have not been tested. Therefore, a sampling campaign was conducted to assess differences in soil properties caused by the construction of dykes. The results show that, under present fertilization practices, although dykes may inhibit flood-borne sediments, this does not lead to a systematic reduction in nutrients that typically limit rice growth within areas producing three crops per year. Concentrations of total nitrogen, available phosphorous, and both total and available potassium, and pH were higher in the surface layer of soils of three crop areas when compared to two crop areas. This suggests that yield declines may be caused by other factors related to the construction of dykes and the use of chemical inputs, and that care should be taken when attempting to maintain crop yields. Attempting to compensate for yield declines by increasing fertilizer inputs may ultimately have negative effects on yields.

1. Introduction

Rice production in major rice producing countries has rapidly increased since the green revolution, ensuring sufficient supplies of this key staple crop as global population grew. Whilst the land area dedicated to rice production expanded during this period, most of the production growth was due to the use of inorganic fertilizers and modernized production practices (Muthayya et al., 2014). To ensure that future yields grow by 1–1.2% annually to guarantee sufficient supplies at accessible prices (Global Rice Science Partnership, 2013), production intensification must continue. This is achieved thanks to fast growing and high yielding rice varieties that have allowed for two or three crops to be grown on a single field within a year. However, yield declines attributed to soil and nutrient management have been seen in intensive long-term experiments (Dawe et al., 2000; Ladha et al., 2003). This raises concerns for the sustainability of rice yields and total production in major rice producing countries.

Vietnam is one such country where the sustainability of its production system is increasingly coming into question, particularly in the Mekong River Delta (MRD). Over recent decades, Vietnam’s agriculture policy has focused on significantly increasing its rice production. This has been achieved thanks to increased use of fertilisers, pesticides and

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high yielding rice varieties, the mechanization of agricultural practices, and increasing the land area under cultivation. Within the MRD, the country’s most important rice producing region, further increases in total production have been achieved through the extensive construction of flood management infrastructure that regulate the extension of seasonal flooding from the Mekong River.

Whilst the MRD experienced gradual development of flood management infrastructure during the 20th century, the most significant developments occurred towards the latter half of the 1990s (Kaközlen, 2008; Triet et al., 2017). As agriculture within the MRD was restricted by the timing of the seasonal floods, the construction of a low dyke system allowed for farmers to delay the flooding of fields. Combined with the introduction of high yield rice varieties, farmers were able to grow and harvest two crops of rice before floods overtopped the dyke and flooded the fields. In the 2000s, partly as a response to high floods at the beginning of the decade, the dyke system was further extended and heightened, with the construction of a high dyke system (Triet et al., 2017). With the construction of the high dykes, farmers were then able to fully regulate irrigation and add a third rice crop to the annual production cycle. Rice production within the MRD is now dominated by the two and three crop systems (Tran and Weger, 2017). As a result of the low and high dyke construction, the total rice production tonnage within the Mekong Delta increased from 12,832 in 1995 to 23,831 thousand tons in 2016, representing 55% of the country’s rice production in 2016 (GSO, 2020). Coupled with policy reforms, the intensification of rice production in the MRD, along with elsewhere in Vietnam, helped the country’s transition from an importer in the 1980s, to major exporter in the 1990s (Nielsen, 2003). In 2017, Vietnam was the third largest global exporter of rice (FAO, 2019). This extensive transformation of the nation’s agriculture is commonly seen as a major driver of Vietnam’s economic transition (López Jerez, 2019).

However, there are growing concerns regarding the long-term consequences and sustainability of the dyke system and intensive production practices within the MRD, particularly in relation to the high dykes. These concerns relate to both local effects (commune and provincial) and regional consequences (Mekong delta and national). At the regional scale, despite reducing flood risks within the dyke compartments, the construction of the high dykes in the upper area of the MRD has shifted flood risks downstream (Triet et al., 2017). At the local scale, whilst the removal of flood risk through high dyke construction has had many positive effects on livelihoods in the short term, their long term economic benefit is currently being debated (Chapman et al., 2016; Nguyen et al., 2018). The profitability of farming within the high dykes, compared to within the low dykes has been decreasing through time. Tran et al. (2018) found that the profit of farmers that produced within the high dyke reduced from being 57% larger than farmers within the low dyke area, after initial construction of the high dyke, to 6% after 15 years. This decrease in income was largely due to costs associated with increased use of fertilizer and pesticides that became necessary to sustain yield in the three-crop system.

A loss of natural flood sediments has been suggested as part of the reason why fertilizer inputs have increased within the high dyke area. This is partially due to upstream flow regulation (Konodolf et al., 2014), beyond Vietnam’s borders, which affects sediment loads to the delta in its entirety. Within the high dyke area, a loss of sediment inputs onto the fields also occurs as a direct result of the inhibition of flood waters entering the fields. These sediments are largely seen as important sources of nutrients, notably potassium (Ho et al., 2006), which are essential for rice growth. As well as being critical for national food rice production, the MRD provides numerous ecosystem services that local farmers recognize as important both for livelihoods and wellbeing. These services relate to water quality, aquatic animals, habitats and pest management; all of which have experienced a decline over recent decades (Berg et al., 2017).

The increased use of pesticides has been associated with declining yields of both fish and rice, and also negative health effects (Berg and Tam, 2018). Further, whilst rice production has increased, the collection of aquatic animals and wild vegetables have decreased (Nguyen et al., 2018). The use of the dyke system has therefore been a double-edged sword, it has enabled farmers to produce rice year round, but has caused unintended environmental consequences (Yuen et al., 2021) and reduced some of the inherent benefits that natural floods provide to farmers.

As a result of declining yields and an increased awareness of the value of floods for other ecosystem services, the government has introduced policies to reduce some of the negative effects occurring from the complete removal of the annual flood. These policies would help increase the sediments reaching fields, but have been largely ineffective due to a lack of implementation caused by farmers not being concerned enough to forego planting a third seasonal rice crop (Tran and Weger, 2017). However, the long term effect of increased agricultural intensity may not solely be determined by changes in sediment flows, but changes in soil properties due to direct land management.

As flood durations change, so too does the moisture regime of the soil. The high dyke system allows for soils to be non-saturated during periods of time in which they would historically have been flooded. In turn, this may increase the degradation of organic matter as a result of increased heterotrophic respiration, potentially reducing soil organic carbon (SOC) and mobilizing chemically bound nutrients (Livsey et al., 2019). Changing the flood frequency of a floodplain, as within An Giang, may lead to reductions in SOC stocks and concentrations within the province’s soils (Yin et al., 2019). The concentration of SOC has been linked to yields, with increasing SOC concentrations being beneficial to yields in some cereals (Oldfield et al., 2019). Also, SOC limits yield reductions in the production of rice using alternate wetting and drying when compared to traditional flood irrigation (Carrijo et al., 2017). Therefore, shifting from a single, relatively long, flood event to multiple events during the year may reduce SOC and the yield benefits it provides. As well as being related to flooding, soil respiration may be further increased as a result of increased ploughing, which breaks down aggregates and roots. However, the addition of the third crop to the annual production cycle also means there may be increased organic matter inputs to the soil, changing the soil carbon and nutrient balances.

One such area of the MRD that has experienced rapid production intensification is An Giang province, situated in the upper area of the Vietnamese MRD. Within the province, the yield to fertilizer ratio is decreasing within the high dyke system (Chapman et al., 2016). As a result, farmers within the high dyke area are increasingly relying on fertilizer to compensate for the reductions in productivity, and in doing so, reducing profits. Because fertilizer costs are likely to increase (Cordell et al., 2009), the trend of increasing fertilizer inputs does not seem to be sustainable for economic reasons, and most importantly, it does not seem to support the expected rice yields. It has been estimated that improving sediment flows within An Giang province could lead to US$15 million savings, annually, resulting from reduced fertilizer requirements (Chapman et al., 2016). Furthermore, the flood waters could also benefit the farmers of An Giang by improving soil conditions; e.g., by increasing pH and washing away accumulated toxins.

To the authors understanding, no studies have been conducted so far to quantify the effect of the dyke system on soil properties within the MRD, leaving a gap in our understanding of the consequences of highly intensified production systems on paddy soils in this area. To fill this gap, we asked:

1. In general, what are the drivers of the spatial patterns in soil properties within An Giang?
2. Can differences in soil properties and nutrient content be seen between the two crop (low dyke) and three crop (high dyke) growing areas within An Giang?

Farmers in the high dyke areas of the MRD have reported larger quantities of fertilizers being used, and also declining yields, compared to farmers within the low dyke (Linh et al., 2013; Tran et al., 2018). Therefore, we hypothesize that, compared to the low dyke area, soils
within the high dyke area will have relatively lower concentrations and stocks of key macro- and micro-nutrients. Further, we hypothesize that this reduction in soil nutrient status is due to the restriction of nutrient rich sediments onto fields within the high dyke area. To test these hypotheses, we first confirmed the earlier farmers’ reports by conducting an ad-hoc survey. Second, we sampled soils and shallow groundwater to determine nutrient concentrations in the two crop (low dyke) and three crop (high dyke) areas. Finally, we discuss sustainability risks associated with nutrient management related to the dyke system.

2. Methods

2.1. Study location

An Giang province is located within the northern area of the MRD within Vietnam (Fig. 1). Being predominantly an agricultural province, 84% of its land is dedicated to agriculture, of which 87% is used for rice production (AGSO, 2016). Agriculture within the province is intimately linked to the Mekong River, where rice production was historically regulated by the annual flood. Entering the country close to Chau Doc city and Tan Chau district, the Mekong River braids down south-eastwards along the eastern edge of the province. The river is central to transport, industry and agriculture. Precipitation patterns create a distinct wet and dry seasonality. Mean annual precipitation for the period 2006–2015 was 1253 mm, mainly falling in the May to November wet season (1094 mm) (AGSO, 2016, 2011).

As with other areas of the MRD, An Giang’s rice production has experienced a rapid transformation over recent decades. Rice production was previously dominated by a single flooded or floating rice crop, but this has been replaced by the production of two and three rice crops within the low and high dyke system. Average yields, after initial rapid increases, are now stagnating and potentially progressing towards declines (Fig. 2a). At the same time, the production area has dramatically expanded (Fig. 2b). The approximate timing of individual rice crops grown within An Giang can be seen in Fig. 2(c) (Brown and My Phung, 2010). Presently, rice is produced year round within the province.

2.2. Sampling methods

Sampling was conducted between 6th and 19th March, 2019, after harvesting of the spring rice crop, but before planting of the autumn crop, so that fields were not water logged. Twelve communes, three from each of four districts were selected for soil sampling (Table S1). These communes were selected as they had both two-crop and three-crop fields. Within each commune, we attempted to sample at three sites along two transects, where the transects ran parallel to each other in each of the two-crop and three-crop fields. The sample sites on an individual transect were always in different fields, located approximately 200–400 m apart and at least 100 m from the field boundary. Due to scheduling of the harvest, it was not always possible to conduct sampling at three sites for each transect, or to locate the transects parallel to one another. Despite this, the sampling design is nearly complete (Fig. 1), and 59 individual fields were sampled.

At each site, soil samples were taken for analysis of texture, pH, soil organic carbon (SOC), total nitrogen (TN), total phosphorous (TP), total arsenic (TAS) at three depths (0–20, 20–40, and 40–60 cm) using a soil auger. The sampling of TAS was included as flood sediments have also been recognized as a potential source of arsenic within An Giang province (Minh et al., 2019), and TAS may therefore be affected by changes in flooding caused by the dyke system. The 0–20 cm samples were also used for analysis of available phosphorous (aP), total potassium (TK), available potassium (aK), available zinc (aZN), and cation exchange
capacity (CEC). The sample for each site, at each depth, was created through the homogenization of five sub-samples which were taken at the center of the site and four equidistant points around a 10 m radius circle around the site center. The sub-samples obtained were then homogenized, visible roots were removed, and they were stored in sealed plastic bags. A single bulk density (BD), for each depth, was taken at the center of each site, with a BD ring being driven horizontally into the soil profile at each depth interval’s midpoint.

When possible, a water sample was taken at the center point of each site for analysis of total nitrogen (TN$_w$), total phosphorous (TP$_w$), total arsenic (TAS$_w$) and pH (pH$_w$). The sample was obtained by digging a pit until reaching saturated soil. To take the sample, the pit was allowed to fill with water, which was then emptied, and this was repeated three times, before a sample was taken. Water samples were frozen whilst awaiting transportation to the laboratory for analysis. Due to the depth of the water table, it was possible to obtain a water sample only from 49 of our 59 fields.

2.3. Laboratory methods

Laboratory analysis was conducted at the Advanced Laboratory, Department of Science, Can Tho University. For soil samples, pH was determined using a 1:5 soil: water suspension, TN was via the Kjeldahl method, TP using the spectrophotometry method, TAS via the graphic furnace atomic absorption spectrophotometry method, SOC by Walkley-Black wet oxidation. Texture was determined using the pipette gravimetric method, CEC using the 0.01 M Barium chloride method, and aP, aK, and aZn via the Mehlish-3 extractable method. TK was measured by hydrofluoric acid digestion (Bartels, 1996). All soil analysis methods are, unless alternatively referenced, described by Houba et al. (1995). For water samples, pH was determined by the electrometric method, TN by the Kjeldahl method, TP by manual digestion and flow injection analysis and arsenic by the Electrothermal Atomic Absorption Spectrometric method.

2.4. Estimation of soil elemental stocks

Stocks of SOC, TN, TP, TK (Mg ha$^{-1}$) were calculated for each sampling depth, when the respective elemental stock was measured, using:

\[ \text{Stock}_{m,n} = C_{m,n} \times BD_{m,n} \times D_{m,n} \]

where $m$ is the element at the $n^{th}$ sampling depth, $C$ is the element concentration (as percentage on a dry weight basis), BD the soil bulk density (g cm$^{-3}$) and $D$ the thickness of the sampling depth (cm).

2.5. Data analysis and statistical procedure

Linear mixed effect models (LME) (Davison, 2003) were used to compare the effect of the cropping system (2-crop vs. 3-crop) on concentrations of SOC, TN, TP, TAS, the C:N and C:P ratios (both on a mass basis), stocks of SOC, TN and TP, and the physical properties of BD, silt and clay content. For each soil element ($y_{ij}$) for site $i = 1,.., 60$ at sampling depth $j = 1,.., 3$, the LME model was constructed as:

\[ y_{ij} = a_0 + X_\beta + Z_\theta + r_i + \delta_d_{ij} + e_{ij} \]  

(1)

where $a_0$ represents the intercept term, $X$ the dummy variable labelling the cropping system (two or three crops) and $\beta$ the vector of the fixed
effect regression coefficients. In our notation, positive values of \( \beta \) indicate that the three crop system exhibits higher values compared to the two crop system. The vector \( Z \) contains the sampling depths and \( \theta \) the related regression coefficients. We expected these factors had an effect on soil properties and thus are regarded as fixed effects in the LME. Considering the uncertain effect of location, \( \gamma_i \) and \( \delta_i \) stand for the commune specific intercept and regression coefficient respectively, for depth \( d_i \) at site \( i \) at sampling depth \( j \). Including depth both as fixed and random effect allows capturing the overall effect of soil depth on the measured properties, while also accounting for local variation in the soil vertical profiles. Finally, \( \epsilon_{ij} \) is the error term. The model was fitted using the maximum likelihood estimation method.

For each soil element, the histogram and Q-Q plot of the model residuals were plotted to visually inspect for normality. When the residuals did not appear to be normally distributed, the logarithm of the element was instead used as the dependent variable, and the residual results rechecked for normality. Information on whether the dependent variable required transforming is detailed in Table S2.

Removing the fixed effect of sampling depth, a simpler second mixed effect model was then implemented to compare the effect of cropping system on soil properties on a depth by depth basis, considering each of the three sampling depths individually for SOC, TN, TP, and the physical properties of BD, silt and clay content. This model was also implemented for aP, TK, aK, aZn, TK stock, and CEC for the single soil layer in which they were measured (0–20 cm), and for TN\(_w\), TP\(_w\), and TAS\(_w\). Removing sampling depth, the model in Eq. (1) simplifies to:

\[
y_i = \alpha_0 + X\beta + \gamma_i + \epsilon_{ij},
\]

where we kept only cropping system as fixed effect (with coefficient \( \beta \)), and location (commune) as the only random effect (with intercept \( \gamma_i \)). The relationship between soil properties and element concentrations were explored through Pearson’s correlation coefficient. All statistical analysis was conducted using the Statistics and Machine learning toolbox within MATLAB, version R2017a (The Mathworks Inc., Natick, Massachusetts, USA).

### 2.6. Survey questions

As part of the field campaign, farmers and commune agriculture officers were surveyed to gather information regarding the agricultural histories of the sites selected for soil sampling. The survey was carried out by the An Giang University members of the team, who also translated the responses to English. The survey was composed of ten questions and its main objective was to gather information regarding the agricultural sites: how long rice had been cultivated, number of crops grown per year, and the year of construction of the high dyke, if present. Additional information regarding agricultural yields, fertilizer use, perceptions of farmers and commune agriculture officers regarding trends in yields and fertilizer use were requested in the survey. For open ended questions, trends were codified by recording the incidence of words mentioned and whether they were positive or negatively related to the construction of the dyke system. The questions are detailed in Table S3. Survey questions were asked in all communes except Tan Tuyen. Where responses were given by commune officers, answers were often provided for both high dyke and low dyke areas. Therefore, results reported here are aggregated at the commune level rather than at the individual person level. On average, two people participated to each of our 12 interview sessions, including farmers and officers.

### 3. Results

To contextualize the results of the soil sampling, we first present the results from the responses to the survey questions. We then present the soil sampling results and make a comparison between the sites inside and outside of the high dyke area.

#### 3.1. Survey question summary

The high-dykes around the three-crop sites, selected for soil sampling, were constructed between 2008 and 2013, and were on an average eight years old at the time of sampling. The range in construction ages for low dykes around the two-crop fields was much greater, with the oldest being constructed in 1975 (My Khanh commune, Long Xuyen city) and the newest constructed in 2005 (Luong An Tra commune, Tri Ton district). Land-use prior to the construction of the low-dyke system varied, with sites in Tri Ton generally not being used for rice production prior to construction of the dykes. Other areas produced either floating rice or paddy prior to the dyke construction, with known production of rice from the 1970s in some instances.

In the majority of the communes (ten), respondents highlighted that after construction of the high dyke, per crop fertilizer application needed to be increased in the three-crop area compared to what had been used previously or was higher than is currently used in the respective two-crop
Fig. 4. Results of the Pearson’s correlation coefficient (top right) with correlations being marked significant at $p < 0.05$ and $p < 0.01$ with * and ** respectively. Graphical representation of the correlation results (bottom left) have solid trend lines when correlation is significant ($p < 0.05$) and dashed lines when they are not. Available P data are not shown as they did not correlate with any other soil property. Soil texture percentages are relative to the three component particle sizes (sand, silt, clay). As texture was dominated by silt and clay, these two components were considered together.
area (Fig. 3a). In half of the communes, respondents also noted reduced yields inside the three-crop area, in at least one of the season’s rice crops (Fig. 3b). In those communes, respondents noted that yields of a given crop in the first one to three years after the high dyke was built were comparable to those in the low dyke area. However, after this, yields began to decrease. Over the last three seasons, yields were on average 5% less for the winter-spring and summer-autumn crops in the three crop area compared to the two crop area. The greatest observed difference in yields was in the winter-spring crop of Vinh Phuoc commune, Tri Ton district, where yields were 23% less (i.e., a difference of 1.5 tons ha\(^{-1}\)) in the high dyke area. Dao Huu Canh commune of Chau Phu district reported higher yields in the three crop area during the previous year, being 0.8 tons ha\(^{-1}\) greater than the two crop area during the winter-spring crop. The increase in fertilizer use and the decrease in yield resulted in a yield-to-fertilizer reduction in nine communes (Fig. 3c).

In the open-ended question related to general observations of changes in rice production since the construction of the high-dyke, four general themes occurred in responses from interviewees. Six respondents noted that crop pests and diseases were more prevalent in the three-crop system since construction of the high-dyke. It was also noted by one person that, since the construction of the high-dyke, rat and snail populations had also increased in the two-crop areas. Respondents attributed this increase in pest and disease incidents as being due to both the loss of floods across the full agricultural area and also due to year round production which allowed pests to move between crops of different seasons. Recognizing the potential nutrient value of flood-borne sediments, five respondents mentioned that they believed the construction of the high-dyke had led to a reduction in flood derived nutrients. It was also noted in three communes (Vinh Phuoc, My Hoa, My Khanh) that flood dynamics had changed over recent years. This included flood inundation rates increasing more rapidly compared to historically, and then also retreating faster. In four communes (Vinh Phuoc, Luong An Tra, Phu Hoi, My Hoa), interviewees raised the general concern that the land within the three-crop area never has time to rest and recover.

### Table 1
Estimated parameters of the linear mixed effect models (LME) for soil organic carbon (SOC), total nitrogen (TN), total phosphorous (TP), total arsenic (TAS), organic carbon to nitrogen ratio (C:N), organic carbon to phosphorous ratio (C:P) and stocks of SOC, TN and TP, available phosphorous (aP), total potassium (TK), available K (aK), available Zn (aZn), total potassium stock, and cation exchange capacity (CEC). LME are fitted for each soil element at each sampling depth; the coefficient for ‘2-crop/3-crop’ is positive when the soil property in the 3-crop system has higher value than in the 2-crop system.

<table>
<thead>
<tr>
<th></th>
<th>0-20 cm</th>
<th>20-40 cm</th>
<th>40-60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intercept</td>
<td>2-crop/3-crop</td>
<td>Intercept</td>
</tr>
<tr>
<td>SOC</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Est</td>
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<td>0.150</td>
<td>0.495</td>
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<tr>
<td>SE</td>
<td>0.152</td>
<td>0.086</td>
<td>0.193</td>
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<td>p-Val</td>
<td>&lt; 0.01</td>
<td>0.088</td>
<td>0.013</td>
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<tr>
<td>TN</td>
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</tr>
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<td>0.976</td>
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<td>0.069</td>
</tr>
<tr>
<td>p-Val</td>
<td>&lt; 0.01</td>
<td>0.027</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>TP</td>
<td>-1.600</td>
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<td>0.076</td>
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<tr>
<td>p-Val</td>
<td>&lt; 0.01</td>
<td>0.937</td>
<td>&lt; 0.01</td>
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<td>TAS</td>
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<tr>
<td>p-Val</td>
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<td>&lt; 0.01</td>
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<td>C:N</td>
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<td>&lt; 0.01</td>
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<td>&lt; 0.01</td>
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<td>&lt; 0.01</td>
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<td>TP stock</td>
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<td>&lt; 0.01</td>
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<tr>
<td>p-Val</td>
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<td>0.017</td>
<td>&lt; 0.01</td>
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<tr>
<td>aP</td>
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<td>0.398</td>
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</tr>
<tr>
<td>SE</td>
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<td>0.108</td>
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<tr>
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<td>&lt; 0.01</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>p-Val</td>
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3.2. General patterns in soil properties

In general, soil texture was dominated by silt and clay, being classified as clay, silty clay, silty loam clay, or silt loam (Fig. S1). Sample sites in Luong An Tra were the exception, where the sand fraction was much larger, reaching up to around 70%. Fig. 4 shows the correlations among soil properties for the 0–20 cm layer. A significant (p < 0.01) negative relationship was found between BD and SOC, TN, TP, and C:N and C:P ratios, but a significant (p < 0.01) positive relationship appears between BD and TK. The combined sand-clay percentage had a significant negative relationship with SOC and TP (p < 0.05), and the C:N ratio (p < 0.01), and a significant (p < 0.01) positive relationship with TK, aK, Zn and CEC. Soil pH had a significant (p < 0.01) negative relationship with SOC, TN, TP, C:N, C:P, and a significant (p < 0.01) positive relationship with TK, CEC, aZn, p < 0.05). Similar trends and significances were also found in the 20–40 cm and 40–60 cm soil depths (Table S6, Table S7).

3.3. Variation in soil properties between two and three crop fields

Depth had a significantly negative effect (p < 0.01) on concentrations and stocks of SOC, TN, TP and AS, as well as on C:N and C:P ratios, but no significant differences were detected between soils under two or three crops per year (Table S4). Similarly, for physical properties, there was a statistically significant decline in silt content (p < 0.05) and increase in BD (p < 0.01) with depth, but no significant difference was seen between soils under two or three crops per year (Table S5).

Considering differences in soil elements at individual depths (Table 1) for properties which were analyzed at all three sampling depths, no significant difference was found in any element between soils under two or three crops per year, other than TN and pH in the 0–20 cm layer. At this depth, TN concentrations and pH were significantly higher (p < 0.01 and p < 0.05 respectively) in the high dyke areas. However, for elements where lab analysis was only conducted for the 0–20 cm layer, TK, aK, and aP were significantly higher (p < 0.01) in the high dyke area than in the low dyke area (Table S1). No significant difference was determined at any individual soil depth for silt and clay content, or for BD, between two and three crop areas (Table 2).

3.4. Water quality results

For the obtained water samples, there was no significant difference in pH and concentrations of TN and TP between the two and three-crop areas (Table S8). Arsenic concentrations were above minimum detectable limits in only two water samples. Although no parameters were significantly related to the cropping system, pH had a significant negative effect on TN_w and a significant positive effect on TP_w (Fig. S2).

4. Discussion

4.1. General drivers of soil properties

Several expected trends in soil properties can be observed in the results. Commonly, BD and SOC are inversely related (Rawls et al., 2003). This relationship was seen within the surface soil layer (Fig. 4), as well as in the deeper soils (Table S6 and Table S7). Further, the positive trend in BD and negative trend in SOC concentrations with increasing depth (Table S4) are expected (Jobbágy and Jackson, 2001). The significant positive relationship between SOC with both TN and TP, as well as the limited range of C:N and C:P ratios observed demonstrate that there is little variation in organic matter composition, and they are no different from general trends seen elsewhere (Cleveland and Liptzin, 2007). Increasing soil acidity suppresses organic matter decomposition (Zhang et al., 2020). This effect is likely seen in our results, where there is a large variability between soil pH between sites, and a strong negative and significant correlation between pH and SOC concentrations (Fig. 4). Although a positive correlation is expected between SOC and CEC (Soares and Alleoni, 2008), the negative relationship seen in Fig. 4 can be explained by the large variability in pH and its control of SOC. Sites with the lowest pH had the greatest SOC values, resulting in pH being the more dominant regulator of CEC. These results demonstrate that common controls of soil elements are evident within the soils of An Giang. Further, these controls appear to dominate soil properties within the district when compared to land management and the number of crops produced.

4.2. Soil properties and nutrient contents in two crop and three crop areas

Farmers and commune officers interviewed during this study reported that, in three-crop areas, fertilizer use had increased in the majority of communes (Fig. 3a), yields decreased in half of the communes (Fig. 3b), and yield-to-fertilizer ratios decreased in three-quarters of communes (Fig. 3c). Previous studies have also reported increased use of fertilizer inputs on three-crop production areas when compared to two-crop areas (Tong, 2017; Tran et al., 2018), and yield-to-fertilizer ratios in three-crop areas have been shown to be half of those found in two-crop areas (Howie, 2012). Also, farmers and commune officers in five of the communes suggested that one of the problems caused by the construction of the high-dyke is the loss of flood-borne nutrients onto the three-crop area.

Indeed, in long-term intensive rice experiments, reductions in yields have been largely linked to soil nutrient depletion (Dave et al., 2000; Dobermann et al., 2000a). Flood sediments are recognized as a valuable source of nutrients for agriculture (Buri et al., 1999), so any reduction in sediment input could also result in long-term nutrient depletion. For example, in Bangladesh, sediments are a valuable source of N, P,
calcium, sulphur, magnesium, and manganese (Hirst and Ibrahim, 1996).

These pieces of evidence led to the hypothesis that there would be a negative effect of the high-dyke system on the nutrient status of soils in the three-crop areas when compared to the two-crop areas within the low-dyke. The results of the soil analysis do not support this hypothesis and, in some instances, are contrary to it. Concentrations of TN were significantly greater \((p < 0.01)\) in the three-crop area between 0 and 20 cm. The production of two or three rice crops per year can result in an accumulation of N even when all above ground biomass is removed (Dawe et al., 2000). This is likely due to increased net primary productivity (NPP) resulting in greater below ground biomass inputs, which increase soil organic matter. Increased NPP is also the intended consequence of fertilization, which has been shown to increase soil nitrogen in other intensive rice systems (Livsey et al., 2020). Here, we found that the increase in TN concentrations were not coupled with increased SOC concentrations, changes in the stocks of SOC or TN or the C:N ratio. This would suggest that the change in TN, although significant, is mild.

Although concentrations and stocks of TP were not significantly different, AP was greater in the three-crop areas. As most of the rice stubble and residues are burned in place on the field after harvesting, the majority of P inputs remains within the field (Nhận et al., 2016). Therefore, it is not surprising that P concentrations are not lower in the three-crop area than the two-crop area.

In the MRD, flood sediments are seen as important for the provision of K (Chapman et al., 2016; Hoa et al., 2006; Linh et al., 2017). Therefore, there is a particular concern within An Giang that this loss of K inputs onto three-crop fields needs to be compensated for. The present study found that concentrations of TK and aK were significantly greater \((p < 0.01)\) in the three-crop areas between 0 and 20 cm. Recalcitrant K \((TK \text{ minus } aK)\) was neither significantly larger or smaller. As this study is not longitudinal, we cannot directly interpret whether this means that fields in the three-crop system are gaining K faster or losing it slower than in the two-crop system. However, as yield decreases are not reported in the two-crop system, and that recalcitrant K is not increasing, this would suggest the increase in K concentrations in the three-crop systems is due to increased fertilizer use. Further, whilst the use of N, P and K has rapidly increased over recent decades in the MRD, the most dramatic change since the 1990’s has been the increase in K inputs. Whilst the tonnage of N and P used for rice production in the delta approximately doubled between 1991 and 2011, K inputs grew 40 times larger (Nguyen, 2017). Therefore, it is likely that any loss of K inputs derived from flood sediments are compensated for by fertilizer additions, thus explaining the elevated K concentrations in the three-crop area. Therefore, we can rule out the possibility that K limits rice yields in the three-crop system.

There was a significant increase in pH within three crop areas at 0–20 cm when compared to two crop areas (Table 1). However, the effect of this increase on yields is unclear as, between sites, pH varied from 3.7 to 6.3. Within this range, an increase in pH may have both a positive effect when the initial value is low and negative yield effect when the initial value is high. There appears to be no negative effect of the high dyke system on the investigated macro and micro nutrients, when compared to soils within the low dyke area and given current land management practices. This does not fully discount the potentially negative effect that the dyke system and the associated restriction of sediments, combined with land management within the high dyke areas, has on other nutrients which may also be limiting.

Whilst there is concern about the loss of sediments and deterioration of soil quality caused by the dyke system, the potential effect of the high dyke, its restriction of the floods, the intensity of the three-crop system, and its effects on yields are far more complex than just being related to crop nutrition and soil fertility. We suggest that accounting for ecosystem-level interactions between crop and consumers (herbivores) and pathogens could offer an alternative explanation of the declining yields. In this interpretation, attempts to mitigate crop loss through nutrient management may ultimately lead to negative yield consequences.

Research on the effect of alternative cropping systems in the MRD has focussed on the integration of upland crops and their effect on soil properties which are commonly considered markers of soil health. The replacement of at least one of the three annual rice crops with upland crops can increase SOC, porosity and aggregate stability (Linń et al., 2018). Given the low pH and high SOC contents of the soils within the study site, it is unlikely that B deficiency is a problem within the high dyke area.

In general, considering that crop residues were being retained and burned on fields, and the low sand content of the studied soils, the principal pathway for micro-nutrient depletion in the observed rice fields is via grain harvesting. Micro-nutrient depletion is being increasingly reported as a problem throughout the world (Tan et al., 2005). But whilst being reported, this is more an emerging problem than an acute one. The farmers and commune workers interviewed within this study, as well as elsewhere, suggested yield declines occurred after three years of production within the high dyke area. It is unlikely, given that plant residues remain on the field, that micro-nutrients would decrease at a rate sufficient to become limiting and cause such a rapid effect on yields within this short time period (Debbermann et al., 2000b).

Based on these findings, the loss of flood-borne sediments for nutrient provision on the three-crop land may be overstated as a principal concern for maintaining rice production in An Giang. In particular, this is true in those areas furthest away from the main river channel. Suspended sediment concentrations decrease exponentially with distance from the Mekong River (Hung et al., 2014). Therefore, differences in sediment inputs between two- and three-crop fields becomes less dramatic with increasing distance from the river channel.

Although the loss of flood-borne sediments may not have a negative effect on crop nutrient provision under current fertilization practices, the loss of the flood may have other effects on soil quality. Linń et al. (2017) found that three crop rice production resulted in lower aggregate stability, and higher BD and soil penetrative resistance, when compared to rice production mixed with upland crops. Aggregate stability is known to have a negative relationship with BD (Idowu, 2003). Repeated wetting and drying of soils can cause aggregates to break down (Xu et al., 2017), and could thus cause changes in BD. In An Giang, the shift from a single flooding event to either two or three events may cause this change, but no statistically significant difference was found between two and three crop areas (Table 2 and Table S5). Although bulk density is only one of the properties related to soil structure and its degradation, our results suggest that there is no difference in soil physical properties between two and three crop areas. Further, although the complete inhibition of floods onto fields within three crop areas also restricts the input of sediments onto the fields, there was no significant difference in soil texture between the two rice growing areas (Table 2 and Table S5). Similarly, there was no significant difference in SOC concentrations, a regulator of BD (Rawls et al., 2003), and stocks between the two and three crop areas (Table 1 and Table S4). This may partially explain the lack of an observed difference in BD between the two types of land use, but is also an indicator that it is not a driver of observed changes in yields in three crop areas.

4.3. Dykes, nutrient management and sustainability

Whilst there is concern about the loss of sediments and deterioration of soil quality caused by the dyke system, the potential effect of the high dyke, its restriction of the floods, the intensity of the three-crop system, and its effects on yields are far more complex than just being related to crop nutrition and soil fertility. We suggest that accounting for ecosystem-level interactions between crop and consumers (herbivores) and pathogens could offer an alternative explanation of the declining yields. In this interpretation, attempts to mitigate crop loss through nutrient management may ultimately lead to negative yield consequences.
nematodes within the soil compared to less intensive systems or rotations. The agricultural practices which integrate fish into the rice production system have been shown to significantly change soil microbial communities (Zhao et al., 2021). Also, combined with the rice and the fish. The flooded field provides a habitat to benefit both the rice and the fish. The flooded field provides a habitat for the fish, whilst the fish consume rice pest (Xie et al., 2011). The shortening of the standing water period and connectivity of fields to the river system has removed the access of fish, which would traditionally predate numerous crop pests. As well as predating pests, the agricultural practices which integrated fish into the rice production system have been shown to significantly change soil microbial communities (Zhao et al., 2021). Also within studies comparing the use of organic vs chemical fertilizers, chemical fertilizers have been shown to reduce the diversity of bacterial communities (Guanghua et al., 2008). As the composition and abundance of microbial communities’ effects yields (Wu et al., 2018), the removal of fish from fields and the high use of fertilizer, particularly in areas producing three rice crops, may have negative effects on soil microbial communities, and thus yields.

5. Conclusion

There is increasing awareness that a three-crop system in the MRD, grown in areas protected by a high-dyke, may not be sustainable. Initial benefits of producing three rice crops in a year are being gradually negated by decreasing yields and increasing management costs. Despite yields from individual crops are decreasing, the production of a third crop still allows farmers with three-crop fields to produce more than their two-crop counterpart. However, they are becoming increasingly reliant on the use of inorganic fertilizers and pesticides to aid yields. Although farmers are concerned that they need to replace the nutrients traditionally provided by the seasonal floods, we found that soil properties within the three-crop system are not significantly different compared to the two-crop system, when considering current fertilization practices, except for some nutrient concentrations being higher within the three-crop system. Therefore, it is likely that any further loss of yields may be due to other factors. Further increasing the use of inorganic fertilizers to compensate for yield declines may ultimately have a negative yield consequence due to the complex ecosystem-level interaction between inputs, plant growth and pests or pathogens. Although the use of fertilizer subsidies has been suggested by some authors (Chapman et al., 2016), solutions to sustainable rice production within An Giang lay within more integrated and diversified production systems.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107589.

References


without a dyke, potentially promoting improved yields and improving sustainability. Thus, intra or inter-annual crop rotation can have numerous other beneficial effects.

With the construction of the high-dyke, rice production is effectively year round within An Giang. Further, the timing of planting and harvesting, which were historically dictated by the flood, are now at the choice of the farmer. Combined, this ensures both an abundant and stable food supply and habitat for crop pests. In fact, continuous cropping also ensures refuge sites for pest populations, and an extension of their breeding season (Singleton, 2003). Consistent with this idea, a lack of synchrony has previously been recognized as a regulator of rice plant disease occurrence in the Philippines (Cabunagan et al., 2001). Changes in production intensity and frequency have been linked to increasing rodent damage to crops, with the loss of floods decreasing competitive pressure for certain rat species; e.g., Rattus argentiventer (Lan et al., 2005). Without the flood, the lack of a natural reset of rodent populations results in an increasing percentage crop damage (Brown and My Phung, 2010). When attempts to deal with lower yields as a nutrient problem are implemented, increased availability of food sources for rodent population might actually worsen the problem.

Pest related damage is not only an issue of improvements in habitats and food availability, but also in improvements in the quality of the food consumed by pests. Increasing use of fertilizer can increase incidents of pests and diseases, being closely linked to herbivorous pests (Lu et al., 2007). Increased nitrogen inputs, particularly in areas that are densely seeded with high yielding rice varieties, result in dense canopies which are beneficial for disease development (Huan et al., 2008). Further, increased use of N fertilizer can dilute silicon (Si) concentrations in plant tissues. As low Si concentration is favored by herbivores, the increase in nutrient inputs may ultimately lead to more detrimental than positive effects, increasing their susceptibility to crop pests (Rashid et al., 2017).

In addition to above ground risks, intensive mono-culture rice production can also have negative consequences below ground. Monocultures of continuous rice have higher abundance of plant-parasitic nematodes within the soil compared to less intensive systems or rotations (Nguyen et al., 2020). There is also potential for autoxotoxicity, with self-inhibition of rice grown in short rotation (Bennett et al., 2012).

There are also well recognized benefits of less intensive production system within the MRD. Intensive rice cultivation has limited the mutual benefits from integrated fish and rice systems. These systems are known to benefit both the rice and the fish. The flooded field provides a habitat for the fish, whilst the fish consume rice pest (Xie et al., 2011). The shortening of the standing water period and connectivity of fields to the river system has removed the access of fish, which would traditionally predate numerous crop pests.

As well as predating pests, the agricultural practices which integrated fish into the rice production system have been shown to significantly change soil microbial communities (Zhao et al., 2021). Also within studies comparing the use of organic vs chemical fertilizers, chemical fertilizers have been shown to reduce the diversity of bacterial communities (Guanghua et al., 2008). As the composition and abundance of microbial communities’ effects yields (Wu et al., 2018), the removal of fish from fields and the high use of fertilizer, particularly in areas producing three rice crops, may have negative effects on soil microbial communities, and thus yields.

5. Conclusion

Although farmers are concerned that they need to replace the nutrients traditionally provided by the seasonal floods, we found that soil properties within the three-crop system are not significantly different compared to the two-crop system, when considering current fertilization practices, except for some nutrient concentrations being higher within the three-crop system. Therefore, it is likely that any further loss of yields may be due to other factors. Further increasing the use of inorganic fertilizers to compensate for yield declines may ultimately have a negative yield consequence due to the complex ecosystem-level interaction between inputs, plant growth and pests or pathogens. Although the use of fertilizer subsidies has been suggested by some authors (Chapman et al., 2016), solutions to sustainable rice production within An Giang lay within more integrated and diversified production systems.


