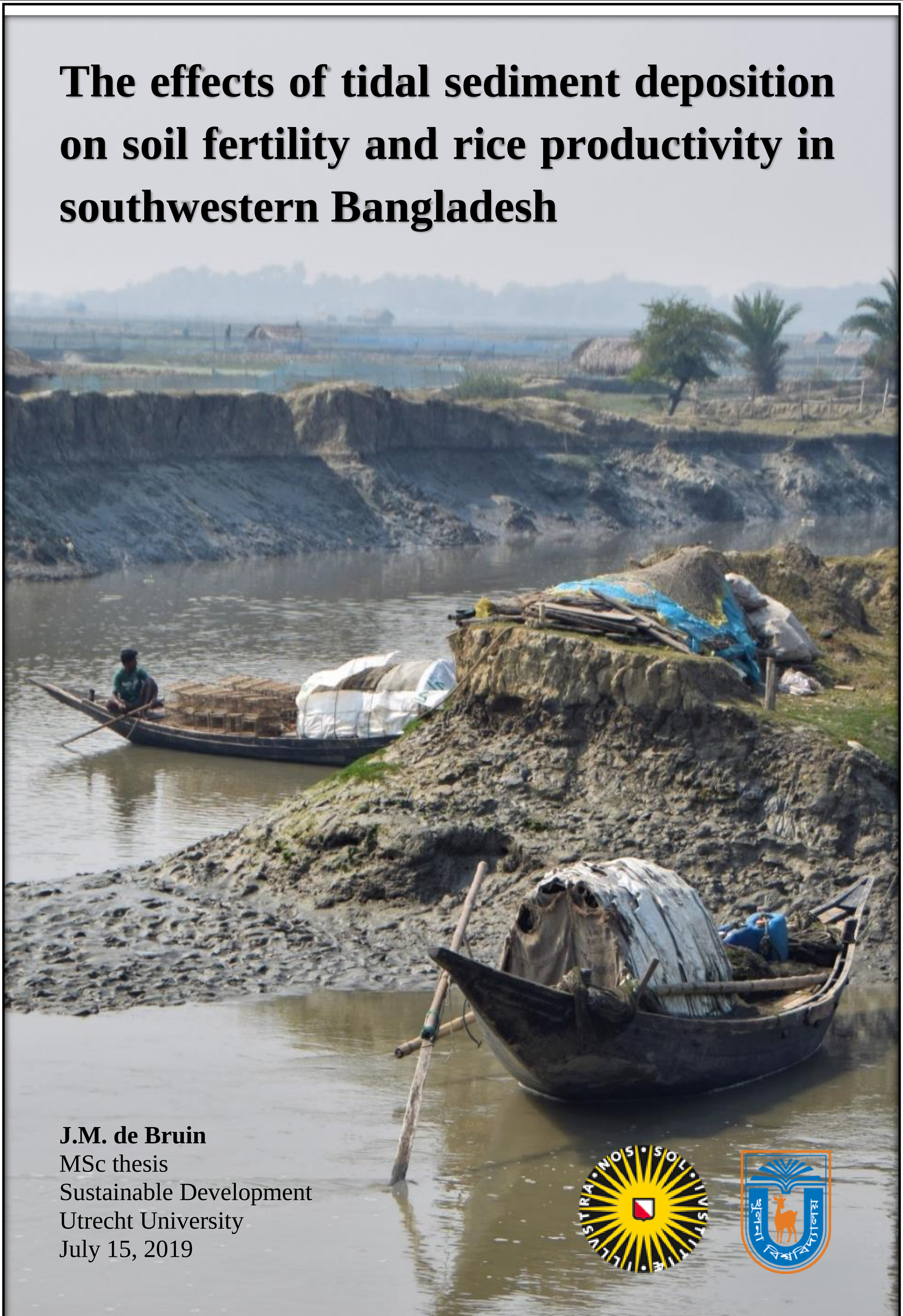
The effects of tidal sediment deposition on soil fertility and rice productivity in southwestern Bangladesh



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Cover photo: View of Beel Pakhimara near the main inlet (own work)

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Abstract

In southwestern Bangladesh, construction of polders aimed to protect the coastal region from flooding and salinity intrusion, while reclaiming land to improve agricultural productivity. However, these polders ignored the natural sediment dynamics, consequently resulting in river siltation and land subsidence that is associated with widespread waterlogging. Managing sediments by re-allowing tidal flooding is found to effectively improve the health of rivers, solve waterlogging problems, and support agricultural productivity. Additionally, it is often mentioned that tidal sediments improve soil fertility. There is, however, no literature that supports this hypothesis. To better understand the sustainability of sediment management strategies, this study examined the effects of tidal sediment deposition soil fertility and rice productivity in three tidal basins.

To study soil fertility, a rice growth experiment was set up to determine rice productivity in fresh sediments and old sediments from Beel Pakhimara, Beel Khuksia, and Polder 32. In this experiment, rice is grown in the tidal sediments, compost mixtures, and after applying a washing treatment. Next, rice productivity is compared to the differences in sediment characteristics, plant tissue composition, and nutrient availability in the pore water. The results find that rice productivity is significantly higher in the old sediments from Beel Pakhimara and Polder 32, and there are no significant differences between fresh and old sediments in Beel Khuksia. Rice productivity in the compost mixtures is significantly higher in all study locations compared to the original sediments. No significant differences are found in the applied washing treatments.

In conclusion, tidal sediments do not improve soil fertility, and compost application is necessary to support rice productivity. Nitrogen deficiencies are observed in all study locations, and indicate the need for additional nitrogen fertilization. Phosphorus is the main controlling nutrient, and is mobilized by two interacting biogeochemical processes related to iron and sulphate reduction. The impact of salinity on rice productivity is limited, and can be explained by the capability of the salt tolerant Boro variety used in this study. To fully understand the impacts of tidal sediments on soil fertility, seasonal variability and other rice varieties should be included in further studies.

Key words Tidal sedimentation, Soil fertility, Rice productivity, Nutrient availability, Southwestern Bangladesh

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1. Introduction

Bangladesh is situated in the dynamic Ganges-Brahmaputra-Meghna (GBM) river delta and is home to a growing population of 170 million people. It is considered one of the most vulnerable countries to natural and human-induced environmental changes due to its susceptibility to environmental hazards including monsoon flooding, tropical cyclones and sea level rise (Brammer, 2014; Auerbach et al., 2015; Rogers & Overeem, 2017). In the 1960s, the government of Bangladesh engaged in the Coastal Embankment Project (CEP) to develop a well-designed polder system. The main objective of the CEP was to protect the southwestern coastal region from salt water intrusion and flooding, while reclaiming land for agricultural production and settlements (Saari & Rahman, 2003; Tutu, 2005). Today, a total of 139 embanked polders have been constructed, accounting for 6000 km of dykes that encircle 1.12 million hectares of land (Rogers & Overeem, 2017).

Unfortunately, the CEP project ignored the socio-ecological system of the southwestern region by restricting tidal inundation and sediment deposition on the floodplains that would naturally sustain land elevation and soil fertility (Tutu, 2005; Rogers & Overeem, 2017; Roy et al., 2017). This consequently resulted in rapid siltation of the river beds, reduced river drainage capacities, river congestion, and land subsidence inside the polders. Together with insufficient maintenance of embankments and sluices, polders are often associated with widespread flooding and waterlogging (Nowreen et al., 2014; van Staveren et al., 2017; Gain et al., 2017; Roy et al., 2017; Wilson et al., 2017).

Tidal river management (TRM), or temporary de-poldering, is considered a sustainable delta management strategy to cope with waterlogging caused by river congestion in southwestern Bangladesh (Shampa, 2012; Seijger et al., 2019). TRM involves restoring the tidal in- and outflow by temporary connecting a low-lying beel[1] with an adjacent tidal river, called a tidal basin (Shampa, 2012; Amir et al., 2013). Sediment-laden water enters the beel during the (twice-daily) high tides, leaving part of the sediments inside after water retreats during the low tides. Over time, sediment deposition elevates the lands and provides new soils to promote agricultural productivity. Sediment management with TRM is found to effectively increase drainage capacities of the rivers, thereby solving waterlogging issues in the southwestern delta region (Paul et al., 2013; Gain et al., 2017; van Staveren et al., 2017; Talchabhadel et al., 2018).

1.1 Problem definition and relevance

New dynamic polder management strategies are required to sustainably improve the livelihoods of the people living in the highly sensitive and fragile environment of southwestern Bangladesh. Re-introducing sedimentation with TRM is considered an effective method to mitigate climate change effects, solve waterlogging problems, and promote sustainable agriculture (Gain et al., 2017; Al Masud & Azad, 2018a). It is often mentioned that fresh sediments provided by TRM will improve agricultural productivity by increasing soil fertility (Tutu, 2005; Kibria, 2011; Gain et al., 2017; van Staveren et al., 2017). However, it is unclear if, and to what extent, tidal sediments actually improve soil fertility. Soil fertility forms the basis of agricultural productivity, and is fundamental to sustain livelihoods. Therefore, this study will explore the effects of tidal sediment deposition on soil fertility in different geographical locations considering spatial variation of soil properties, nutrient availability, and salinity. This is essential to understand the sustainability of sediment management practices including TRM, and can be applied for decision-making on long-term application of sediment management with the aim to sustainably enhance local livelihoods. The outcomes of this study are applicable to Bangladesh, but may be evaluated for application in other deltas.

[1] Beels are described as bowl-shaped depressions in the polder landscape of southwestern Bangladesh. They can develop after deprivation of the silt deposition inside the polders and are highly susceptible to waterlogging (Van Staveren et al., 2017).

1.2 Research questions

In this study, it will be examined if fresh sediments are capable of naturally improving soil fertility. It will do so by determining the nutrient availability of tidal sediments in different polders, and identifying the response of rice when grown on these sediments. For this, the following research question will be answered:

How does tidal sediment deposition affect soil fertility in southwestern Bangladesh, and how does this affect rice productivity?

The following sub-questions are posed to support answering the main question:

- What are the differences in soil properties between the study locations?
- What are the differences in rice productivity between the study locations?
- What are the differences in nutrient availability between the study locations?
- What are the main biogeochemical processes that regulate nutrient availability in the sediments?

1.3 Hypothesis

Tidal sediment deposition is assumed to naturally improve soil fertility, creating favourable conditions for agriculture. Therefore, it is hypothesized that rice productivity is higher in soils with fresh sediments by providing beneficial nutrients for plant growth. However, the beneficial effects of fresh sediments may vary depending on geographic location and sediment properties, and may be suppressed by unfavourable conditions including soil salinity.

1.4 Living Polders

This study is conducted as part of the Living Polders project at Utrecht University. The main objective of this project is to determine how living polders, in which controlled flooding and sedimentation allow the land surface level to keep up with sea level rise, can enhance sustainable livelihoods of communities in urbanizing deltas. Specifically, this thesis is associated with *Step 2* and *Step 4* of the first PhD project that comprehends the physical boundary conditions of these living polders. *Step 2* involves plant experiments to test the fertility of the soil and fresh sediments. *Step 4* involves determining optimal rotation schemes at different geographical locations considering spatial variation of sediments, soil fertility, risk of salinization, and level of accretion.

1.5 Thesis outline

In the following of this thesis, Chapter 2 provides an overview of the study area, describing the physical geography of southwestern Bangladesh in relation to agricultural productivity and soil fertility, and introducing the principles of TRM; Chapter 3 describes the methodology of this study, including the study locations, data collection, the experimental setup of the rice growth experiment, the performed geochemical analyses, and statistical analyses; Chapter 4 represents the results and analyses of this research work; Chapter 5 reflects on the results, discusses the implications of the findings, and provides new ideas for future research; and finally, Chapter 6 presents conclusions about the effects of tidal sediment deposition on soil fertility and rice productivity.

2. Study area

2.1 Southwestern Bangladesh

The Ganges-Brahmaputra-Meghna (GBM), or Bengal, delta is one of the world's largest delta systems, formed by rivers that carry sediment-laden water into the tectonically active Bengal basin (Wilson & Goodbred, 2015; Gain et al., 2017; Rogers & Overeem, 2017). The physical geography of Bangladesh is highly diverse and dynamic, where rivers discharge, tidal movements, occasional earthquakes and cyclones constantly drive sedimentation and erosion (Brammer, 2014; Dewan et al., 2015). The major rivers carry over a billion tons of sediment annually, which is distributed throughout the delta by fluvial and tidal processes (Islam et al., 1999). The main sediment carriers are monsoon river discharges from upstream, and tidal movements that redirect part of the fluvial sediments that end up in the Bay of Bengal (Rogers et al., 2013; Wilson & Goodbred, 2015).

The southwestern coastal region of Bangladesh (Figure 2.1) is a unique brackish aquatic ecosystem located at the mouth of the Ganges river and the tidal floodplains (Brammer, 2012). The region is characterized by tidal-dominated rivers, streams and water-filled depressions (Nowreen et al., 2014). The 22 million people living in this low-lying part of the delta are considered highly vulnerable to environmental impacts related to sea level rise, cyclones, salinity intrusion, extreme rainfall, waterlogging and river flooding (Overeem & Syvitski, 2009; Roy et al., 2017). The Coastal Embankment Project (CEP) was set up to reduce vulnerability by providing flood protection and increasing agricultural productivity in the southwestern region (Gain et al., 2017). As is mentioned in the introduction, this consequently changed sediment dynamics, resulting in rapid siltation of the river beds, reduced river drainage capacities, river congestion, land subsidence, and widespread waterlogging (Nowreen et al., 2014; van Staveren et al., 2017).

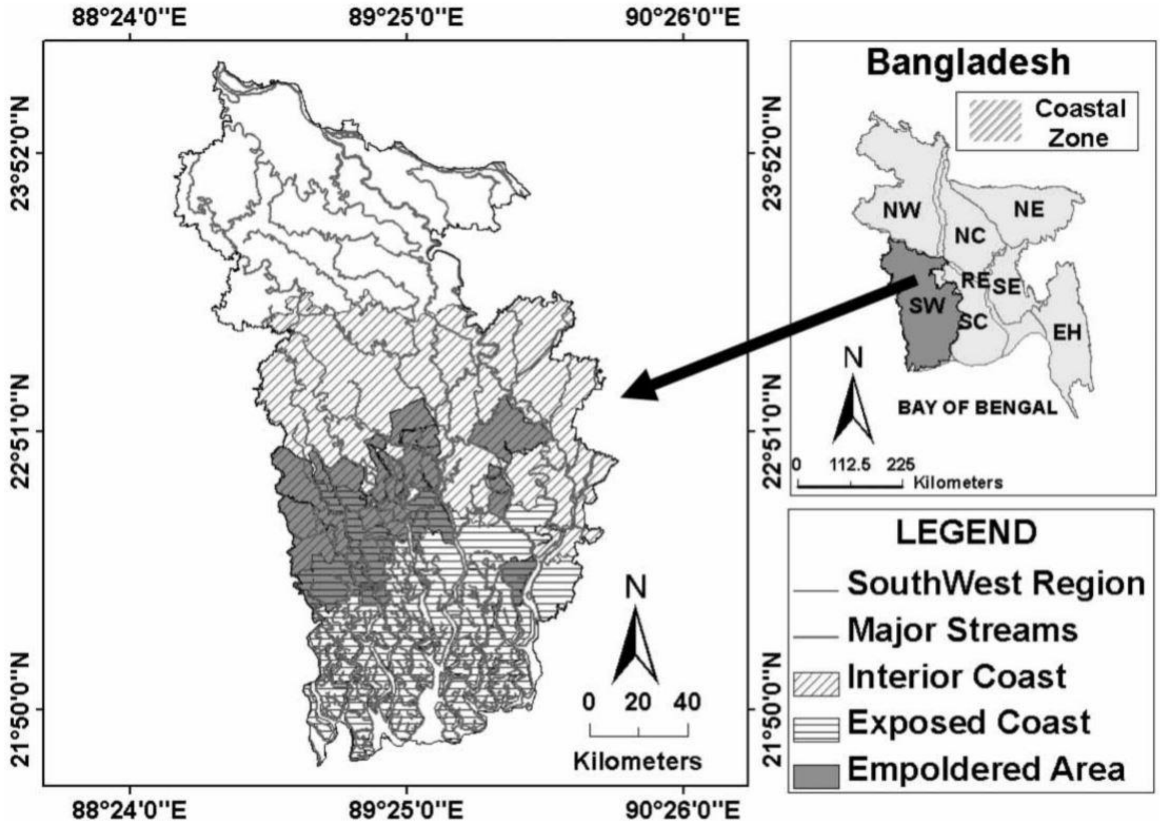

Figure 2.1 Southwestern coastal Bangladesh with indicated polder system (derived from Nowreen et al., 2014).

2.2 Agricultural productivity

Bangladesh is an agricultural economy, where 76% of the people live in rural areas and agriculture contributes for 19.3% of the gross domestic product (GDP) (Shelley et al., 2016). In the coastal region of Bangladesh, about 85% of the people are directly depending on agriculture to sustain their livelihoods (Hofer & Messerli, 2006; Lazar et al., 2015). Rice is the main staple food, and over 95% of the people depend on rice for their daily caloric intake (Mahmud et al., 2017).

There are three distinct agricultural seasons in Bangladesh. The monsoon or Kharif-II season (June – November), the cool and dry Rabi season (November – March), and the hot and humid Kharif-I season (March – June) (Lazar et al., 2015). In the wet Kharif-II season, fresh water availability is high and farmers generally cultivate rainfed Aman rice, jute, and sugarcane. In this season, monsoon floods provide fresh water, sediments, and nutrients that improve soil fertility and increase organic matter content (Overeem & Syvitski, 2009; Banerjee, 2010). However, seasonal related flood damage and cyclonic events can result in crop failure (Hofer & Messerli, 2006). In the dry Rabi and Kharif-I season, when freshwater becomes scarce and salinity increases, farmers generally cultivate groundwater-irrigated Boro and Aus rice, or switch to cultivation of vegetables and spices, as well as poultry and duck farming (Hofer & Messerli, 2006; M. T. Uddin & Nasrin, 2013).

Rice productivity in Bangladesh significantly increased after 1960 (1.05 to 2.2 tons per hectare between 1972 and 2010), and is directly related to the development of irrigation systems, adoption of modern high yielding rice varieties (HYVs), and the application of chemical fertilizers and pesticides (Huq & Shoaib, 2013; Shelley et al., 2016). However, intensive agriculture with HYVs, imbalanced use of agrochemicals, and limited addition of crop residues consequently results in soil degradation and nutrient depletion, thereby limiting the sustainability of the agricultural system (Pagiola, 1995; Moslehuddin & Laizoo, 1997; Shelley et al., 2016). This, together with natural and human-induced environmental changes, is increasing agricultural vulnerability that will ultimately affect the livelihoods of thousands of farmers that are unable to adapt (Rawlani & Sovacool, 2011; Brammer, 2014).

2.3 Soil fertility

Agricultural productivity is directly depending on soil fertility, which is defined as ‘the capacity of a soil to provide physical, chemical and biological requirements for growth of plants for productivity, reproduction and quality relevant to plant type, soil type, land use and climatic conditions’ (Abbott & Murphy, 2003). In other words, ‘fertility is the potential nutrient status of a soil to produce crops’ (Huq & Shoaib, 2013). The fertility status of soils in Bangladesh is extremely variable due to physiographic and microclimatic variation (Islam, 2008; Huq & Shoaib, 2013). In general, soil fertility levels are low and fertilizer management is required to support agricultural productivity (Huq & Shoaib, 2013). However, resulting nutrient imbalances are associated with a decline in soil fertility, thereby decreasing agricultural productivity (Pagiola, 1995; Hossain, 2001; Shelley et al., 2016).

Key plant nutrients are nitrogen (N), phosphorus (P), and potassium (K) (Koerselman & Meuleman, 1996). Nitrogen is the most important, and most limiting factor regarding rice productivity in Bangladesh. Low N supplies are directly related to the low contents of organic matter (OM), with averages ranging between 0.05 – 0.9% throughout the country, and 1.0 - 1.5% in the coastal region (Huq & Shoaib, 2013; Alam et al., 2017). Due to its low supply, application of nitrogen fertilizers is essential to support agricultural productivity (Moslehuddin & Laizoo, 1997). Other limiting factors for soil fertility in Bangladesh include the availability of macronutrients phosphorus (P), that is often present in different unavailable and fixed forms, potassium (K), sulfur (S), and calcium (Ca). Availability and deficiency of micronutrients also play an important role, especially those of iron (Fe) and zinc (Zn) (Huq & Shoaib, 2013). The soil nutrient composition is controlled by complex biogeochemical processes and feedbacks that mobilize nutrients and make them available for plant uptake. These are often related to factors including redox potential or oxidation, pH, and salinity (Yang et al., 2010; Saaltink et al., 2018).

2.4 Salinity

Increasing salinity is one of the major environmental concerns regarding agricultural productivity. The tidally active southwestern region is continuously exposed to the effects of salinity (Islam, 2016; Alam et al., 2017). In this dynamic system, salinity levels decrease in the monsoon season when freshwater availability is high, and increase in the dry season when freshwater availability is low. In the most southern situated regions, tidal flooding with saline water is recognized throughout the year, while it is only recognized during the dry season in upstream regions (Hugh Brammer, 2014).

The increasing salinity impacts are related to environmental changes including reduced upstream river flow, low rainfall, tidal storm surges, and sea level rise (Mahmuduzzaman, Ahmed, Nuruzzaman, & Ahmed, 2014; Shameem, Momtaz, & Rauscher, 2014). Expansion of salinity affected areas is widely recognized, and increased from 8,330 km^2 to 10,560 km^2 between 1973 and 2009 (Mahmuduzzaman et al., 2014; Alam et al., 2017). In the coastal region of Bangladesh, about 30% of the coastal area is recognized as having a saline soil (Huq & Shoaib, 2013). Saline soils restrict plant growth, and are associated with high values of salt ions (Cl, Na, and Mg), nutrient deficiencies of nitrogen and phosphorus, poor organic matter content, and low soil pH (Haque, 2006; Alam et al., 2017).

2.5 Sediment management

Polder systems in southwestern Bangladesh are associated with rapid siltation of the river beds, ultimately resulting in widespread flooding and waterlogging. This directly affects local livelihoods by affecting soil fertility, increasing soil salinity, decreasing income, drinking water scarcity, affected sanitation, loss of livelihoods, and severely damaged schools and infrastructures (Tutu, 2005; Nowreen et al., 2014; Gain et al., 2017). In the Jessore, Satkhira, and Khulna districts, waterlogging related losses in agricultural production directly affected the livelihoods of about one million people (Awal, 2014).

The local people identified the polders as the main cause of waterlogging and decided to restore tidal flows in order to control sedimentation. In this way, lands inside the polders are raised, and drainage capacities of the rivers gradually increase. Introducing tidal flooding and sedimentation was first seen in September 1990, when the people of the Dakatia beel breached the embankments, and is currently known as Tidal River Management (TRM) (Tutu, 2005; Gain et al., 2017; van Staveren et al., 2017). TRM involves restoring tidal in- and outflow by temporary removal of an embankment section adjacent to a low-lying beel. With the twice-daily high tide, water and sediments from the adjacent tidal river flow into the beel. With the twice-daily low tide, the water flows out of the polder or beel, leaving part of the sediments inside. Over time, deposition of fresh sediments is able to raise low-lying lands that can be reclaimed for agricultural use (Zakir Kibria, 2011; van Staveren et al., 2017).

Sediment management strategies that include tidal flooding and sedimentation are considered essential to raise land levels and offset rates of sea level rise and land subsidence (Brammer, 2014). Tidal river management has been experimented with in several polders and is assumed to play a large role for sustainable polder management in southwestern Bangladesh (Gain et al., 2017). TRM is found to effectively deposit sediments, reduce waterlogging, and restore river drainage capacities and navigability. After operation, it is considered that agricultural lands, villages, and roads are protected from flooding, and economic productivity is increased (Gain et al., 2017). However, varying success stories with TRM are associated with several disadvantages and challenges. The main challenge is that during TRM operation, tidal floodplains remain inundated for several years, thereby limiting economic activity. This, together with a delay in, or lack of, compensation payments results in conflicts with the local people (Amir et al., 2013; Paul et al., 2013; van Staveren et al., 2017). Another challenge is to ensure even distribution of sediments throughout the tidal basin to avoid permanently waterlogged lands (Gain et al., 2017). Regarding agricultural productivity, it is surprising that instead of inundating the fields with fresh water and sediments, TRM is using brackish and saline water and sediments to inundate the fields. After operation, this may have negative effects on soil fertility (Seijger et al., 2019).

3. Methodology

3.1 Study locations

Soil fertility of tidal sediments is examined at three tidal basins in southwestern Bangladesh, which were selected based on their geographic location and experience with tidal sedimentation. The selected locations are *Beel Pakhimara*, *Beel Khuksia*, and *Polder 32*, and are situated in the Satkhira, Jessore, and Khulna districts respectively (Figure 3.1). Selection of these study locations allows for examination of spatial variation of soil properties, nutrient content, and soil salinity. A description of each selected location is presented below, and their characteristics are listed in Table 3.1.

Beel Pakhimara is situated in Polder 6-8 in Satkhira District, Jalapur Union of Tala Upazila. The beel is located in the southeastern part of the polder and covers 700 hectares (Gain et al., 2017). The adjacent Kobadak river has been experiencing river siltation due to human interventions including polder construction. This consequently resulted in reduced drainage capacity of the river and widespread drainage congestion, affecting local livelihoods by severe waterlogging (Shampa, 2012). TRM was proposed to be implemented in 2011 in order to mitigate drainage congestion in the area. However, conflicts with the local people about proper compensation hindered the process. Eventually, *Beel Pakhimara* was connected to the Kobadak river to re-allow tidal movement and sedimentation inside the tidal basin in 2015, and is still ongoing (Gain et al., 2017). The canal is expected to be closed in 2020, when the beel is sufficiently filled with sediment and suitable for cultivation (Cornwall, 2018). Looking at soil fertility of fresh sediments in *Beel Pakhimara* can give a clear indication if people will benefit from TRM after operationalization.

Beel Khuksia is situated in Polder 24 in Jessore District, and extends over the Keshabpur and Monirampur Upazila. The tidal basin in the beel covers about 860 hectares (Ullah & Rahman, 2011; Gain et al., 2017). Siltation of the adjacent Hari river resulted in reduced drainage capacity and waterlogging, directly and indirectly affecting 15,000 people living in the tidal basin (Ullah & Rahman, 2011). The local people realized that implementation of TRM was the best solution to solve the waterlogging problems, but were unwilling to provide their lands without compensation (IWM, 2017). With no alternative solution, TRM was operationalized in 2006, and finished in 2012. A canal was constructed to connect the beel with the Hari river near Maynapur village. Fine sediments settled inside the beel, with varying rates of sediment deposition throughout the area (Talchabhadel et al., 2018). Even though the drainage capacity of the Hari river was restored, waterlogging problems inside the beel were not fully solved (Ullah & Rahman, 2011; Gain et al., 2017). Currently, agricultural practices have returned to the raised lands, making *Beel Khuksia* a relevant study location to examine the soil fertility several years after sediment deposition.

Polder 32 is situated in Dacope Upazila in Khulna District, close to the border of the Sundarbans mangrove forest. The total area covers 8097 hectares, with 6500 hectares of cultivable land, and is surrounded by the rivers Sibsa, Dhaki, Chunkuri, Bhadra, and Sutarkhali (BWDB, 2013). In 2009, Cyclone Aila hit the coastal region of Bangladesh, causing embankment failures, tidal flooding and displacement of thousands of people. In *Polder 32*, the embankments breached at five sites. During the 2-year embankment repair, the impact of sediment starvation and elevation loss became clear when large areas were submerged during the high tides. Over time, land elevation declined due to restricted sediment deposition, land compaction, deforestation and the increased tidal range. Re-introducing tidal inundation after Cyclone Aila elevated the lands with a sediment rate of ~18 centimetres per year, demonstrating the significant effect of tidal sediment deposition on elevation recovery (Auerbach et al., 2015). Even though sedimentation processes in *Polder 32* are not controlled or operationalized by TRM, the same concept applies. It's geographic location close to the Bay of Bengal makes *Polder 32* an interesting site to study soil fertility in a highly saline environment.

Table 3.1 Study location characteristics.

Study location	**1**	**2**	**3**
District	Khulna	Satkhira	Jessore
Polder	32	6-8	24
Beel		Pakhimara	Khukshia
Area (ha)	8097	700	860
River connection	Sibsa river	Kobadak river	Hari river
Population	30,000		15,000
Experience with tidal sedimentation	2009 – 2011*	2015 - ongoing	2006 - 2012
Sediment deposition	Land elevation near breached embankment points.	Waterlogging only solved near embankment cut-point.	Waterlogging only solved near embankment cut-point.

*Embankment breaches in Polder 32 have not been restored throughout the polder, leaving a tidal channel throughout the polder.

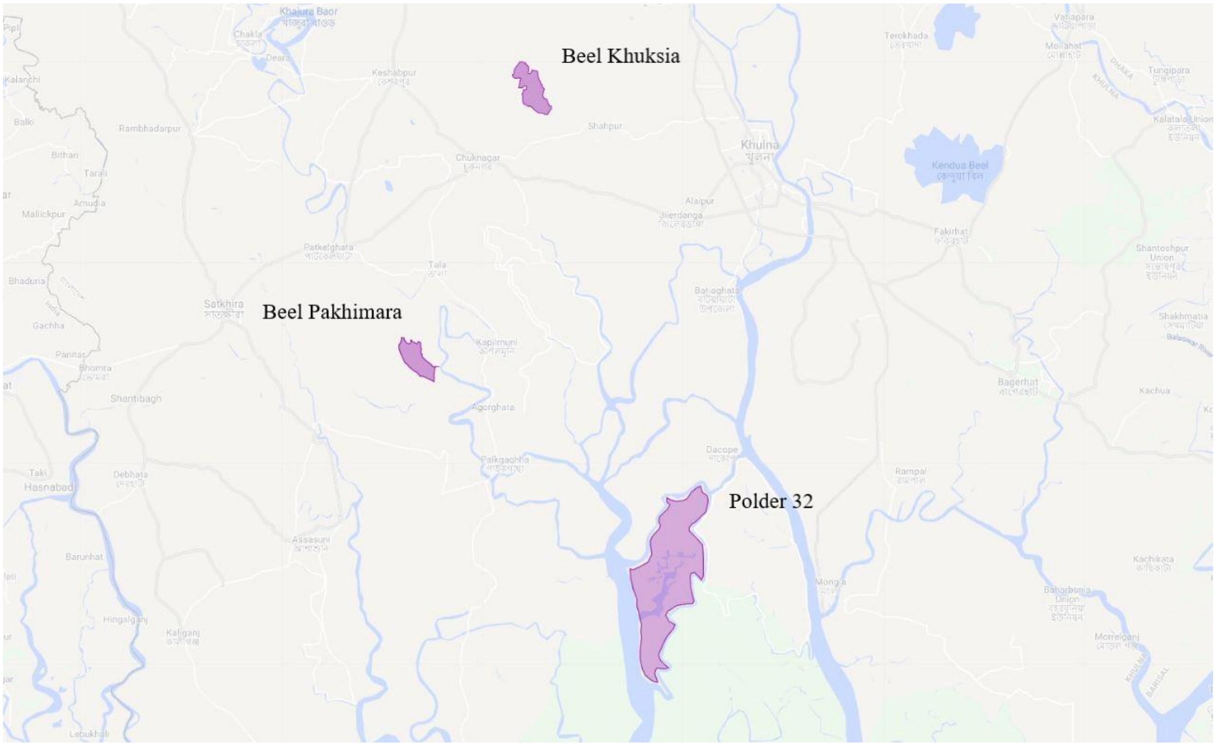

Figure 3.1 Study locations in southwestern Bangladesh.

3.2 Sediment collection

At each study location, sediment samples were collected at three different sites (Table 3.2; Figures A1.1-A1.3; Appendix I). These include sediment near the inlet or embankment breach point (sediment-inlet), sediment far from inlet or embankment breach point (sediment-far), and sediment outside the tidal basin that is used as a control by representing the old sediment prior to flooding (sediment-control). The sediment outside the tidal basin is collected in a non-flooded and harvested paddy field. By doing this, farmers easily allowed for sampling without the risk of affecting their yields. Besides, it is assumed that in these soils, the effects of applied fertilizers on plant growth are minimized since the harvested rice has already taken up additional nutrients to a certain extent.

Farmers determine soil fertility by qualitatively identifying top soil conditions (Ali, 2003). First, it was assumed that fresh sediments mix with old sediments by land preparation practices including plowing. However, sediment deposition inside the tidal basins significantly raised the lands, reaching between 1-2 metres in some areas (Auerbach et al., 2015; Gain et al., 2017; Talchabhadel et al., 2018). Local farmers indicated that they prepare the paddy fields by plowing to a depth of 20 cm. Taking this into account, it is unlikely that mixing of fresh and old sediments will occur. Therefore, samples are taken from the topsoil to a depth of 20 cm. A total of 15 L sediment was collected per sample site, with exception of Polder32-inlet and Polder32-far where 30 L was collected for additional treatment replicates (see section 3.3).

Table 3.2 Coordinates and fieldwork dates per sample location.

Location	Date	Sample	Latitude (N)	Longitude (E)
Beel Pakhimara	23-01-2019	Inlet	22°40'17.34"	89°15'12.69"
		Far	22°39'53.27"	89°14'44.95"
		Control	22°39'36.01"	89°15'18.43"
Beel Khuksia	24-01-2019	Inlet	22°52'35.98"	89°21'07.33"
		Far	22°54'15.93"	89°19'49.45"
		Control	22°54'00.38"	89°19'19.05"
Polder 32	26-01-2019	Inlet	22°33'43.09"	89°28'32.51"
		Far	22°31'19.58"	89°28'13.26"
		Control	22°34'26.79"	89°27'14.74"

3.3 Experimental setup

A rice growth experiment was conducted at Khulna University in the period January – March 2019. Rice (*Oryza sativa* L.) was grown in sediment-inlet, sediment-far, and sediment-control samples of each study location. The rice variety used in this study is the salinity tolerant Boro BRRI dhan 28 (BR 28)[2], and was selected for its local availability, seasonal adaptability and widespread cultivation in southwestern Bangladesh during the cool and dry Rabi season (Hossain et al., 2013; Lazar et al., 2015).

[2] Traditional rice crops in Bangladesh are Boro, Aus and Aman. Boro rice is grown during the dry winter season (January - May) and is irrigated with groundwater. Boro rice was cultivated on an area of 4.76 million hectares in 2012-2013 (Mahmud et al., 2014). The most popular high yielding modern varieties (HYVs) of Boro rice are BRRI dhan 28 (BR 28) and BRRI dhan 29 (BR 29), together covering 60% of the rice area in the Boro season of 2005 (Hossain et al., 2013). Adoption of HYVs is considered crucial for cultivation in tidal basins containing brackish water (Kibria, 2011). BR 28 is a saline tolerant variety that was introduced in coastal Bangladesh in 1994. The plants reach a height of 90 cm, have a growth duration of 140 days and an average yield of 6 tonnes per ha (Ghosh, 2016). This variety is widely adopted in areas that are affected by different levels of salinity, including the districts Satkhira, Khulna, and Jessore. High yields and eating quality are found to be the most important aspects for BR 28 adoption (Hossain et al., 2013).

A basin of 8.75 m^2 (3.5 x 2.5 m) with three compartments (two of 2.5 x 1 m and one of 2.5 x 1.5 m) was setup in a field to create a separate environment for each study location (Figure 3.2). This open air experiment allows for seasonal environmental conditions regarding air temperature, humidity, sunlight, wind, and rainfall. The bottom of the compartments were covered with polyethene sheets to maintain continuous flooding conditions[3], which is generally practiced by rice farmers. The compartments were filled with pond water that is used for irrigating the paddy fields of Khulna University, and was the most 'fresh' water source available (EC 1.31 mS cm^{-1}). At weekly intervals, additional pond water was added to maintain a water level between 12-14 cm, with exception of week 5 and 6 when the compartments were filled with rainwater. Water inside the basin compartments were regularly checked for salinity, and the nutrient composition of additional pond water was analysed to ensure there were no undesirable fluctuations in water chemistry. The basins were frequently cleaned to avoid contamination of materials such as leaves, twigs and dead insects.

To prepare the soil for the rice growth experiment, sediment samples were sun dried for two days and gently broken down with a hammer. According to local farmers, rice is not likely to survive on tidal sediments without additional fertilizers. Therefore, mixtures of 50% sediment and 50% organic compost were made with part of the collected sediments. For each sample site there are ten replicates per study location (inlet, far, and control), with five replicates including tidal sediment, and five replicates including the compost mixture. Plastic pots (diameter 20 cm, depth 17 cm) with perforated base were filled up to 10 cm with the collected sediment samples and compost mixtures. Additional holes are made at 12 cm to allow flooding conditions inside the pots. In four replicates per sample location (two in tidal sediment, and two in compost mixture), a pore water sampler (10 Rhizon CSS 10 cm (female luer); Rhizosphere, Wageningen, The Netherlands) was installed horizontally at a depth of 5 cm below the sediment surface, with the tip reaching 5 cm from the pot wall (Figure 3.3).

A total of 110 pots were coded and placed in rows in the compartments (Table 3.3). These include 30 pots for Beel Pakhimara, 30 pots for Beel Khuksia, and 50 pots for Polder 32. An additional treatment is applied to the samples from Polder 32 (inlet and far) to examine the effect of leaching. Soluble salts are able to leach into the groundwater during the monsoon season, thereby reducing the effect of soil salinity on plant growth over time. River water around Polder 32 is considered most saline as it is located close to the Bay of Bengal, and is therefore chosen for this treatment. This 'washing' treatment was conducted by applying 500 ml water to the pots, and repeating this 10 times every 10 minutes before placing them into the compartments.

Rice plants were grown from seeds for 35 days in a nursery bed at Khulna University and were manually transplanted into the experimental sediments. Manually transplanting rice from a nursery bed into the field is commonly practiced in southwestern Bangladesh. The nursery bed was located in a paddy field where the same pond water is used for irrigation. This soil is considered fertile and suitable for rice cultivation. Therefore, a soil sample from the nursery bed was analysed to compare the soil properties and nutrient content with the experimental sediments.

Three rice seedlings were planted in the centre of each pot at a depth of 3 cm. Prior to transplanting, the pots were filled with sediment and softened by placing the pots inside the water-filled compartments for 24 hours. Individual seedlings with the same height were selected to transplant from the nursery bed. To optimize plant growth, the pots are placed at a spacing density of 22,5 x 22,5 cm^2 (Baloch et al., 2002). Within the first week, seedlings that showed symptoms of drying out were removed and replaced

[3] Maintaining flooding conditions in paddy fields is beneficial for rice production by reducing water stress, controlling weeds, and providing a stable physical, chemical, and microbiological environment in the root zone (Sahrawat, 1998). In flooded, or submerged, paddy fields, fertility advantages include accumulation of organic matter and neutralization of pH, both influencing the release and availability of plants nutrients (Sahrawat & Narteh, 2002; Sahrawat, 2012).

with new ones from the nursery bed[4]. There are several factors that could relate to crop failure, including bad transplantation, altered root development, or random chance.

Various rice farming practices were studied in the field, and were applied in this study to include local knowledge and experience. These practices include (1) replicates containing compost, (2) sun drying the sediment before usage, (3) planting three seedlings together, (4) spacing between the pots, and (5) application of pesticides to avoid any harmful effects of insects on plant growth[5]. This study does not include application of agrochemical fertilizers, as these will significantly change the chemical composition of the soil and thereby alter results.

Table 3.3 Coding scheme of replicates per compartment. For each study location (Pakhimara, Khuksia, and Polder 32), there are ten replicates per sample site (inlet, far, and control). In Polder 32, ten additional replicates represent the washing treatment (inlet and far). *Red boxes* indicate replicates with tidal sediment. *Green boxes* indicate replicates with compost mixtures. *Yellow boxes* indicate replicates where a pore water sampler was installed.

	1	2	3	4	5	6	7	8	9	10
1	PI1	PI2	PI3	PI4	PI5	PI6	PI7	PI8	PI9	PI10
2	PF1	PF2	PF3	PF4	PF5	PF6	PF7	PF8	PF9	PF10
3	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
4	KI1	KI2	KI3	KI4	KI5	KI6	KI7	KI8	KI9	KI10
5	KF1	KF2	KF3	KF4	KF5	KF6	KF7	KF8	KF9	KF10
6	KC1	KC2	KC3	KC4	KC5	KC6	KC7	KC8	KC9	KC10
7	32I1	32I2	32I3	32I4	32I5	32I6	32I7	32I8	32I9	32I10
8	32F1	32F2	32F3	32F4	32F5	32F6	32F7	32F8	32F9	32F10
9	32C1	32C2	32C3	32C4	32C5	32C6	32C7	32C8	32C9	32C10
10	32IW1	32IW2	32IW3	32IW4	32IW5	32IW6	32IW7	32IW8	32IW9	32IW10
11	32FW1	32FW2	32FW3	32FW4	32FW5	32FW6	32FW7	32FW8	32FW9	32FW10

3.4 Harvest and dry mass

The rice plants were harvested 45 days after transplantation (DAT), or 80 days after sowing (DAS). After harvesting, shoots and roots were separated and washed with tap water before drying. The plant tissue was sampled in paper bags and air-dried in a forced-draft oven for 48 hours at 70°C, and 24 hours at 80°C (Campbell & Plank, 1998). Above- and belowground plant material (shoots and roots) were individually weighed and ground (Mixer Mill MM 400, Retch) for further analysis. Due to time limit, rice plants were grown throughout the vegetative phase (~65 days) until the start of the reproductive phase, and were therefore harvested before reaching maturity. The final growth stage is identified by panicle initiation, where production of the panicle primordia is recognized by a small furry tip inside the main stem. At this point, rice plants generally reach a height of approximately 50 cm (Moldenhauer et al., 2013; Dunn & Dunn, 2018). Even though the plants did not reach their optimal height, a clear

[4] Seedlings that have been replaced at day 3 include PI1, PI3, PI4, 32F2 and 32F4. Seedlings that have been replaced at day 7 include PI2, PI3, KI3, KI5, KF4, and 32F1. Replicate PI3 has been removed twice. It is notable that seedlings were only replaced on tidal sediments without compost, and on sediments from inlet and far away.
[5] After recognizing a variety of insects inside the compartments, the agrochemical pesticide Nitro 505 EC (Chlorpyrifos (50%) and Cypermethrin (5%), Autocrop Care Ltd., Dhaka, Bangladesh) was applied to avoid potential harmful impacts on plant growth. Besides affecting harmful insects, this broad spectrum pesticide will affect beneficial insects, thereby limiting variation in soil biological fertility.

indication of rice productivity and yield can be determined in terms of plant height, tillering number, and dry mass (Fageria, 2007). Height was measured from the soil surface to the tip of the tallest plant, and the total number of active tillers were counted.

3.5 Geochemical analysis

A series of geochemical analyses was performed on the collected sediments, pore water and plant tissue to test the soil fertility at the different study locations. An overview of the performed analyses is represented in Table 3.4. These analyses and associated results are described separately, but will be integrated later on to obtain conclusions.

3.5.1 Sediment analysis

Sediment samples were stored for two months in oxic conditions, and were freeze dried and ground prior to analysis. The bioavailable nutrient content of inorganic elements in dried soil samples is determined by ICP-OES after extraction treatment with 0.01 *M* $CaCl_2$ for two hours in a 1:10 (w/v) extraction ratio (Houba et al., 2000). Nitrogen contents were measured on an elemental CN analyser after pre-treatment with 1 *M* HCl to remove carbonates (NA1500, Fisons Instruments). Sulfur and organic carbon contents were measured on an elemental CS analyser without pre-treatment (CS-300, LECO). The soil organic matter (SOM) and carbonate contents were quantified with thermogravimetric analysis (TGA). The SOM was indicated by the loss on iginition (LOI), which was calculated by the thermal weight loss between 105-550°C (Kucerik et al., 2016). To calculate the SOM, a correction was applied based on Van Gaans et al. (2011). The carbonate content was indicated by the thermal weight loss between 550-800°C (Howard, 1965).

Grain size distribution and textural class of the sediment samples were determined using a grain particle sizer (Mastersizer 2000, Malvern Instruments). Particles less than 8 µm are classed as clay, between 8-63 µm as silt, and above 63 µm as sand (Konert & Vandenberghe, 1997). The textural class was determined by using the soil texture calculator from the Natural Resource Conservation Service Soils (USDA, n.d.). The initial sediments are compared to pre-treated sediments, where organic matter and carbonates are removed with 6% hydrogen peroxide and 1 *M* HCl in a 1:20 (w/v) ratio, and particles were peptized with ultrasound and a peptization fluid (0.1 *M* $Na_4P_2O_7 \cdot 10H_2O$; 0.04 *M* Na_2CO_3).

Sequential extraction methods were applied to determine solid speciation of phosphorus (based on Ruttenberg, 1992) and iron (based on Poulton & Canfield, 2005; Claff et al., 2010; Raiswell et al., 2010). The steps involved in these methods are represented in Tables 3.5 and 3.6, respectively. Total P in all extracts except the CDB extract (step 2) were measured spectrophotometrically using the molybdenum blue colorimetric method (Riley & Murphy, 1958). Total Fe in all extracts except the CDB extract (step 4) were measured spectrophotometrically using the 1,10-phenanthroline method (APHA, 2005) after reduction of Fe(III) to Fe(II) with 0.4 *M* hydroxylamine hydrochloride. In addition, Fe(II) was measured spectrophotometrically to calculate Fe(III) in the HCl step (step 2) by extracting Fe(II) from total Fe (Lenstra et al., 2019). Total P and Fe in the CDB extracts were measured by inductively coupled plasma optical emission spectroscopy (ICP-OES) after ten times dilution (1:9) (ICP-OES, Spectro Acros). Extraction step 1 for both P and Fe (and 2 for P) are usually performed under anoxic conditions, but were performed in oxic conditions considering sample storage was not anoxic. This may have affected preservation of solid P and Fe speciation in the soil.

Analytical precision of ICP-OES and sequential extraction results was determined by measuring three independent replications for three out of ten samples. These include Pakhimara-inlet, Khuksia-control, and Polder 32-inlet for sequential P and ICP-OES, and Pakhimara-far, Khuksia-inlet, and Polder 32-far for sequential Fe. Means of three replications are used in the results. Analyses with elemental CN analyser, elemental CS analyser, TGA, and grain particle sizer were performed using one replicate per sediment type.

3.5.2 Pore water analysis

Pore water analysis is essential for soil fertility, since it contains dissolved nutrients that are available for plant uptake. Pore water samples were collected by the Rhizon samplers and stored in 15 mL polyethene tubes. This is done three times ($t = 1 - 3$) during the rice growth experiment: at day 4, 25, and 43. The samples from two replicates (either with or without compost) are combined to ensure sufficient quantities for chemical analysis. Therefore, the results represent average nutrient concentrations of two pots. Directly after sample collection, soil salinity was measured in terms of electroconductivity (EC) using an EC-meter, pH was measured using a pH-meter, and ammonium (NH_4^+) and phosphate (PO_4^{3-}) concentrations were determined spectrophotometrically based on (Helder & De Vries, 1979) and (Riley & Murphy, 1958), respectively. Ion chromatography (IC) was performed to identify anion concentrations (mg L^{-1}) including nitrate (NO_3^-), nitrite (NO_2^-), chloride (Cl^-), phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}). Pore water samples that exceeded detection limits for chloride and sulphate were diluted ten times (1:9). The elemental concentration (mg kg^{-1}) were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES) after 1:100 v:v acidification with 69% HNO_3 (ICP-OES; Spectro Arcos). Results of both IC and ICP-OES were used to calculate alkalinity, or the buffer capacity, of the soil solution by extraction total anion concentration in meq L^{-1} (F^-, Cl^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2-}) from the total cation concentration in meq L^{-1} (Ca^{2+}, Fe^{2+}, K^+, Mg^{2+}, Mn^{2+}, Na^+, NH_4^+). Alkalinity is expressed as bicarbonate (HCO_3^-) in mg L^{-1}. Samples of applied pond water for irrigation were analysed similarly, excluding pH, ammonium, and phosphate measurements.

3.5.3 Plant tissue analysis

Plant tissue of the cultivated rice was chemically analysed in order to determine nutrient uptake, which is directly linked to the nutrient bioavailability in the soil. Due to time limit, plants have not been analysed individually. Plant material of five replicates per sample site (either with or without compost) was mixed and ground again to ensure homogeneous conditions. Therefore, the results represent average nutrient content of five replicates. From four sample sites a total of five replicates (two with, and two without compost) were analysed to check for variability between results of the individual and mixed plant materials. The elemental content (e.g. P, K, Ca, Fe, As) of the plant material was analysed using total reflection X-ray fluorescence (S2 Picofox, Bruker) after treatment of 50 mg sample with 4 ml Triton X-1% solution. The nitrogen and carbon contents were determined using an elemental CN analyser (NA1500, Fisons Instruments).

3.6 Statistical analysis

To study significant differences in dry mass between study locations, a one-way analysis of variance (ANOVA) was performed ($p < 0.05$). Significant differences in dry mass between rice grown on sediments and compost mixtures were determined by performing an independent t-test ($p < 0.05$). This statistical method is also used to identify significant differences for the washing treatment ($p < 0.05$). The variables were tested for homogeneity of variances with a Levene's test ($p > 0.05$). Both statistical methods were performed to identify which replicates are most fertile. All statistical analyses were carried out in SPSS 25.

Table 3.4 Series of geochemical analyses performed on sediments, pore water and plant tissue.

Sample type	Analysis	Data collection
Sediment	Inductively coupled plasma optical emission spectroscopy (ICP-OES) following extraction with 0.01 *M* $CaCl_2$	Total bioavailable Fe, K, Na, Mg, Mn, Zn, Si
	Elemental CN analyser	Total N, Total C
	Elemental CS analyser	Total S, Total C
	Thermogravimetric analysis (TGA)	Soil organic matter (SOM), Carbonates
	Grain particle sizer	% sand, silt, clay
	Sequential extraction method for solid P speciation	P-speciation (Table 2.5)
	Sequential extraction method for solid Fe speciation	Fe-speciation (Table 2.6)
Pore water	Ion chromatography	F^-, NO_2^-, NO_3^-, SO_4^{2-}, Cl^-, Br^-
	Inductively coupled plasma optical emission spectroscopy (ICP-OES)	Total Ca, Fe, K, Na, Mg, P, Zn, Si
	Ammonium colorimetric	NH_4^+
	Inorganic phosphate colorimetric	PO_4^{3-}
	Electric conductivity (EC) meter	Salinity
	pH-meter	pH
Plant tissue	Total reflection X-ray fluorescence	Total P, S, Cl, K, Ca, Mn, Fe, Zn, As
	Elemental CN analyser	Total N, Total C

Table 3.5 List of steps used in the sequential extraction procedure of phosphorus based on Ruttenberg (1992).

Step		*P-extractant*	*Seperated P fraction*	*Term*
1		1 *M* $MgCl_2$, 30 min	Exchangeable P	Exchangeable-P
2	A	Citrate-dithionite-bicarbonate (CDB), 8 h	Fe-bound P	Fe-bound
	B	1 *M* $MgCl_2$, 30 min		
3	A	Na acetate buffer (pH 4), 6 h	Amorphous apatite and carbonate bound P	Ca-P
	B	1 *M* $MgCl_2$, 30 min		
4		1 *M* HCl, 24 h	Crystalline apatite and other inorganic P	Inorganic-P
5		Ash at 550°C, 2 h; 1 *M* HCl, 24 h	Organic P	Organic-P

Table 3.6 List of steps used in the sequential extraction procedure of iron, a combination of extraction steps based on Poulton & Canfield (2005)[1], Claff et al. (2010)[2] and Raiswell et al. (2010)[3]. Note that step 1 is carried out separately from the rest of the extraction scheme.

Step		*Fe-extractant*	*Seperated Fe fraction*	*Term*
1[3]	A	0.17 *M* Sodium citrate/ 0.6 *M* sodium bicarbonate/ 0.057 *M* ascorbic acid (pH 7.5), 24 h	Labile Fe in ferrihydrites and (oxyhydr)oxides	Ferrihydrite
		1 *M* $MgCl_2$, 1 h		
1 [1,2]	B	1 *M* $MgCl_2$, 1 h	Exchangeable Fe	Exchangeable-Fe
2 [2]		1 *M* HCl, 4h	Easily reducible Fe(III) oxides including ferrihydrite and lepidocrocite;	Easily reducible oxides
			Fe carbonates and FeS (FeII)	Carbonates and FeS
3 [2]		0.1 *M* Sodium pyrophosphate (pH 10.4), 16 h	Organic bound Fe	Organic-Fe
4 [1,2]		0.3 *M* Dithionite (pH 4.8) with 0.35 *M* acetic acid/ 0.2 *M* sodium citrate (CBD), 4 h	Reducible crystalline Fe oxides	Crystalline oxides
5 [2]		HNO_3 (65%), 2 h	Pyrite	Pyrite

Figure 3.2 Rice growth experiment at Khulna University (own work)

Figure 3.3 Pore water samplers attached to pots (own work)

4. Results

The results from the rice growth experiment and geochemical analyses are presented as follows: first, the differences in sediment characteristics are described; next, variation in rice productivity and plant tissue composition between the sediments is presented; subsequently, nutrient availability and dynamics in the pore water will be studied to identify the main biogeochemical processes. In this section, rice productivity and nutrient availability in the sediments is compared to the compost mixtures and applied washing treatment.

4.1 Sediment characteristics

4.1.1 Particle size and textural class

The grain size distribution and textural classification of the collected sediments are represented in Table 4.1. The lithological class of the collected tidal sediments is dominated by silty loams. The sediments in Beel Pakhimara contain higher % clay, whereas the sediments in Polder 32 contain higher % sand. The control sediments in Beel Pakhimara and Beel Khuksia both have lower % clay, and higher % sand compared to inlet and far. In Polder 32, the control contains higher % clay, and lower % sand compared to inlet and far. The gross distribution of the nursery bed is found most similar to the control samples of all study locations. After removal of organic matter and carbonate particles in the sediments, a gradual shift in distribution is noticed towards higher % clay, and lower % sand. It is notable that the textural class of the sediment samples collected within Beel Pakhimara and Beel Khuksia are the same, and changes are only seen in Polder 32.

Table 4.1 Grain size distribution (clay < 8 µm, silt 8 - 63 µm, and sand > 63 µm) and textural classification (soil texture calculator; USDA, n.d.) of the original and pre-treated sediment samples.

	Original samples				Samples after pre-treatment			
Sample	% Clay	% Silt	% Sand	Textural class	% Clay	% Silt	% Sand	Textural class
Pakhimara-inlet	24	68	9	Silt loam	31	60	9	Silty clay loam
Pakhimara-far	20	68	12	Silt loam	31	59	10	Silty clay loam
Pakhimara-control	13	51	36	Silt loam	36	52	11	Silty clay loam
Khuksia-inlet	11	63	26	Silt loam	18	64	18	Silt loam
Khuksia-far	13	66	22	Silt loam	17	65	18	Silt loam
Khuksia-control	10	53	36	Silt loam	19	59	22	Silt loam
Polder32-inlet	9	36	55	Sandy loam	22	48	30	Loam
Polder32-far	12	48	40	Loam	22	53	25	Silt loam
Polder32-control	19	58	23	Silt loam	36	61	4	Silty clay loam
Nursery bed	13	56	30	Silt loam	34	58	8	Silty clay loam

4.1.2 Organic matter and carbonates

The thermogravimetric analysis (TGA) results including the loss on ignition (LOI) and carbonate content (weight loss 800°C) are presented in Table A3.1 (Appendix 3). The LOI is used as an indicator for soil organic matter, and ranges from 2.2 to 6.3% with a median of 3.5% (Table 4.2). This is slightly higher compared to the organic matter content of other soil series in Bangladesh, that ranged from 0.86 to 4.99% with an average of 2.09% (Islam et al., 2017). Additionally, this is higher compared to LOI measurements in the Sundarbans area, that range from 0.4 to 3.8%, but low compared to the worldwide mean of 7.9% in estuarine tropical mangrove systems (Rogers et al., 2013). The carbonate content of the sediments ranges from 1.5 to 3.8%, with a median of 1.7% (Table 4.2). The carbonate content is highest in Beel Khuksia, and lowest in Polder 32. This is the other way around considering LOI. It should be noted that common tropical minerals like goethite and gibbsite decompose in the loss on ignition (105 - 550°C), and may have interfered with the results (Pallasser et al., 2013).

4.1.3 Electroconductivity and pH

Results from electroconductivity (EC) and pH measured in the pore water samples from both sediments and compost mixtures are presented in Table A3.2 (Appendix 3). Electroconductivity varies between 1.70 - 6.87 mS cm^{-1}, depending on location. The EC values are considered normal when < 4 mS cm^{-1}, medium when between 4 - 6 mS cm^{-1}, and high when > 7 mS cm^{-1} (Islam & Gregorio, 2013). It is observed that the EC is highest in study locations that were recently exposed to brackish river water at the moment they were sampled. These locations include Pakhimara-inlet (6.78 mS cm^{-1}), Khuksia-inlet (6.87 mS cm^{-1}), Khuksia-far (6.73 mS cm^{-1}), and Polder 32-far (6.43 mS cm^{-1}). Restoration of the dyke breach at sampling location Polder 32-inlet explains why this location can be considered normal (3.95 mS cm^{-1}). It is unsure why Pakhimara-far represents normal EC while it is exposed to tidal inundation. The EC levels in the control samples are considered normal in Beel Pakhimara and Beel Khuksia. It can be observed that soil EC decreases over time. This is associated with leaching of salts from the sediments. These mix with the surrounding basin water, thereby changing the basin water EC. This is presented in Figure 4.1. Here, the drop in salinity is explained by excessive rainfall in week 4 and 5. The only exception is Beel Khuksia-control, where soil salinity increased from 1.70 to 2.40 mS cm^{-1}. This is associated with mixing of the relatively fresh pore water with the increasingly saline basin water. For the compost mixtures, soil salinity is lower compared to the sediments. Here, increasing levels of salinity are observed in Pakhimara-inlet and -far, and in Khuksia-control. For the washing treatment, the only difference in salinity is noticed for Polder 32-far.

The soil pH ranges from 7.12 - 8.04 and is considered to be neutral to slightly alkaline. The only exception is Polder 32-control, where soil pH ranges from 6.22 - 6.77. Neutral and alkaline pH levels are controlled by maintaining flooding conditions, and are associated with calcareous soils that contain free carbonates and bicarbonates (Huq & Shoaib, 2013). This is observed with a positive trend when comparing the calculated alkalinity as expressed in mg HCO_3 L^{-1} (Table A6.2) to the pH (Figure 4.2). Throughout the experiment, it is noticed that pH levels have increased in almost all sediments. Only a slight decrease is observed in the replicates from Khuksia-control and Polder 32-inlet.

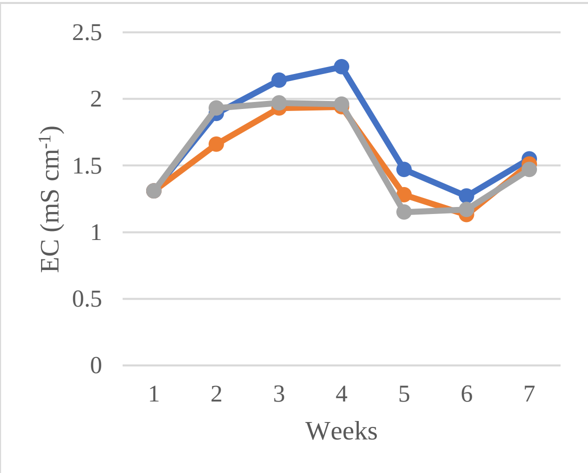

Figure 4.1 Change in EC (mS cm^{-1}) of the basin water throughout the experiment per compartment of each study location, as weekly measured. The blue line represents the basin of Beel Pakhimara, the orange line Beel Khuksia, and the grey line Polder 32.

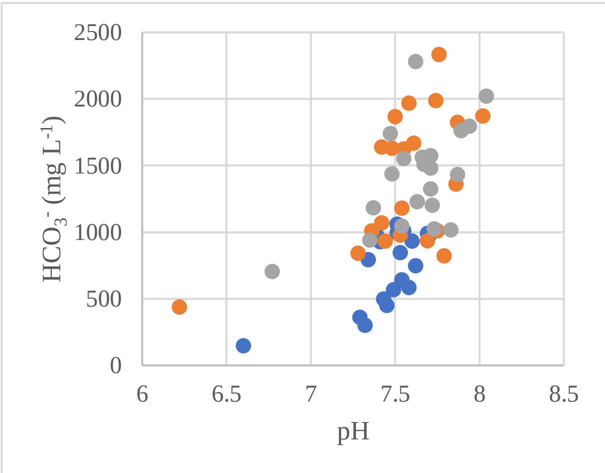

Figure 4.2 The relation between alkalinity expressed as HCO_3 (mg L^{-1}) and pH. The colours indicate measurements at day 4 (blue), day 25 (orange), and day 43 (grey).

4.1.4 Nitrogen, sulfur, and carbon contents

Total N, S and C contents are presented in Table A3.3 (Appendix 3). The Total N content of the sediments ranges between 0.06-0.24% with a median of 0.11%. For interpretation of the results, N contents are classified as follows: Very low is < 0.9%; Low is 0.09-0.18%; Medium is 0.18-0.27; and Optimal is 0.27-0.36% (Haque, 2006; Islam, 2008). Medium N contents are noticed in Pakhimara-control (0.21%), Polder 32-far (0.24%), and the Nursery bed (0.23%). The N contents of all other sediments are Very low or Low. The Total S content ranges between 0.04-0.22% with a median of 0.11%, and is highest in Pakhimara-inlet (0.15%), Pakhimara control (0.17%), Polder 32-far (0.22%), and the Nursery bed (0.20%). The critical limit for Total S is considered 7-11 mg kg^{-1}, but is predominantly high in the saline coastal region of Bangladesh (Neue & Mamaril, 1984; Huq & Shoaib, 2013). This is confirmed in the results, where Total S varies between 400-2200 mg kg^{-1}. Sulfur is available for plants in inorganic form, and is mainly present in the soil as reduced sulfide (S^{2-}) and oxidized sulphate (SO_4^{2-}), that are derived from mineralization of Organic S, atmospheric input, pesticides, fertilizers, and pyrite oxidation (Lucheta & Lambais, 2012; Saaltink et al., 2016). The Total C content ranges from 1.53-4.91%, with a median of 1.98%. In the control sediments from Beel Pakhimara and Beel Khuksia, Total C is higher compared to inlet and far. In Polder 32, far contains the higher C content.

4.1.5 Phosphorus contents

The P composition of the different sediments is presented in Table A3.3 (Appendix 3) and Figure 4.3. Total P is calculated by the sum of all fractions. Inorganic-P, or detrital apatite P, is the most important P fraction and ranged from 42-55.7% with a median of 51.2%, followed by Fe-P (18.8-24.3%; median 22.2%), Ca-P (14.6-20.8%; median 17.7%), Organic-P (5-17.9%; median 9.3%), and Exchangeable-P (0.7-3.4%; median 1.3%). The Inorganic-P fraction is not analysed for the Nursery bed and Polder 32-far. Therefore, these sediments are not included in the percentage calculation. The sediments from Beel Khuksia contain the highest concentration of P, followed by Beel Pakhimara and Polder 32. This is associated with variable concentrations of Inorganic-P, which is not available for plant uptake (van der Grift et al., 2018). When extracting the Inorganic-P fraction from the Total P, the potential bioavailable P pool remains. The Exchangeable-P fraction represents the bioavailable P that is easily taken up by plants (Van der Grift et al., 2018), and ranges from 3 to 16 mg kg^{-1}, with a median of 6 mg kg^{-1}. Taking into account the critical level of 8 mg kg^{-1} that is considered by the Olsen method, bioavailable P contents are in the low range (Islam, 2008). The bioavailability of other P fractions depends on biogeochemical processes, and is assumed to decrease with the increasing strength of chemicals used for sequential extraction (Q. Zhang et al., 2006). Phosphorus in Ca-P form can be considered bioavailable (Zhu et al., 2002), and P in Fe-P form can become bioavailable after flooding, when anoxic conditions result in reductive dissolution of iron oxides (van der Grift et al., 2018). The Organic-P concentration is important considering P cycling and availability, and is depending on biological processes in the soil (Stewart & Tiessen, 1987). Concentrations of Organic-P are high in Pakhimara-control and the Nursery bed, and can be related to accumulation of Organic-P from plant residues, or application of fertilizers and/ or manure in the paddy fields. This is, however, not noticed in the control sediments of Khuksia and Polder 32.

4.1.6 Iron contents

The Fe composition of the different sediments is presented in Table A3.3 (Appendix 3) and Figure 4.4. Total Fe is calculated by the sum of all fractions excluding Ferrihydrite. Pyrite is the most important Fe fraction and ranged between 25.9-42.6% with a median of 34.0%, followed by Easily reducible oxides (16.2-47.5%; median 33.1%), Carbonate Fe and FeS (7.5-41.9%; median 16.8%), Organic-Fe (6.5-10.9%; median 8.7%), Exchangeable-Fe (0-1.1%; median 0.6%), and crystalline Fe oxides (0.3-0.7%; median 0.5%). Total Fe is high in most sediments (> 5000 mg kg^{-1}), except for Pakhimara-far, Khuksia-control, and Polder 32-inlet. The main differences in Fe fractions between study locations is noticed for pyrite, which is considerably higher in Beel Pakhimara, and Organic-Fe, that is low in Beel Khuksia. Large variation in Fe contents is noticed for Carbonate Fe and FeS, and Easily reducible oxides. The concentration of soluble Fe(II), or ferrous iron, in the soil solution is considered bioavailable, and is related to the amount of organic matter and reducible Fe(III) oxides that increases Fe(II) availability after submergence (Sahrawat, 2004; Nozoe et al., 2009). The Easily reducible oxide fraction is similar for Beel Pakhimara and Beel Khuksia, with higher conents in Khuksia-far, and lower contents in Polder 32. However, the Ferrihydrite extraction results indicate that not all easily reducible oxides are bioavailable. Part of Easily reducible oxides is therefore considered unavailable for plants, except for Polder 32, where contents of Ferrihydrite exceed the contents of Easily reducible oxides. Considering Ferrihydrite as the potential bioavailable pool of Total Fe (Raiswell et al., 2010), it ranges from 15.0-44.0% with a median of 23.4%.

4.1.7 $CaCl_2$ extraction

The potential bioavailable nutrients in the sediments were measured after extraction with 0.01 *M* $CaCl_2$. The results are presented in Table A4.4 (Appendix 4). The nutrient content of K and Fe are 0 mg kg^{-1}, and P was not measurable. The main bioavailable nutrients determined by this extraction are the salinity related nutrients Mg, Na and S, together with low contents of Mn and Si. This is not surprising considering the brackish soil conditions. It is questionable if these results are applicable to this experiment, since they represent the nutrients that are directly available for plant uptake in aerobe conditions. However, flooding conditions in the rice growth experiment maintain anaerobe conditions that will consequently change nutrient bioavailability.

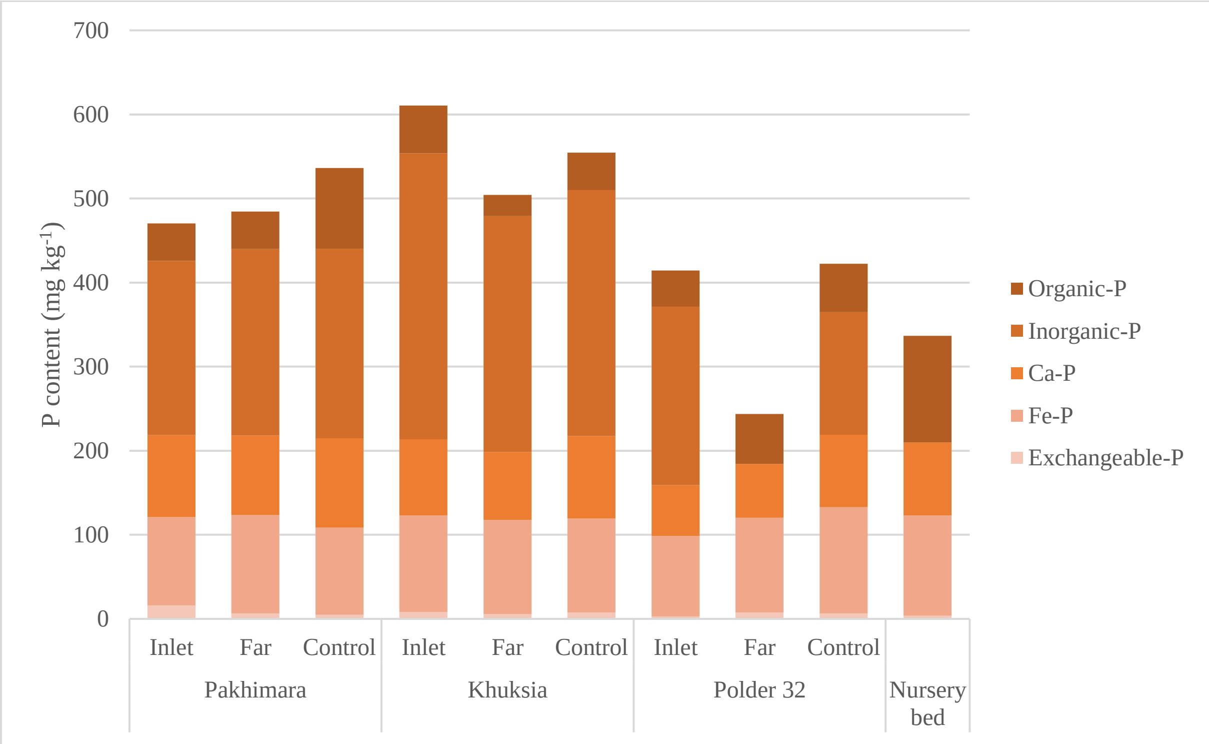

Figure 4.3 Sediment composition in mg kg^{-1} of P for each study location and the nursery bed, indicating contents of Exchangeable-P, Fe-P, Ca-P, Inorganic-P, and Organic-P.

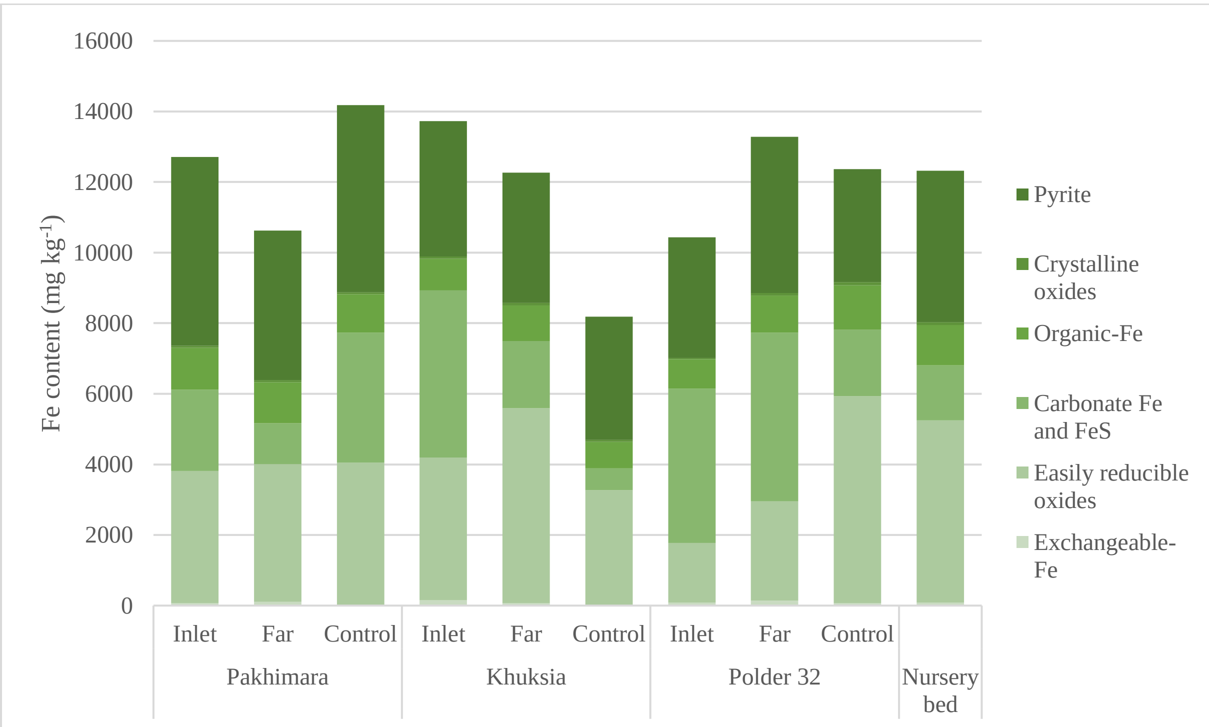

Figure 4.4 Sediment composition in mg kg^{-1} of Fe for each study location and the nursery bed, indicating contents of the Exchangeable-Fe, Easily reducible oxides, Carbonate Fe and FeS, Organic-Fe, Crystalline oxides, and Pyrite.

4.2 Rice growth experiment

4.2.1 Rice productivity

The study locations with the highest rice productivity are considered to have the highest soil fertility. In this study, rice productivity is based on the total dry mass, that is linearly correlated with the tiller number ($R^2 = 0.86$). The results from the rice growth experiment, including height, tiller number, and dry mass are presented in Table A4.1 (Appendix 4). The results, including their significance, from rice productivity in each study location on both sediments and compost mixtures are presented in Table 4.2. Rice productivity in the sediments is presented in Figure 4.5a, and rice productivity in the compost mixtures is presented in Figure 4.5b.

Rice productivity is significantly higher in all compost mixtures compared to the tidal sediments. The highest productivity in the tidal sediments is observed in Pakhimara-control and Polder 32-control. The lowest productivity is noticed in Pakhimara-inlet, Khuksia-control and Polder 32-far. For the compost mixtures, the highest productivity is noticed in Pakhimara-inlet and Polder 32-control, and the lowest in Khuksia-far and Khuksia-control. It is surprising that productivity in Pakhimara-inlet largely increased by adding compost, going from the least to one of the most productive study locations.

The main hypothesis of this study is that fresh sediment will improve soil fertility, and thereby increase rice productivity. However, the control samples that represent old sediments are significantly higher in Beel Pakhimara and Polder 32 compared to the fresh sediments from inlet and far. There are no significant differences between the control samples and fresh sediments in Beel Khuksia. These results clearly indicate that fresh sediments do not improve soil fertility, and that compost application is necessary to optimize productivity. When looking at the applied washing treatment in Polder 32 (inlet and far), no significant differences in productivity are observed compared to the untreated replicates. This most likely indicates that this treatment is not adequately performed.

Table 4.2 Mean total dry mass (g) of the rice plants per study location when grown on sediments and compost mixtures for all study locations. Significant differences between sediment and compost mixtures are indicated with p-values ($p < 0.05$; independent t-test). Significant differences between study locations are indicated with different letters, and non-significant differences are indicated with the same letter ($p < 0.05$; one-way ANOVA).

	n per type	Sediment mean	S.D.	Compost mean	S.D.	p-value
PI	5	0.93^{a}	0.49	5.30^{ab}	0.96	0.000
PF	5	2.42^{bd}	0.47	4.27^{ac}	0.99	0.005
PC	5	3.64^{c}	0.51	4.34^{ac}	0.45	0.048
KI	5	2.25^{b}	1.51	4.49^{ad}	1.41	0.042
KF	5	1.82^{ab}	0.76	3.23^{c}	0.94	0.032
KC	5	1.74^{ab}	0.36	3.88^{cd}	0.61	0.000
32I	5	2.12^{b}	0.23	4.15^{cd}	0.24	0.000
32F	5	1.74^{ab}	0.61	4.31^{ac}	1.12	0.002
32C	5	3.22^{cd}	1.26	6.00^{b}	0.54	0.002
32IW	5	2.27^{b}	0.14	4.06^{cd}	0.71	0.001
32FW	5	1.65^{ab}	0.35	4.93^{ad}	1.07	0.001

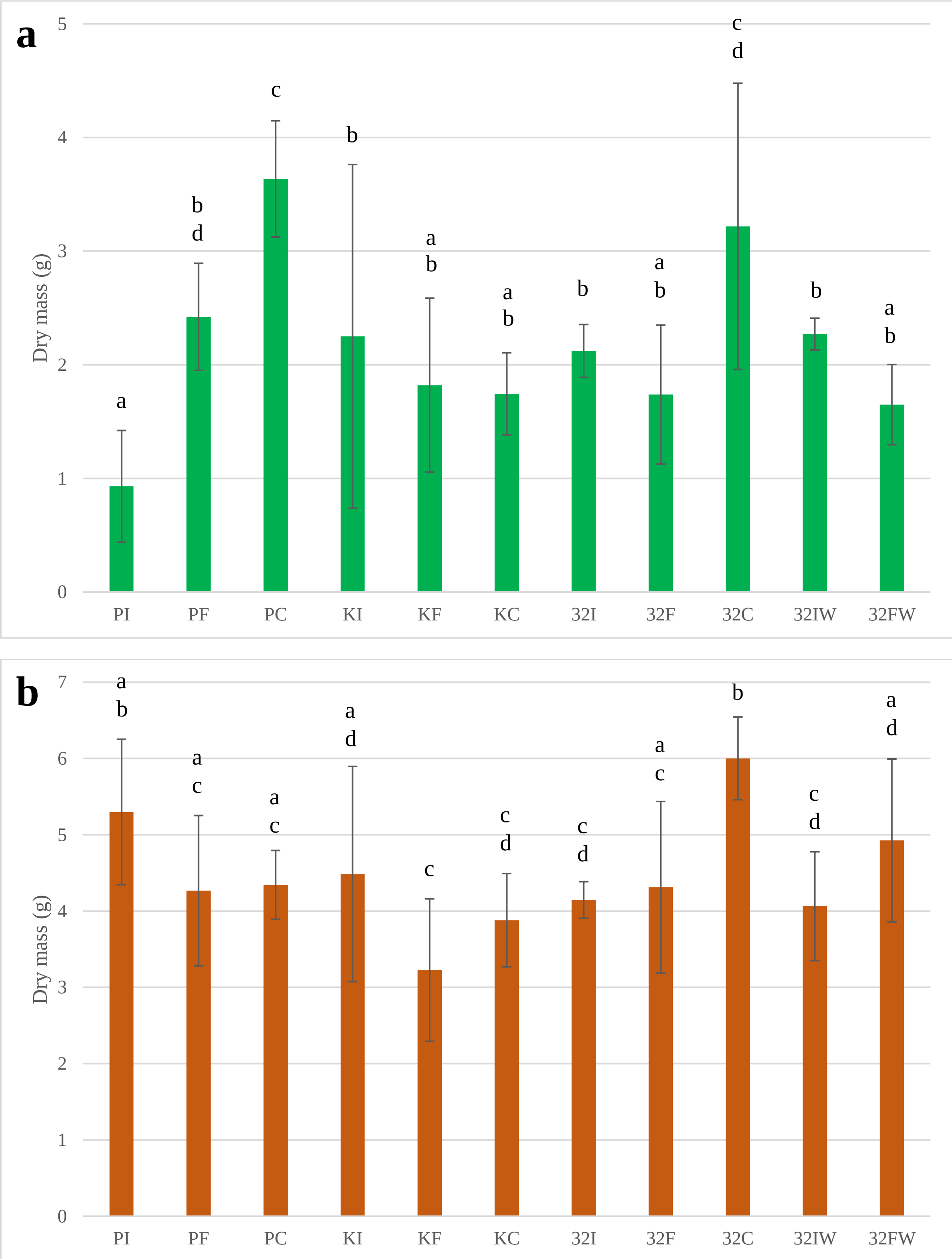

Figure 4.5 Mean total dry mass (g) of the rice plants per study location when grown in tidal sediments (a) and compost mixtures (b). Error bars represent standard deviation. Significant differences between study locations are indicated with different letters ($p < 0.05$), and non-significant differences are indicated with the same letters ($p > 0.05$).

4.2.2 Plant tissue composition

The mean elemental contents of shoot and root tissue per study location grown on tidal sediments and compost mixtures are presented in Table A5.1 (Appendix 5). The individually analysed replicates from four study locations are presented in Table A5.2 (Appendix 5). The means and standard deviation from five individual replicates are compared to results from the mixed plant samples. This is visualised for Total P in Figure 4.6. In general, elemental contents of the mixed samples are close to the calculated mean from the individual replicates. This means that the plant mixtures give a clear average representation of the nutrient content in all replicates. The results only varied in the shoot tissue from Beel Pakhimara-far, where contents of K, Ca, Mn, and Fe in the replicates largely differ from those in the plant mixtures. This might be related to how fine the plant material was ground prior to analysis. Where the individual replicates are ground once, the mixed samples have been ground a second time as pre-treatment procedure to ensure homogeneous mixtures.

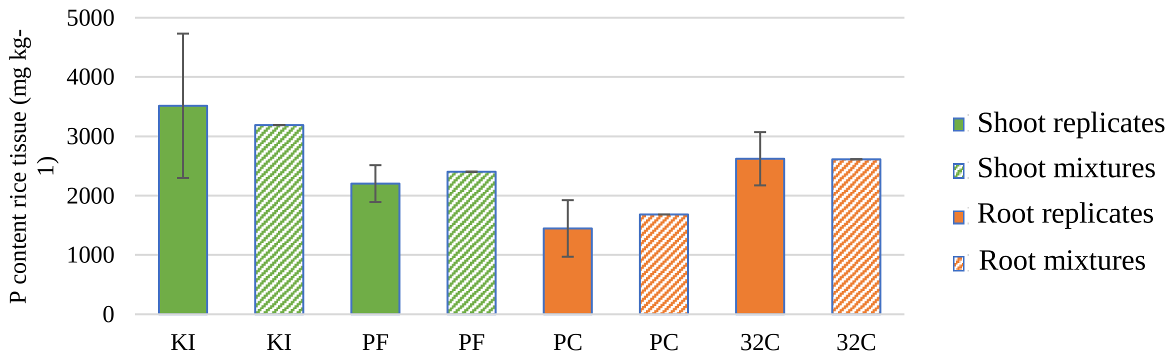

Figure 4.6 Total P results from total reflection X-ray fluorescence to control variation in plant tissue composition between the individually analysed replicates and the plant mixtures (Tables A5.1 - 2). The results represent P contents from Beel Khuksia-inlet sediments (KI), Beel Pakhimara-far compost mixtures (PF), Beel Pakhimara-control sediments (PC), and Polder 32-control compost mixtures (32C). Error bars represent standard deviation.

The results represent differences in nutrient uptake by rice when grown on tidal sediments and compost mixtures for all study locations. Macro nutrients that determine the plant tissue composition are N, P, K, S, Cl, and Ca. Micro nutrients are Mn, Zn, Fe, and As. The optimal range and critical deficiency levels of nutrients in rice tissue are described by Dobermann & Fairhurst (2000), and are listed in Table 4.3. The results show that except for Khuksia-inlet, the N contents are below the critical level of 2.5% in both sediments and compost mixtures. The P contents are above the critical level, and mostly within the optimal range. Higher P contents are observed in the compost mixtures. It is estimated that an N:P ratio > 16 indicates P limitation, where an N:P ratio < 14 indicates N limitation (Koerselman & Meuleman, 1996). The N:P ratio in the rice plants is found to range between 5 and 11 in the shoots, and between 2 and 9 in the roots. This implies that N is the main limiting nutrient in all study locations on both sediments and compost mixtures. In addition, the results indicate that P is primarily taken up by the shoots in the sediments, and that P is primarily taken up by the roots in the compost mixtures. Nitrogen is primarily taken up by the shoots in both sediments and compost mixtures.

The shoot contents of K are above the critical limit, and mostly within the optimal range. Higher contents of K are noticed in the compost mixtures, with levels reaching 3.08%. The contents of K are much lower in the roots compared to the shoots. The contents of S are generally found sufficient, with considerably high contents in the roots. The S contents in the compost mixtures are lower compared to the sediments, and are often below the critical limit. The highest Cl contents are present in the shoots, and are not influenced by compost application. The shoot contents of Ca are often below the critical level in both sediments and compost mixtures, which might indicate Ca deficiencies. However, higher Ca contents are observed in the roots.

The contents of Mn are found sufficient in all rice plants, and are higher in the tidal sediments compared to the compost mixtures. This is different for Zn, where shoot contents ranging between 11 – 23 mg kg^{-1} indicate Zn deficiencies in all study locations. This is, however, not surprising considering Zn deficiencies are found common in the Ganges floodplains and coastal saline areas (Akter et al., 2012). In addition, Zn deficiencies are common in submerged and alkaline soils when Zn is absorbed to bicarbonate (Sahrawat, 2012). On the other hand, Fe contents are much higher than the suggested optimal range. Mean contents in the shoots are 0.65%, and 1.30% in the roots. These findings indicate potential iron toxicity by exceeding the critical toxicity limits of 300 and 700 mg kg^{-1} in the shoots (Olaleye et al., 2001; De Dorlodot et al., 2005). Radial oxygen loss, or the oxidizing capacity, from the rice plants promotes precipitation of Fe oxides in the root zone, thereby limiting uptake and potential Fe toxicity (Sahrawat, 2004). This most likely explains the high Fe contents in the roots, that is generally associated with co-precipitation of other nutrients. The As contents in the shoots range between 1 and 7 mg kg^{-1}. In Boro BRRI 28 rice, shoot As contents below 7.4 mg kg^{-1} are not likely to exceed the maximum permissible limit of 1 mg kg^{-1} in the rice grains that is set by the WHO (Abedin et al., 2002; Bakhat et al., 2017). The As contents in the roots are much higher compared to the shoots, ranging between 4 – 163 mg kg^{-1}. This is associated with co-precipitation of As with Fe or S in the roots, limiting translocation of As from roots to shoots (Smith et al., 2008; Bakhat et al., 2017).

Table 4.3 Optimal ranges and critical deficiency levels of nutrients in rice leaf tissue between tillering and panicle initiation (based on Dobermann & Fairhurst, 2000).

		Optimum	Critical level	
Nitrogen	N	2.90 – 4.50	< 2.50	%
Phosphorus	P	0.20 – 0.40	< 0.10	%
Potassium	K	1.80 – 2.60	< 1.50	%
Sulfur	S	0.15 – 0.30	< 0.11	%
Calcium	Ca	0.20 – 0.60	< 0.15	%
Manganese	Mn	40-700	< 40	mg kg^{-1}
Zinc	Zn	25 - 50	< 20	mg kg^{-1}
Iron	Fe	60 – 100	< 70	mg kg^{-1}

4.2.3 Effects on rice growth

The relation between rice productivity in dry mass and uptake of the major nutrients N, P, K, and S are studied using scatter plots (Figure 4.7a-d). Increasing tissue contents of P (Figure 4.7b) and K (Figure 4.7c) are associated with increasing rice productivity. These nutrients are supplied by compost, and are considered the main nutrients that control productivity. Rice productivity is not associated with increasing N contents in the plant tissue (Figure 4.7a). This further explains N limitation in the study locations, which is not supplied by adding compost. Improving N availability will most likely increase productivity. Lastly, higher S contents are associated with decreasing productivity (Figure 4.7d). However, higher productivity in the compost mixtures is often associated with S deficiencies. Even though this relation implies a negative effect of S uptake, it might actually promote productivity in the sediment replicates.

In the coastal region of southwestern Bangladesh, increasing salinity levels are considered one of the major impacts regarding agricultural productivity (Gain et al., 2014). Therefore, it may be risky to promote sedimentation with brackish or saline water. When comparing rice productivity to the soil EC, a negative trend is observed when rice is grown on the sediments (Figure 4.7e). However, this correlation is very weak, which suggests that the impact of salinity on rice productivity is limited. In the compost mixtures that have lower EC levels, no trend is observed in relation to rice productivity.

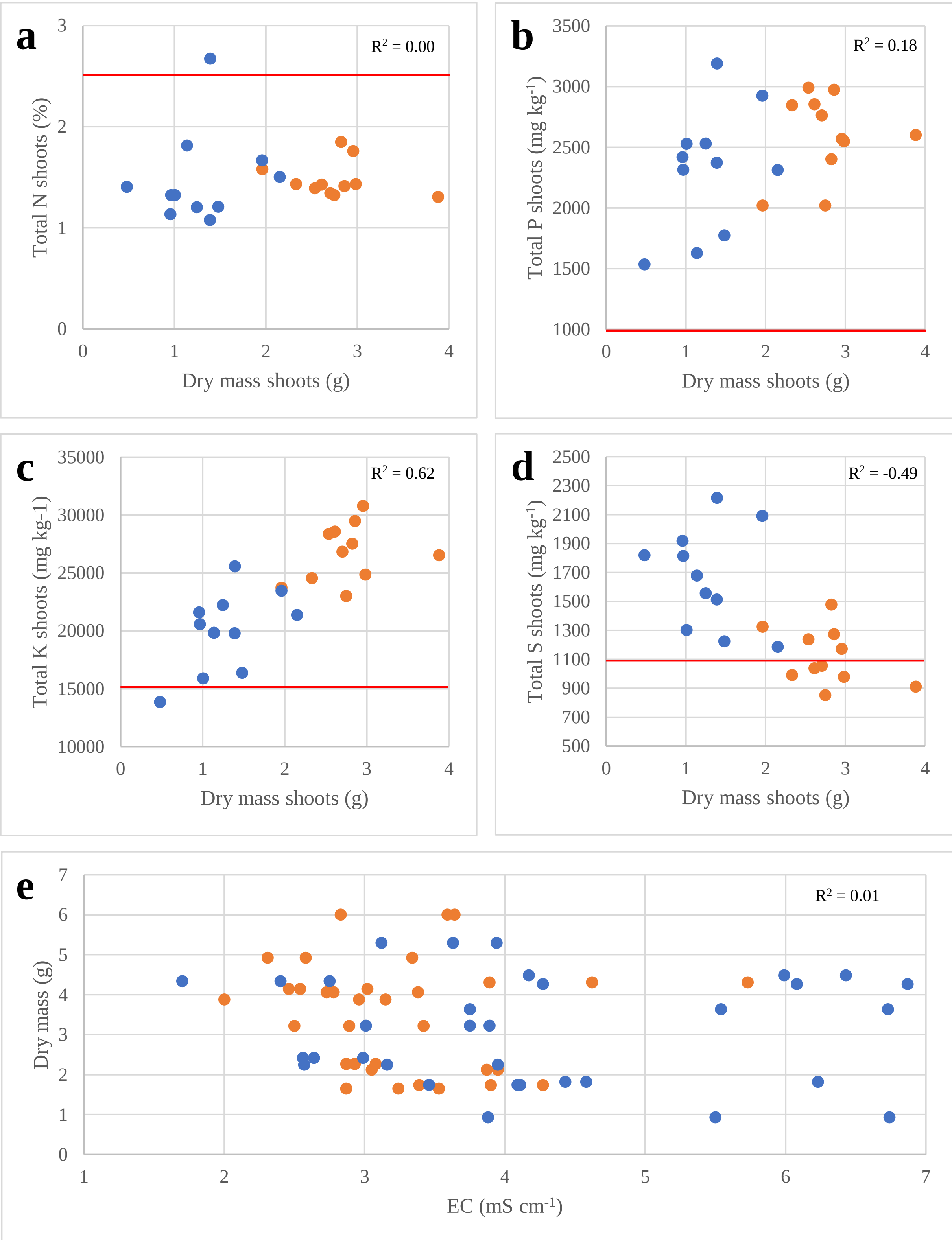

Figure 4.7 Scatter plots indicating the relation between rice productivity, nutrient uptake and soil EC. Total dry mass is related to Total P (a), Total N (b), Total K (c), and Total S (d). The relation between total dry mass and soil EC is presented in (e). The red lines indicate the critical deficiency level based on Dobermann & Fairhurst (2000). The sediment replicates are indicated in blue, and the compost replicates are indicated in orange.

4.3 Pore water composition

4.3.1 Pond water

The nutrient composition of the applied pond water is presented in Table A6.1 (Appendix 6). The pond water composition is studied to identify to what extent this may have influenced nutrient availability in the pots. Nutrient concentrations are generally low, especially for Fe, Mn, and P, and remain relatively stable over time. Fluctuations are mainly observed for Cl, SO_4, Ca, Mg, Na, and S, and are associated with changes in salinity. The NO_3 concentrations fluctuate between low (0 – 3 mg L^{-1}) and medium (3 – 10 mg L^{-1}) levels and might influence nitrogen concentrations in the pore water (Buchner, 2012).

4.3.2 Nutrient dynamics

The nutrient composition of the pore water is presented in Table A6.2 (Appendix 6). Nitrogen is the most important nutrient and main limiting factor for rice, and is primarily taken up in the forms of NH_4 and NO_3 (Shouichi, 1981). Initial NH_4 concentrations vary between 0.26 – 2.77 mg L^{-1}. Even though NH_4 production is favoured in submerged soils (Sahrawat, 2012), concentrations decline in all study locations (Figure 4.8a). The same trend is observed for NO_3, Ca, K, and salinity related ions including Na, Cl, SO_4 and Mg. The declining concentrations of NH_4, NO_3, Ca, and K are most likely associated with plant uptake, where salinity related ions are either taken up or leached into the surrounding basin water. The same dynamics are recognized in the compost mixtures, except for the concentrations of Ca and K that show increasing dynamics.

The concentrations of PO_4 are found to increase over time (Figure 4.8b). The increasing concentrations of PO_4 are associated with mobilization of P in submerged soils. Together with PO_4, increasing concentrations are observed for Si. Increasing concentrations of Fe are observed in the pore water samples from Polder 32. The PO_4 concentrations are used from the colorimetric results, considering that analysis directly after sampling provides the highest accuracy. It should be mentioned, however, that using contaminated water and unclean lab materials resulted in incorrect standards for both NH_4 and PO_4. Even though alternative standards are used for the calculations, these factors may have influenced accuracy of the results and are therefore considered indicative.

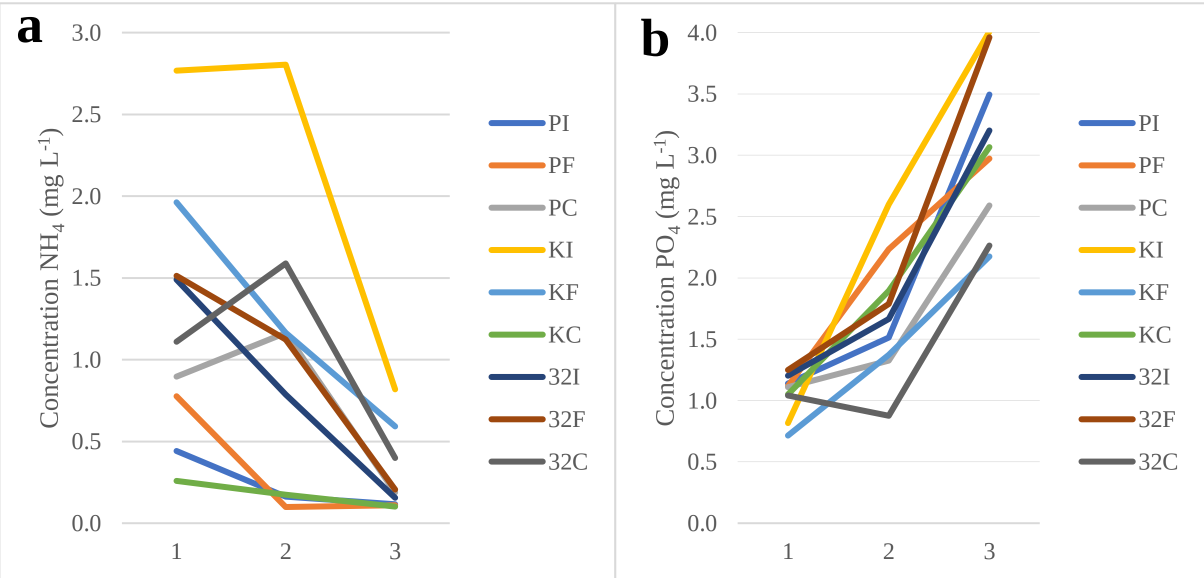

Figure 4.8 Change in porewater concentrations for NH_4 (a) and PO_4 (b) throughout the experiment in the tidal sediments for each study location measured at day 4 (1), day 25 (2), and day 43 (3).

4.3.3 Soil chemical processes

The majority of available nutrients in the pore water (*n* = 66) are salinity-related ions. Salinity is depending on concentrations of the major salt components Na and Cl , which are linearly correlated (R^2 = 0.94). Chloride is the main conservative element, and is exponentially correlated with EC (R^2 = 0.87). The relation between Cl and other salinity related ions include Mg (R^2 = 0.65), and SO_4 (R^2 = 0.44). Sulphate is linearly correlated with Total S concentrations (R^2 = 0.99).

The results find that nutrient availability is mainly influenced by soil chemical processes, and that there is a minor influence of conservative mixing in the samples. This is studied by comparing the relation between the conservative Cl concentrations with SO_4 and Ca (Figures 4.9a,b). The trendlines in these figures are based on pond water and average sea water concentrations of these nutrients (Millero, 2013). The concentrations of both Ca and SO_4 are located above the trendlines, indicating nutrient enrichment from internal processes. This is most likely associated with dissolution of calcium carbonates and pyrite oxidation in the soil.

Furthermore, some interesting relations are observed regarding SO_4. The decreasing SO_4 concentrations are associated with increasing levels of PO_4 (Figure 4.9c), and increasing alkalinity (Figure 4.9d). Increasing PO_4 concentrations are often accompanied by increasing Fe concentrations, when PO_4 is mobilized from reduced Fe(III) complexes. However, there is no clear relation between increasing PO_4 concentrations and Fe (Figure 4.9e).

4.3.4 Compost application

When comparing the nutrient availability in the sediments and compost mixtures, higher concentrations of PO_4, NO_3, Fe, K, and Si are observed in the compost mixtures. Lower concentrations are observed for Cl, SO_4, Ca, Mg, and Na. This mainly indicates that compost supplies additional plant nutrients. Lower concentrations of salinity related ions are related to declining EC levels, and can be explained by a dilution factor of the sediments. In addition, higher concentrations of, for example, NO_3 in the compost mixtures are present in the pore water for a longer time compared to the sediments. The high Si concentrations are interesting, and suggests that Si is present in the applied compost. Where Si concentrations do not change with increasing PO_4 in the sediments, increasing PO_4 is accompanied by increasing Si in the compost mixtures (Figure 4.9f).

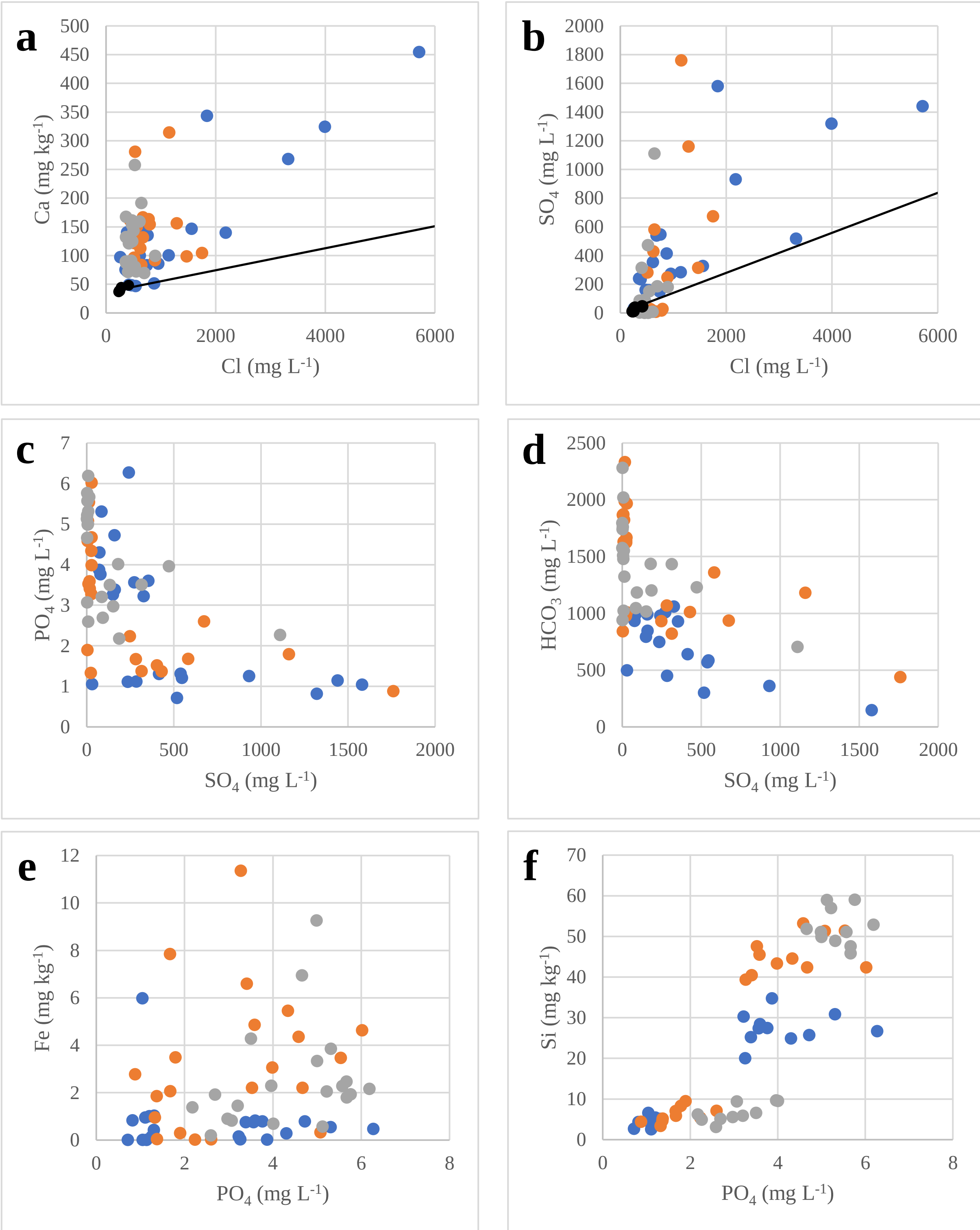

Figure 4.9 Scatter plots indicating the relation between pore water nutrients for Cl and Ca including a pond-sea water trendline (a), the relation between Cl and SO_4 including a pond-sea water trendline (b), the relation SO_4 and alkalinity in HCO_3 (c), the relation between SO_4 and PO_4 (d), the relation between PO_4 and Fe (e), and the relation between PO_4 and Si (f). The colours indicate measurements at day 4 (blue), day 25 (orange), and day 43 (grey).

5. Discussion

First, the presented results will be discussed to identify the main biogeochemical processes that determine rice productivity in Beel Pakhimara, Beel Khuksia, and Polder 32. Next, the importance of crop residue management is reviewed. Finally, limitations of this study are described, and future research perspectives are proposed.

5.1 Soil fertility and biogeochemical processes

This study examined the effects of tidal sediment deposition on soil fertility and rice productivity in southwestern Bangladesh. The selected study locations are Beel Pakhimara, Beel Khuksia, and Polder 32. Here, two fresh sediments are collected within the tidal basin, which are compared to old sediment that is collected in a nearby non-flooded rice field. The results find that the old sediments are more productive in Beel Pakhimara and Polder 32, whereas there is no difference in productivity between the fresh and old sediments in Beel Khuksia. This gives a clear indication that tidal sediments negatively affect soil fertility. However, the results from Beel Khuksia suggest that several years after tidal sediments have deposited, fertility levels of fresh sediments become similar to the old sediment. This implies that the negative effects on fertility may be noticed on short-term, but that land cultivation and soil formation will limit these consequences on the long-term.

Rice productivity largely varies between study locations, and it is found difficult to estimate which of the numerous factors and processes are mainly responsible for this variation. The lithological class of the fresh and old sediments is dominated by silty loams, with more sandy textures in Polder 32. There are no clear observations that particle distribution or the lithological class is related to rice productivity. However, limited OM in the sediments may explain why N is limiting in all study locations (Huq & Shoaib, 2013). Because N is limiting, P availability is assumed to largely control fertility levels.

There are two biogeochemical processes mobilize PO_4 for plant uptake. First, PO_4 mobilization is partly regulated by Fe(III) reduction, and is favoured in submerged anaerobe conditions (Sahrawat & Narteh, 2002). Phosphates are adsorped to Fe(III) complexes, or present as Fe-hydroxyphosphates. Reducing Fe(III) oxides to ferrous Fe(II) will release PO_4 into the soil solution. Reducing Fe-oxyhydroxides are considered the main source of P for rice in absence of fertilizers (Becker & Asch, 2005), and is depending on the amount of organic matter and reducible Fe(III) in the sediments (Nozoe et al., 2009). This process is mainly recognized in the compost mixtures, where increasing concentrations of PO_4 are accompanied by increasing concentrations of Fe(II). However, another process is observed in the tidal sediments. Even though PO_4 concentrations in these sediments increase over time, Fe(II) concentrations remain low. This can be explained by reduction of SO_4 to S that will decouple PO_4 from Fe(III) complexes. This will release PO_4 in the soil solution, while Fe(II) and S precipitate as FeS. In this way, PO_4 availability increases, while Fe(II) concentrations remain low (van Diggelen et al., 2014; van Dijk et al., 2019).

Regulating P availability is associated with amorphous Fe and Fe-P contents in the sediments (Loeb et al., 2008; Saaltink et al., 2018). Pyrite oxidation, on the other hand, will increase SO_4 concentrations and regulate P availability differently (Saaltink et al., 2018). Additionally, pyrite oxidation generally results in soil acidification by producing sulphuric acid (Cook et al., 2004). Considering that pH levels are the neutral to alkaline range, and that pyrite oxidation controls high concentrations of SO_4, the calcaereous soils provide sufficient buffer capacities. This implies that there is a limited risk of developing acid sulphate soils through pyrite oxidation, which could impact plant growth by limiting nutrient availability and enhancing heavy metal toxicity (Bolan et al., 2001).

5.2 Crop residue management

Improving crop residue management is key to sustainably increase rice productivity with the aim to support livelihoods and maintain food security in southwestern Bangladesh. The benefits from crop residues regarding soil fertility reduce the demand for inorganic fertilizers and irrigation water, and ultimately increase rice productivity and economic profitability (Uddin & Fatema, 2016). The results from this study confirm the importance of crop residue management by significantly increasing rice productivity in all study locations.

Crop residues improve OM contents in the soil, thereby improving nutrient recycling of C, N, P, and K (Mandal et al., 2004; Zhang et al., 2008). However, in this study, N limitation is also recognized in replicates that have been grown on compost mixtures. This is most likely associated with poor N contents in the rice tissue, that will limit N supply from rice crop residues that are used for compost (Singh et al., 2005). Even though NO_3^- concentrations in the pore water were higher with compost, the findings of this study imply that additional N fertilization is required for optimal crop production. The increase in rice productivity is mainly associated with increasing concentrations of Si, P, and K in the pore water, and is observed by higher concentrations of P and K in the rice tissue. Additionally, crop residues decrease salinity levels, thereby reducing the impacts of salinity related ions on plant growth. The Si concentrations in the plant tissue are not measured. However, high levels of Si in the pore water suggest that this nutrient is present in the applied compost that presumably consists of rice crop residues. This is confirmed by the fact that rice plants benefit from Si nutrition and therefore accumulate Si in relatively high amounts (Rao & Susmitha, 2017). Silicon management increases rice yields by increasing nutrient availability (N, P, K, Ca, Mg, S, Zn), decreasing nutrient toxicity (Fe, Mn, P, Al), and minimizing biotic and abiotic stresses (Ma & Yamaji, 2008). This may partially explain why plant tissue concentrations of Fe and Mn are lower in the compost mixtures compared to the sediments. In addition, studies find that Si significantly improve rice growth, while limiting As uptake (Tripathi et al., 2013; Wu et al., 2016). The benefits from Si recycling imply the importance of rice crop residues to increase rice productivity (Marxen et al., 2016).

There are, however, several challenges regarding crop residue availability. First, crop residues often provide other purposes, including fuel, animal feed, bedding, biogas production, and industrial materials. Second, rice straw disposal from the fields is time intensive. Therefore, as a cost-effective solution, it is common that the fields are burned after harvest. This is directly associated with OM removal, and depletion of C, N, P, K and S in the soil (Singh, 2005). Improving awareness about the importance of crop residue management should be considered in all agricultural systems, but especially in fresh sediments with relatively low nutrient availability and high salinity.

5.3 Limitations and perspectives

The main limitations regarding this study are related to the experimental setup. Firstly, the conducted pot experiment is a great way to study rice productivity and nutrient availability. In this small environment, water levels and contamination are properly controlled, and pore water samples can be easily extracted. However, this small scale experiment can only give an indication of soil fertility in the field. Nutrient dynamics only represent a small fraction of the total study area, and rice growth is limited by the pot size. To improve significance in this study, more replicates can be made with a larger set of sediment samples from the study area. Therefore, a larger experimental basin and more pore water samples are required. Including more study locations would give a more detailed indication of the spatial variation in soil fertility throughout southwestern Bangladesh. Field experiments in the different study locations can also be suggested.

Secondly, this study gives a clear indication regarding rice productivity in terms of dry mass. However, the rice plants are harvested before reaching maturity. To study more inclusive yield components, a longer experiment should be conducted where the rice plants are fully grown. Thirdly, results should be compared to the best available control. There is a large difference between the non-cultivated fresh sediments and cultivated old sediments. The use of a different control from a non-cultivated area may provide different results. However, these sediments are hardly found in the field. Besides, the original sediments in the tidal basins have been cultivated prior to flooding, and are therefore likely to be similar to the sediments in nearby non-flooded paddy fields.

Fourthly, it was proposed to use Aman rice and mimic monsoon conditions in the rice growth experiment. However, seed germination failed due to different environmental conditions in the dry Rabi season and bad seed quality. By using the Boro BRRI 28 rice seedlings from Khulna University, rice seedlings are grown under the right seasonal conditions. The results are directly applicable to the productivity of this Boro variety, which is capable of surviving in saline conditions. However, different results will be retrieved when Aman or Aus rice varieties, or other cultivated vegetables, are used. In addition, seasonal variation of sediment deposition will constantly change the fertility status of the soil regarding the amount of deposited sediment, soil texture, and salinity. Including seasonal variability and other rice varieties would give a better perspective about seasonal and annual productivity. For example, when leaching of salt related ions lowers salinity during the monsoon season. This effect is inadequately studied with the washing treatments, and may be considered for new experiments.

Fifthly, and lastly, the results of this study mainly presents physical and chemical soil characteristics. The soil biological characteristics are not examined. The use of a broad spectrum pesticide eliminated the harmful and beneficial effects of biological fertility characteristics. Variation in productivity is often associated with microbial interactions, and may provide new information regarding soil fertility.

5.4 Future research

5.4.1 Sediment distribution

Even though the results indicate that tidal sediments do not improve soil fertility, proper sediment distribution is required to solve waterlogging problems and improve agricultural productivity. In general, most sediments are deposited in the frontal part of the tidal basin, restricting tidal flows to reach distant areas (Al Masud et al., 2018b). Local farmers near the inlet are therefore likely to experience more benefits compared to those in other areas. To support agricultural productivity throughout a tidal basin, appropriate measurements including canal management and rotation of inlets should be considered to avoid uneven sedimentation (Gain et al., 2017; Al Masud et al., 2018b). Model simulations can be used to identify the most effective ways to improve sediment transport and deposition inside a tidal basin. This may also be used to control flooding with saline water, thereby potentially reducing the impacts on soil salinity (Talchabhadel et al., 2018). Additionally, systematic rotation schemes are required to continuously control sediments between tidal basins and avoid river siltation on the long-term. This will ultimately improve the sustainability of sediment management strategies like TRM (Paul et al., 2013; Gain et al., 2017).

5.4.2 Arsenic contaminated soils

In Bangladesh, arsenic contaminated groundwater is a widespread problem that poses a threat to human health (Hugh Brammer & Ravenscroft, 2009). Dietary exposure of As is not restricted to drinking water (Williams et al., 2005). Arsenic accumulation in soils is directly related to irrigation with As contaminated groundwater, and increases dietary exposure through crop uptake (Williams et al., 2005). Rice is particularly susceptible for As uptake, and increasing concentrations in the soil consequently results in As accumulation in the rice grains (Meharg & Rahman, 2003; Williams et al., 2005; Rahman, et al., 2008; Hua et al., 2011). Beside posing a threat to human health, As contamination is posing a threat to sustainable agriculture (Hugh Brammer & Ravenscroft, 2009). Yield losses between 7.6-24% of harvested Boro rice are associated with As soil contamination (Huhmann et al., 2017). In this study, limited effects are observed regarding contamination of As in the pore water and plant tissues. However, sediment management may provide a potential solution for As contaminated soils. The field study from Huhmann et al. (2017) found that replacing the top 10 cm of an As contaminated soil with an uncontaminated soil temporarily improves crop yields. Similarly, tidal sediments may replace a contamined soil by adding a fresh uncontaminated top soil. This potentially increases yields, and provides new perspectives regarding health standards.

5.4.3 Sustainable nitrogen fertilization

Even though crop residue management is capable of significantly increasing soil fertility, N deficiencies still remain. This problem is globally recognized in rice soils and limits rice productivity. Therefore, N fertilizers, mainly in the form urea, are widely used to support crop productivity (Choudhury & Kennedy, 2004). However, the agricultural benefits gained by N fertilizers are directly associated with environmental and health impacts regarding excessive N availability in agricultural soils (Zhang et al., 2015). This is related to imbalanced and incorrect N application, together with poor timing of application (Singh, 2005). The resulting impacts include soil organic matter depletion, groundwater contamination and eutrophication through leaching of NH_4^+ and NO_3^-, and atmospheric pollution and greenhouse gas emission through N_2O and NH_3 production (Choudhury & Kennedy, 2004; Zhang et al., 2015). Nitrogen management is fundamental to reduce these impacts, and achieve sustainable development. Balanced nutrition is required, and can be maintained by improving the N supply and demand per cropping season, rice variety, and growth stage (Dobermann & Fairhurst, 2000). Increasing N use efficiency will increase rice productivity, reduce environmental impacts, and sustain soil fertility. Education and awareness programmes about the most sustainable and effective nutrients management practices should be considered to support local livelihoods in managed polder systems, and elsewhere (Mondal et al., 2013).

6. Conclusions

Dynamic polder management strategies are are required to sustainably enhance the livelihoods of people living in the southwestern coastal region of Bangladesh. Re-introducing tidal sedimentation inside polders will elevate the lands and provides new soils to promote agricultural productivity. This study examined if tidal sediments are capable of naturally improving soil fertility. The results find that fresh sediments do not improve soil fertility, and conclude that the general perception in literature about fresh sediments and soil fertility is incorrect. Rice productivity in fresh sediments from Beel Pakhimara and Polder 32 is significantly lower compared to old sediments. There are no significant differences between fresh and old sediments in Beel Khuksia. From the compost mixtures, where productivity is significantly higher compared to the sediments, it can be concluded that compost application is more important than the freshness of the sediments. The washing treatment is inadequately performed, and does not present clear results about the effects of leaching on soil fertility. The sediments are characterized by silty loams, low organic matter, and sufficient buffer capacities. Nitrogen availability is the main limiting nutrient in both sediments and compost mixtures. Phosphorus is the main controlling nutrient, and its availability is regulated by two biogeochemical processes. First, phosphate is mobilized by reducing iron complexes. Second, phosphate is mobilized by reducing sulphates. These processes are interacting, and depending on pyrite, iron-bound phosphorus, and iron oxyhydroxides contents in the sediment. Phosphorus availability is promoted by compost application, and is accompanied by increasing levels of silicon and potassium that both favour rice productivity. There are no clear indications about the effects of other micro nutrients on rice productivity. Additionally, the results indicate that salinity related impacts are limited. This implies that adoption of salinity tolerant rice varieties is essential to avoid crop failure in tidal basins, especially in the dry season. The effects of tidal sediments on soil fertility should be further explored by including seasonal variation and other rice varieties. Lastly, tidal sediments can improve agricultural production by increasing land availability that supports continuous crop cultivation. However, to optimize production, farmers are depending on their capacities to sufficiently manage nutrients with compost and nitrogen fertilizers in order to sustain their livelihoods.

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Appendix 1: Sample locations

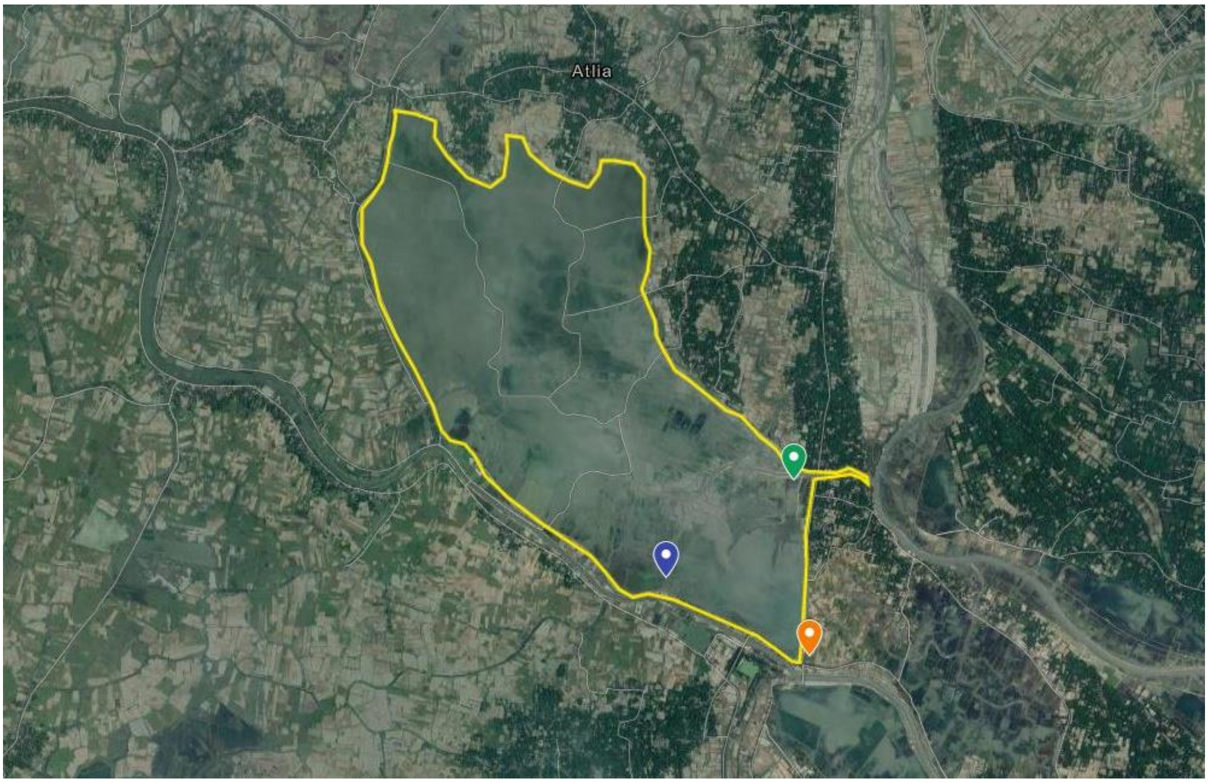

Figure A1.1 Sample sites in Beel Pakhimara, with inlet indicated in green, far indicated in blue, and control indicated in orange.

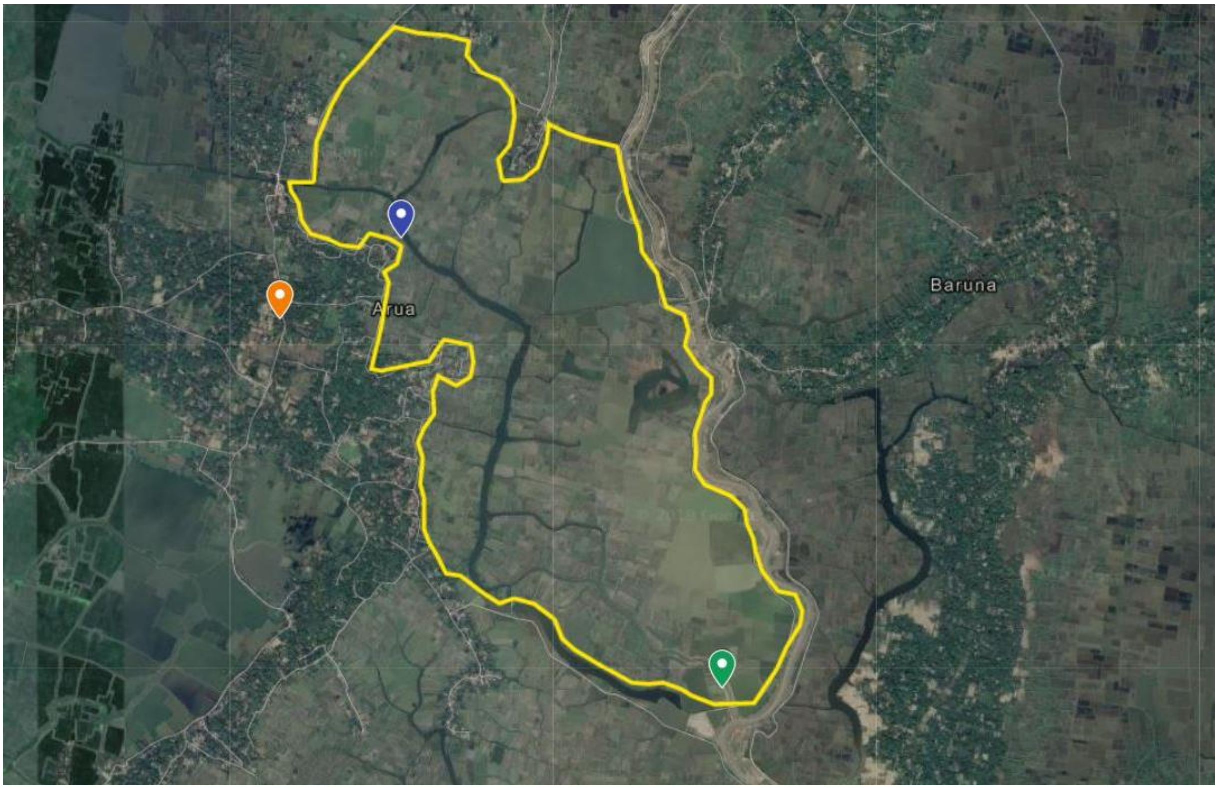

Figure A1.2 Sample sites in Beel Khuksia, with inlet indicated in green, far indicated in blue, and control indicated in orange.

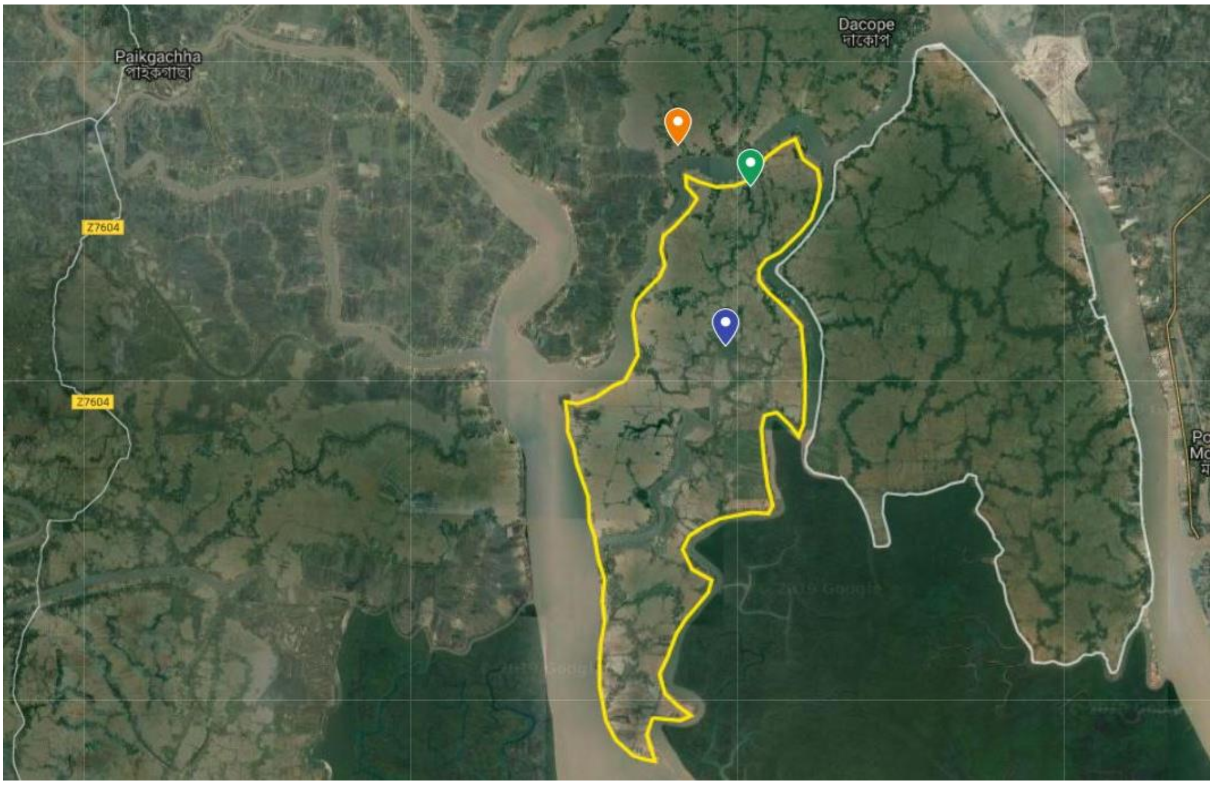

Figure A1.3 Sample sites in Polder 32, with inlet indicated in green, far indicated in blue, and control indicated in orange.

Appendix 2: Visual representation rice experiment

Figure A2.1 Sample collection in Polder 32 (left) and sun drying of sediments (right) (own work)

Figure A2.2 Preparation of basins (left) and applying pond water for irrigation (right) (own work)

Figure A2.3 Nursery bed at Khulna University (left) and transplanting rice (right) (own work)

Figure A2.4 Insects found in pots (left) and application of pesticide Nitro 505 EC (right) (own work)

Figure A2.5 Harvesting (left) and drying rice plants (right) (own work)

Appendix 3: Sediment composition

Table A3.1 Results of thermogravimetric analysis (TGA) indicating the weight loss (%) within each thermal range. The table includes the LOI (%) that is calculated by the weight loss between 105 - 550ºC, and is corrected by subtracting 0.07 times the clay fraction (Van Gaans et al., 2011).

Location	Sample weight (g)	105ºC	450ºC	550ºC	800ºC	1000ºC	LOI
PI	2.86	0.52	3.01	2.15	1.83	0.54	3.5
PF	2.90	0.27	2.55	1.53	2.01	0.40	2.7
PC	2.95	0.43	4.45	1.71	1.38	0.43	5.2
KI	2.94	0.29	2.78	1.49	2.58	0.52	3.5
KF	2.94	0.23	1.89	1.21	2.58	0.44	2.2
KC	2.98	0.22	2.61	0.69	3.54	0.25	2.6
32I	2.86	0.28	2.01	1.05	1.22	0.31	2.4
32F	2.82	0.53	7.03	1.26	1.08	0.41	7.5
32C	2.88	0.54	3.53	1.49	1.24	0.41	3.7
N	2.88	0.63	5.69	1.55	1.52	0.47	6.3

Table A3.2 Soil EC (mS cm^{-1}) and pH results from the tidal sediments (a) and compost mixtures (b), measured on day 4 (1), day 25 (2), and day 43 (3) of the rice growth experiment. The study locations are indicated with letters, where IW and FW imply the washing treatments.

a		Pakhimara			Khuksia			Polder 32				
		I	F	C	I	F	C	I	F	C	IW	FW
pH	1	7.43	7.45	7.62	7.12	7.32	7.43	7.58	7.29	6.60	7.49	7.54
	2	7.78	7.44	7.53	7.69	7.79	7.28	7.42	7.54	6.22	7.36	7.86
	3	7.82	7.83	7.73	7.48	7.72	7.35	7.54	7.63	6.77	7.37	7.87
EC	1	6.74	3.94	2.64	6.87	6.73	1.70	3.95	6.43	6.23	3.75	4.09
	2	5.50	3.63	2.99	6.08	5.54	2.75	3.16	5.99	4.58	3.89	4.11
	3	3.88	3.12	2.56	4.27	3.75	2.40	2.57	4.17	4.43	3.01	3.46

b		Pakhimara			Khuksia			Polder 32				
		I	F	C	I	F	C	I	F	C	IW	FW
pH	1	7.7	7.34	7.6	7.55	7.51	7.51	7.41	7.69	7.39	7.53	7.54
	2	8.02	7.58	7.48	7.74	7.76	7.5	7.42	7.87	7.55	7.61	7.86
	3	7.71	8.04	7.71	7.89	7.62	7.94	7.55	7.66	7.67	7.47	7.87
EC	1	2	3.05	2.54	4.27	5.73	2.5	3.59	2.93	2.78	2.87	2.58
	2	2.96	3.87	3.02	3.9	4.62	2.89	3.64	3.08	3.38	3.53	3.34
	3	3.15	3.95	2.46	3.39	3.89	3.42	2.83	2.87	2.73	3.24	2.31

Table A3.3 Sediment composition of the collected sediments (Inlet, Far, and Control) from Beel Pakhimara, Beel Khuksia, Polder 32, and the nursery bed. P and Fe fractions are indicated in mg kg^{-1}. Total P and Total Fe are calculated by the sum of all fractions excluding Ferrihydrite, which overlaps in the extraction procedures employed with Easily reduced Fe oxides. Total N, S, and C are presented in mass %. The na signifies "not analysed".

	Pakhimara			Khuksia			Polder 32			Nursery bed
	I	F	C	I	F	C	I	F	C	
P: Exchangeable-P	16	6	5	8	6	7	3	8	6	4
P: Fe-P	105	117	104	115	112	112	96	113	127	119
P: Ca-P	98	94	107	91	81	98	61	64	86	87
P: Inorganic-P	207	222	225	340	281	292	212	na	146	na
P: Organic-P	45	44	96	57	25	45	43	60	57	127
Total P	470	484	536	611	504	554	415	244	422	337
Fe: Ferrihydrite	1907	2128	3470	3073	3107	1311	2098	3512	5445	3844
Fe: Exchangeable-Fe	69	107	0	149	68	0	84	138	69	89
Fe: Easily reducible oxides	3747	3898	4048	4043	5528	3274	1686	2814	5870	5158
Fe: Carbonates and FeS	2299	1162	3686	4739	1902	615	4377	4780	1878	1560
Fe: Organic-Fe	1191	1162	1084	895	1008	754	836	1049	1259	1142
Fe: Crystalline oxides	59	57	56	62	65	53	32	74	88	84
Fe: Pyrite	5346	4237	5304	3840	3691	3487	3423	4423	3206	4285
Total Fe	12710	10623	14177	13728	12262	8182	10438	13279	12370	12317
Total N	0.07	0.09	0.21	0.11	0,06	0.10	0.07	0.24	0.12	0.23
Total S	0.15	0.04	0.17	0.11	0.04	0.05	0.11	0.22	0.09	0.20
Total C	1.58	1.67	2.74	2.18	1.70	2.65	1.53	4.91	1.77	2.98

Table A3.4 Bioavailable nutrient contents in mg kg^{-1} following 0.01 *M* $CaCl_2$ extraction for the sediments from each study location.

	Fe	K	Mg	Mn	Na	S	Si
PI	0.01	0	152	0.00	603	95	1.80
PF	0.00	0	67	0.00	100	14	1.39
PC	0.00	0	84	0.17	172	83	0.40
KI	0.00	0	68	0.03	167	31	0.99
KF	0.00	0	45	0.00	107	6	1.06
KC	0.00	0	18	0.00	14	1	1.30
32I	0.00	0	49	0.44	99	24	0.47
32F	0.00	0	92	0.29	316	48	1.02
32C	0.01	0	72	1.26	81	33	2.75
N	0.00	0	100	0.01	342	134	0.68

Appendix 4: Results rice growth experiment

Table A4.1 Plant results from the rice growth experiment indicating the means and standard deviation of height (cm), tiller number, shoot dry mass (g), root dry mass (g), and total dry mass calculated by the sum of roots and shoots (g) of the harvested rice for al study locations with tidal sediments (-) and compost mixtures (+).

	Height (cm)	S.D.	Tillers (nr.)	S.D.	Shoot (g)	S.D.	Root (g)	S.D.	Root + shoot (g)	S.D.
PI-	33.1	3.9	2.4	0.9	0.48	0.3	0.45	0.2	0.93	0.5
PF-	43.5	7.3	6.6	5.1	1.48	1.6	0.94	1.3	2.42	2.9
PC-	43	4.5	8.8	4.2	2.15	1.3	1.48	1.1	3.64	2.4
KI-	40.6	7.6	7.2	2.2	1.39	0.9	0.86	0.7	2.25	1.5
KF-	40.4	5.0	6.00	2.6	1.14	1.4	0.68	0.9	1.82	2.2
KC-	39.6	2.2	3.4	1.1	1.01	0.8	0.74	0.6	1.74	1.3
32I-	40.6	0.9	5.6	0.9	1.25	0.1	0.88	0.1	2.12	0.2
32F-	39.6	3.4	4.8	1.8	0.97	0.7	0.77	0.3	1.74	1.1
32C-	44.3	3.7	9.0	1.5	1.96	0.6	1.26	0.4	3.22	0.9
32IW-	41.2	4.0	4.6	1.5	1.39	0.6	0.88	0.2	2.27	0.8
32FW-	39.3	6.6	3.8	2.1	0.96	1.0	0.69	0.5	1.65	1.5
PI+	42	6.2	11.4	4.2	2.98	1.3	2.32	1.1	5.30	2.5
PF+	45.1	7.2	11.2	4.8	2.82	1.6	1.44	1.2	4.27	2.8
PC+	44.6	2.1	9.0	1.5	2.75	0.4	1.59	0.5	4.34	1.0
KI+	47.9	4.9	9.8	2.4	2.95	1.2	1.53	0.8	4.49	2.0
KF+	43.5	5.2	7.6	2.4	1.96	1.3	1.27	0.9	3.23	2.2
KC+	46.5	1.6	7.2	1.1	2.33	0.8	1.55	0.6	3.88	1.4
32I+	48.6	3.0	9.0	1.7	2.61	0.6	1.53	0.3	4.15	0.9
32F+	47.6	3.9	9.2	1.6	2.54	0.7	1.77	0.3	4.31	0.9
32C+	45.9	2.3	11.8	0.7	3.88	0.2	2.12	0.2	6.00	0.2
32IW+	49.3	6.6	8.0	2.4	2.70	1.0	1.36	0.5	4.06	1.5
32FW+	48.4	5.9	9.0	1.5	2.86	1.0	2.07	0.4	4.93	1.3

Appendix 5: Plant tissue composition

Table A5.1 Plant tissue composition results from the plant mixtures, based on total reflection X-ray fluorescence (mg kg^{-1}) and elemental CN analyser (mass %). The results are presented per study location with tidal sediments (-) and compost mixtures (+) for both shoot and root tissues.

Plant tissue	Study location	Sediment – Compost +	P	S	Cl	K	Ca	Mn	Fe	Zn	As	%N	%C
Shoot	PI	-	1537	1820	12678	13873	1644	309	386	17	2	1.41	37.4
	PF	-	1775	1224	5691	16384	1091	315	370	22	3	1.21	38.1
	PC	-	2314	1186	7050	21398	1130	135	662	15	6	1.50	39.0
	KI	-	3190	2216	10332	25582	1888	282	1128	22	7	2.67	38.8
	KF	-	1630	1678	8035	19847	1591	407	625	22	2	1.81	38.6
	KC	-	2530	1303	5319	15914	2165	342	397	20	2	1.32	38.6
	32I	-	2532	1556	5943	22227	1709	249	1018	15	3	1.20	38.1
	32F	-	2315	1814	7308	20574	1184	132	857	14	3	1.32	38.3
	32C	-	2925	2091	7953	23475	1476	320	1267	23	2	1.67	39.0
	32IW	-	2373	1513	5493	19798	1405	223	891	15	3	1.08	38.9
	32FW	-	2418	1920	7510	21604	1583	179	608	16	3	1.14	39.6
	PI	+	2551	980	7127	24865	864	104	430	13	3	1.43	37.5
	PF	+	2403	1479	8429	27552	1507	75	479	14	7	1.85	38.3
	PC	+	2021	852	7300	23024	965	62	567	12	1	1.32	37.8
	KI	+	2570	1172	8112	30807	1021	70	253	18	1	1.76	37.5
	KF	+	2020	1326	6702	23734	1195	135	766	13	5	1.58	38.8
	KC	+	2847	992	5952	24554	1731	101	598	13	1	1.43	38.3
	32I	+	2855	1039	7252	28580	1181	70	628	11	1	1.43	37.4
	32F	+	2991	1238	7091	28396	1259	85	719	21	2	1.39	38.1
	32C	+	2602	912	6578	26541	962	62	655	15	2	1.31	38.3
	32IW	+	2764	1056	6796	26855	1275	88	583	11	1	1.34	39.0
	32FW	+	2975	1273	7591	29491	1449	79	518	15	1	1.41	39.7
Root	PI	-	1158	4603	5454	7018	3854	335	13664	24	37	0.84	40.0
	PF	-	1021	3197	2500	5223	2525	254	10439	24	58	0.65	42.1
	PC	-	1683	2295	3837	6669	2776	217	16393	16	95	0.71	41.8
	KI	-	4710	11205	14049	16813	6466	719	41421	48	163	1.13	40.0
	KF	-	961	3356	5036	6961	1987	375	10476	22	24	0.88	43.4
	KC	-	1668	2533	4297	5927	4190	236	8881	16	31	0.67	42.9
	32I	-	1614	3623	2857	8126	2876	283	21245	14	50	0.72	41.7
	32F	-	1705	5105	4211	8502	2436	192	18947	12	55	0.73	42.0
	32C	-	1510	5550	7597	13024	1504	279	24129	19	29	0.88	40.5
	32IW	-	1244	3813	2306	6155	2219	192	19673	14	42	0.55	43.2
	32FW	-	1156	3839	2453	5631	2457	137	13989	17	48	0.56	44.1
	PI	+	4453	2537	4516	11933	4459	378	9631	22	24	0.68	42.3
	PF	+	3202	1906	2546	6965	3870	211	6972	15	58	0.85	41.0
	PC	+	2911	2110	3211	6697	3281	165	7090	11	9	0.71	43.3
	KI	+	3884	3071	6457	14634	3527	218	7528	20	14	0.84	40.9
	KF	+	2967	2411	5830	10673	3054	410	9856	9	63	0.76	42.2
	KC	+	3392	2013	4013	7077	4689	310	6357	5	5	0.70	42.1
	32I	+	3639	3357	4807	13217	3725	218	7912	7	4	0.71	42.0
	32F	+	3539	3878	5745	15651	3681	239	8369	16	9	0.77	41.0
	32C	+	2613	2191	4055	9783	2440	129	7711	15	14	0.66	42.1
	32IW	+	3717	2838	3777	9373	3838	183	8115	13	5	0.67	43.2
	32FW	+	3275	2809	3924	10109	3410	197	7217	17	6	0.66	43.9

Table A5.2 Plant tissue composition results from individually measured replicates, based on Total reflection X-ray fluorescence (mg kg^{-1}) and elemental CN analyser (mass %). The results include all replicates from the shoots of KI- and PF+, and roots of PC- and 32C+. The mean and standard deviation are compared to the results from the plant mixtures that are presented in Table A6.1.

Plant tissue	Study location	Sediment – Compost +	P	S	Cl	K	Ca	Mn	Fe	Zn	As
Shoot	KI1	-	4335	2666	9354	24282	2247	339	1374	25	8
	KI2	-	3394	1528	7977	24760	1168	245	762	17	5
	KI3	-	2754	1425	6823	15495	1044	219	529	12	4
	KI4	-	5071	3304	12586	33324	2399	321	2150	26	8
	KI5	-	2018	1138	7007	16680	1203	231	401	0	0
	Mean		3515	2012	8749	22908	1612	271	1043	16	5
	S.D.		1217	927	2368	7204	654	55	723	11	3
	Plant mixture		3190	2216	10332	25582	1888	282	1128	22	7
	PF1	+	2241	1212	5461	19613	815	332	305	20	0
	PF2	+	2187	885	6324	17514	490	188	313	15	0
	PF3	+	2044	1003	6545	15124	719	217	279	15	0
	PF4	+	2690	1243	7478	20032	371	280	273	20	0
	PF5	+	1854	1323	5925	13701	1167	333	300	17	0
	Mean		2203	1133	6346	17197	712	270	294	17	0
	S.D.		311	182	755	2761	309	66	17	2	0
	Plant mixture		2403	1479	8429	27552	1507	75	479	14	7
Root	PC1	-	1478	2651	7501	10430	2393	211	14219	18	81
	PC2	-	1718	2564	5560	8244	2124	209	15671	16	82
	PC3	-	741	1346	2045	5010	2757	205	15933	13	104
	PC4	-	1291	2155	2593	5202	3306	209	15556	15	89
	PC5	-	2008	2338	3702	6834	2929	231	17126	15	104
	Mean		1447	2211	4280	7144	2702	213	15701	16	92
	S.D.		477	521	2246	2260	461	10	1037	2	11
	Plant mixture		1683	2295	3837	6669	2776	217	16393	16	95
	32C1	+	3193	1936	3992	10145	3054	152	9954	14	17
	32C2	+	3024	2361	4113	10243	2823	159	9748	16	17
	32C3	+	2340	2960	6298	13439	2129	104	5899	15	13
	32C4	+	2311	2114	3745	8626	2464	130	6758	15	13
	32C5	+	2243	2598	4977	10802	2344	135	7095	17	14
	Mean		2622	2394	4625	10651	2563	136	7891	15	15
	S.D.		449	404	1044	1755	372	21	1843	1	2
	Plant mixture		2613	2191	4055	9783	2440	129	7711	15	14

Appendix 6: Pore water composition

Table A6.1 Electroconductivity (mS cm^{-1}) and nutrient concentrations from IC (mg L^{-1}) and ICP-OES (mg kg^{-1}) of the additional pond water used for irrigation. Pond water is used five times during the experiment, and is represented by the numbers 1 – 5. Results noted with * represent values with an error of analysis > 10%, and are indicative.

Analysis	**Data**	**1**	**2**	**3**	**4**	**5**
EC	Salinity	1.3	1.1	1.4	1.3	1.5
IC	F^-	0.2	0.2	0.2	0.2	0.2
	Cl^-	277	232	237	249	411
	Br^-	0.9	0.8	0.8	0.8	1.4
	NO_3^-	5.8	3.3	2.9	5.7	1.6
	SO_4^{2-}	38	12	12	14	47
ICP-OES	Ca	45	37	39	38	48
	Fe	0.004	0.001*	0.004	0.000*	0.002*
	K	16	10	10	10	11
	Mg	35	28	29	29	40
	Mn	0.000*	0.010	0.003	0.005	0.008
	Na	272	239	255	262	323
	P	0.769	0.006*	0.049*	0.111	0.138
	S	13	4.5	4.5	4.7	16.7
	Si	5.3	5.4	7.2	7.8	6.5

Table A6.2 Pore water results from colorimetrics (mg L^{-1}), IC (mg L^{-1}), and ICP-OES (mg kg^{-1}). Pore water samples are taken three times during the rice growth experiment (Samples 1-3) from the tidal sediments (-) and compost mixtures (+) for each study location. Results noted with * represent values with an error of analysis > 10%, and are indicative.

			Colorimetric		IC							ICP-OES									
Sample	Location	Compost	NH_4^+	PO_4^{3-}	F^-	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{3-}	SO_4^{2-}	Ca	Fe	K	Mg	Mn	Na	P	S	Si	HCO_3
1	PI	-	0.44	1.14	0.64	5710	1.3	20.1	<0.06	<0.6	1440	455	0.0*	56	381	0.8	2769	1.6	508*	4	-935
	PF	-	0.78	1.12	0.37	1140	5.6	4.2	0.4	0.84	284	100	0.0*	21	110	0.0	714	0.2	98	4	448
	PC	-	0.90	1.11	0.52	383	<0.008	1.5	10.1	<0.6	235	73	0.9	15	66	0.4	429	0.1	83	3	746
	KI	-	2.77	0.82	0.48	3990	21	13.4	1.5	<0.6	1320	324	0.8	51	363	3.4*	2070	0.0*	456	4	-184
	KF	-	1.96	0.71	0.50	3320	15	10.8	0.2	<0.6	518	268	0.0	35	246	1.3	1728	0.0	185	3	301
	KC	-	0.26	1.05	0.54	257	<0.008	0.8	1.2	<0.6	31	97	0.0*	4	30	0.0	201	0.0*	11	5	497
	32I	-	1.49	1.20	0.31	758	<0.008	2.6	17.9	<0.6	547	136	1.0	22	106	1.2	609	0.2	189	5	583
	32F	-	1.51	1.25	0.34	2180	<0.07	7.7	18.5	0.6	932	140	0.1	56	212	0.0	1409	0.2	314	5	360
	32C	-	1.11	1.04	0.08	1840	<0.07	5.7	9.7	<4	1580	344	6.0*	35	283	20.8*	1037	0.0*	556*	7	147
	32IW	-	1.04	1.31	0.27	686	<0.008	2.4	10.2	<0.6	539	149	1.0	22	112	0.6	525	0.0*	188	5	568
	32FW	-	0.58	1.30	0.38	874	<0.008	3.2	7.3	1.11	415	52	0.4	32	80	0.2	781	0.3	144	5	640
	PI	+	0.74	4.30	0.33	416	<0.07	1.4	12.3	66.10	73	49	0.3	47	60	0.3	480	23.2*	28	25*	971
	PF	+	1.07	3.26	0.27	743	0.0434	2.4	16.4	35.80	150	83	0.0	63	111	0.0	518	11.9*	53	20*	792
	PC	+	1.38	3.76	0.52	409	<0.008	1.9	18.7	41.6	79	76	0.8	43	80	0.4	399	16.2*	28	27*	933
	KI	+	1.63	3.56	0.42	954	<0.008	3.1	26.9	43.4	273	86	0.8	87	136	0.3	734	15.5*	96	27*	1009
	KF	+	1.43	3.22	0.41	1559	<0.008	4.5	20.8	27.7	327	147	0.2	106	180	1.8	1004	10.7*	118	30*	1060
	KC	+	0.61	3.87	0.35	383	<0.008	0.9	4.7	22	71	140	0.0	26	89	0.1	316	8.5	27	35*	993
	32I	+	1.68	3.60	0.27	616	<0.008	2.0	27.2	40	354	100	0.8	93	121	0.3	531	15.8*	125	28*	928
	32F	+	1.61	4.72	0.29	538	<0.008	1.9	23.6	73.1	159	47	0.8	92	77	0.1	555	22.6*	58	26*	990
	32C	+	1.36	6.27	0.18	353	<0.008	1.3	10.3	<0.6	241	76	0.5	77	97	0.6	403	25.8*	86	27*	979
	32IW	+	1.37	3.38	0.24	477	<0.008	1.8	20.3	35.1	160	87	0.7	46	105	0.2	387	12.1*	56	25*	845
	32FW	+	1.54	5.31	0.23	462	<0.008	1.7	19.9	>80.3	84	48	0.5	83	88	0.1	450	25.3*	31	31*	986
2	PI	-	0.16	1.51	0.49	1460	<0.008	5.1	<0.06	0.7	403	98	0.0	23	122	0.0	1189	0.1	145	6	1070
	PF	-	0.10	2.23	0.28	892	<0.008	3.3	<0.06	<0.6	248	92	0.0	21	119	0.0	708	0.0*	88	5	931
	PC	-	1.16	1.33	0.58	583	5.3	2.3	0.1	<0.6	23	77	0.9	16	87	0.1	497	0.0*	9	3	977
	KI	-	2.80	2.60	0.58	1750	0.5	5.9	0.08	<0.6	674	104	0.0	31	218	0.0	1260	0.0*	242	7	934
	KF	-	1.16	1.37	0.40	1470	0.0	5.1	<0.06	<0.6	314	99	0.0	24	130	0.1	1041	0.0*	115	5	820
	KC	-	0.17	1.89	0.33	441	<0.008	1.6	<0.06	<0.6	4	161	0.3	2*	53	0.1	319	0.0*	2	9	840
	32I	-	0.79	1.67	0.37	510	<0.008	1.8	2.3	<0.6	282	122	7.8*	19	97	1.1	529	0.2	101	7	1068
	32F	-	1.12	1.79	0.47	1290	2.7	4.6	1.8	<0.6	1160	156	3.5*	47	217	0.2	1220	0.1	408	8	1180
	32C	-	1.59	0.88	0.19	1150	0.0849	4.0	0.1	<0.6	1760	315	2.8*	26	255	8.2*	884	0.0*	630*	4	437
	32IW	-	0.26	1.36	0.24	625	<0.008	2.4	<0.06	<0.6	429	113	1.8	18	137	0.2	592	0.0*	154	5	1010
	32FW	-	0.24	1.67	0.49	642	<0.008	2.6	<0.06	<0.6	582	84	2.1*	32	129	0.3	849	0.2	211	6	1360
	PI	+	0.31	5.07	0.26	671	2.1	2.7	2.5	24.7	7	132	0.3	87	170	0.6	626	10.3*	5	51*	1870
	PF	+	0.71	6.02	0.28	796	<0.008	2.8	27.9	19.9	28	155	4.6*	85	194	0.6	688	11.6*	13	42*	1967
	PC	+	0.47	3.52	0.55	673	<0.008	2.6	1.0	12.3	10	167	2.2	42	144	0.2	568	5.7	5	48*	1629
	KI	+	0.67	3.58	0.44	589	0.6	2.2	4.3	19.5	15	126	4.9*	71	154	1.3	661	9.8	8	45*	1986
	KF	+	0.50	3.41	0.57	778	1.7	3.1	2.9	4.02	17	163	6.6*	69	191	0.9	802	4.3	11	40*	2332
	KC	+	0.38	4.58	0.37	527	1.0	1.9	4.3	7.84	5	281	4.3*	20	146	1.2	439	12.0*	6	53*	1866
	32I	+	0.71	4.34	0.25	547	0.1	2.1	5.2	22.0	26	130	5.5*	80	135	0.5	533	14.9*	11	45*	1639
	32F	+	1.63	5.54	0.24	493	<0.008	2.0	22.5	62.4	12	84	3.5*	97	143	0.2	596	25.2*	8	51*	1822
	32C	+	0.42	3.27	0.36	501	<0.008	2.0	2.5	4.75	26	142	11.4*	63	139	0.5	480	6.1	11	39*	1623
	32IW	+	0.83	3.98	0.23	560	4.5	2.2	1.0	21.6	28	151	3.1*	46	157	0.6	510	11.9*	11	43*	1666
	32FW	+	1.57	4.67	0.20	512	<0.008	2.0	17.7	38.8	28	96	2.2*	78	148	0.2	543	18.9*	12	42*	1009

3	PI	-	0.12	3.49	0.51	636	<0.008	2.4	<0.06	0.6	133	53	0.2	17	64	0.4	751	0.1	48	7	1231
	PF	-	0.11	2.97	0.26	548	<0.008	2.0	<0.06	<0.6	152	72	0.9	17	91	0.7	547	0.1	55	6	1016
	PC	-	0.19	2.59	0.51	431	<0.008	1.7	<0.06	<0.6	9	78	0.2	13	81	0.0	420	0.0*	4	3	1022
	KI	-	0.82	4.01	0.72	894	7.7	3.2	0	<0.6	180	100	0.7	21	130	1.5	839	0.1	65	10	1435
	KF	-	0.59	2.17	0.49	696	0.0	2.7	<0.06	<0.6	186	69	1.4	17	85	0.9	743	0.0*	68	6	1201
	KC	-	0.10	3.07	0.44	363	<0.008	1.4	<0.06	<0.6	2	168	0.8	2*	41	0.9	321	0.1*	2	9	940
	32I	-	0.16	3.20	0.37	366	<0.008	1.4	<0.06	<0.6	86	87	1.4	14	76	0.7	422	0.0*	32	6	1045
	32F	-	0.21	3.96	0.51	522	<0.008	2.1	<0.06	<0.6	472	81	2.3*	30	116	0.6	700	0.2	171	10	1228
	32C	-	0.40	2.26	0.26	642	0.0	2.5	<0.06	<0.6	1110	191	35.4*	16	164	11.5*	637	0.0*	396	5	703
	32IW	-	0.17	2.69	0.31	457	<0.008	1.8	<0.06	<0.6	92	91	1.9	13	101	0.1	483	0.0*	33	5	1182
	32FW	-	0.12	3.50	0.51	401	<0.008	1.8	<0.06	<0.6	314	71	4.3*	29	106	1.2	649	0.3	117	7	1431
	PI	+	0.12	5.76	0.27	459	<0.008	1.8	<0.06	26.6	2	124	1.9	61	134	1.3	461	16.4*	2	59*	1574
	PF	+	0.15	5.31	0.27	612	<0.008	2.3	<0.06	13.3	8	159	3.8*	75	178	1.8	599	7.6	7	49*	2020
	PC	+	0.10	5.00	0.51	502	<0.008	2.0	<0.06	16.6	7	144	3.3*	29	115	0.9	487	8.6	4	50*	1479
	KI	+	0.12	5.57	0.43	478	<0.008	1.9	<0.06	20.8	4	125	2.3*	55	138	1.1	541	8.7	5	51*	1759
	KF	+	0.13	4.66	0.49	472	<0.008	2.2	<0.06	0.9	2	154	6.9*	54	182	2.6*	610	2.4	6	52*	2280
	KC	+	0.10	5.12	0.43	524	<0.008	2.0	<0.06	8.3	1	258	0.6	13	133	1.5	465	7.9	5	59*	1795
	32I	+	0.13	5.66	0.24	416	<0.008	1.6	<0.06	22.1	11	121	2.5*	52	119	0.6	467	13.5*	7	48*	1551
	32F	+	0.11	6.19	0.22	364	<0.008	1.5	<0.06	48.9	8	90	2.2*	58	135	0.5	439	21.6*	6	53*	1561
	32C	+	0.18	4.99	0.41	365	<0.008	1.5	<0.06	7.1	6	132	9.3*	44	119	0.8	402	6.3	5	51*	1508
	32IW	+	0.11	5.22	0.20	474	<0.008	1.9	<0.06	21.7	2	161	2.0*	34	151	0.7	475	14.2	4	57*	1739
	32FW	+	0.13	5.67	0.17	359	<0.008	1.4	<0.06	35.9	14	90	1.8*	41	122	0.4	382	21.1	7	46*	1322