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Sediment properties in flood-based farming systems in the Vietnamese upstream Mekong Delta

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ABSTRACT

The Mekong Delta is a flood-based agricultural landscape the agricultural productivity of which strongly depends on sediment deposition. This study aimed to evaluate the quantity and quality of flood-borne sediments across three areas in Tinh Bien district, An Giang province, including upstream, behind the Melaleuca forest, and downstream. This study compared the quantity and quality of sediments deposited in the fields with flood-based farming models: ratoon rice with natural fish storage (RR-NFS), ratoon rice with fish farming (RR-FF), and lotus with fish farming (L-FF); whereas natural flood fields (NF) were used as control fields. Field sampling was conducted from September to November 2024 (within 78 days). The deposited sediments were collected using net sediment traps. The sediments were analyzed for mass and quality parameters, including texture, pH, electrical conductivity (EC), organic matter (OM), total nitrogen (TN), ammonium (NH_4^+-N), nitrate (NO_3^-N), total phosphorus (TP), available phosphorus (P_2O_5), and total and exchangeable potassium (TK and K_2O). Results showed that sediment deposition was highest at upstream (5.81 ± 1.70 g/m²×d), moderate at downstream (4.34 ± 0.76 g/m²×d), and lowest at behind the Melaleuca forest (3.55 ± 0.28 g/m²×d). The level of sediment deposition in fields of flood-based farming models was significantly lower than that in natural floodplain fields. Sediments were consistently classified as clay loam, dominated by clay (~60%), moderate silt (~33%), and low sand (<10%). Chemical properties indicated slightly acidic pH (5.5 ± 0.2), low EC (0.17 ± 0.11 mS/cm), and high organic carbon (9.57 ± 1.09%), with no significant area differences. Nitrogen contents were moderate (TN = 0.351 ± 0.043%; NH_4^+-N = 21.27 ± 13.48 mg/kg; NO_3^--N = 49.76 ± 17.65 mg/kg), phosphorus was low (TP = 0.021 ± 0.007%; P_2O_5 = 0.449 ± 0.383 mg/kg), while potassium was abundant (TK = 3.77 ± 0.16%; K_2O = 788.9 ± 240.5 mg/kg). The nitrogen, phosphorus, and potassium levels in integrated systems (RR-FF, L-FF) tended to be higher than those in natural floodplain fields. These findings demonstrate that seasonal floods continue to deliver nutrient-rich sediments, especially potassium and organic matter, but declining sediment loads and consistently low phosphorus threaten long-term soil fertility. Integrated farming models provide additional nitrogen and potassium inputs, yet careful management is needed to avoid nutrient imbalance. The study highlights the importance of maintaining flood connectivity as a nature-based solution for sustaining soil fertility and resilient livelihoods in the Mekong Delta.

Keywords: flood-based farming, Mekong Delta, natural-based solution, nutrients, sediment deposition.

INTRODUCTION

The Mekong Delta is recognized as one of Southeast Asia's largest and most fertile sediment plains [Phong et al., 2010], shaped and sustained over time by the continuous deposition of sediments from the Mekong River. Located at the upstream gateway of the Delta, the An Giang province plays a pivotal role in receiving floodwaters, sediment, and nutrient inflows as the Mekong enters Vietnam. The annual flood season, typically occurring from July to November, delivers vast volumes of water, suspended sediments, nutrients, and plankton [Dan and Giao, 2021; Ngoc et al., 2020], which are essential for soil enrichment, ecological regeneration, and supporting traditional agricultural practices. In recent decades, the flood regime in the An Giang province–located at the upstream of the Mekong Delta–has undergone significant changes, showing a clear decline in frequency, intensity, and duration. This shift is largely attributed to the expansion of upstream hydropower projects, changes in land use, and the intensifying effects of climate change [Lu and Siew, 2006]. In the upstream region, Manh et al. (2014) highlighted that hydropower development is the dominant driver of changes in sediment dynamics across the Mekong Delta floodplains.

Further downstream, the An Giang province in the Long Xuyen Quadrangle has been transformed over the past decades into highly productive agricultural land, supported by extensive flood-prevention infrastructure including over 13,000 km of dykes and embankment [Nguyen et al., 2019]. While these structures have brought notable economic benefits and reshaped the rural landscape, they have also led to unintended consequences. Studies suggest that the flood-control dyke system may hinder the natural replenishment of sediments, resulting in soil degradation, increased pest outbreaks, and declining crop productivity [Eslami et al., 2019; Ludwig et al., 2019; Tran et al., 2018; Chapin and Renaud, 2016]. The decline in sediment input, along with the loss of associated nutrients, poses a serious threat to agricultural productivity, ecosystem functioning, and regional economic development [Chapman et al., 2016]. Agricultural input costs are expected to rise due to the need to compensate for this sediment loss. While modern agricultural innovations may offer alternative sources of nutrition, their overall impact on ecological health of the delta remains poorly understood and is still being studied. As a result, the diminished role of natural flooding not only undermines the ecological function of sediment deposition, but also challenges the sustainability of traditional agricultural systems and local livelihoods.

In response to the increasing variability and decline in seasonal flooding, several flood-based livelihood models have been introduced and piloted in the An Giang province to harness the ecological and economic values associated with the flood season. These flood-based livelihood models, such as ratoon rice with natural fish storage or fish farming and lotus with fish farming; aim to capitalize on floodwater and sediment inputs to restore soil fertility, diversify income sources, and enhance the resilience of local communities. In 2024, these models have been implemented across over 120 hectares in the buffer zones of the Tra Su Wetland Reserve and surrounding areas [VietnamPlus, 2024]. Sediments play a fundamental role in shaping landscape of the Mekong Delta and supporting ecological productivity. Rich in organic matter and essential nutrients (e.g., nitrogen, phosphorus, potassium, and micronutrients), flood-borne sediments contribute to improved soil structure, enhanced water retention, and sustained agricultural output. Previous research has demonstrated that the sediments in the upstream Mekong region – particularly in An Giang–exhibit favorable physical and chemical characteristics, including high clay content and nutrient richness, making them particularly beneficial for agroecological practices [Dan and Giao, 2021; Ngoc et al., 2020]. The amount of sediment deposited was found to decline as the distance from the main river channels increased. In a single flood event in 2018, the total volume of sediment delivered to the floodplain was estimated at approximately 5.023 million tons, averaging 14.04 kilograms per square meter [Thi et al., 2020]. However, effective utilization of this resource requires area-specific assessments of sediment quality and composition within each flood-based farming model.

Although several studies have explored sediment dynamics in some areas of the Mekong Delta [Dan and Giao, 2021; Thi et al., 2020; Chapman et al., 2016], there remains a critical gap in systematic and comparative analyses of sediment characteristics across different flood-based livelihood models in An Giang, especially in recently piloted areas. This study aimed to bridge that gap by analyzing and comparing amount and the physical and chemical properties of floodplain sediments across selected livelihood models. The findings are expected to provide the information on the ecological potential and soil improvement capacity of each model, contributing scientific evidence to support the upscaling of sustainable, climate-resilient farming systems in the Mekong Delta amid ongoing sediment decline and climate change impacts.

METHODS

Research areas and flood-based farming models

The research areas are located in a semi-dyke area in Tinh Bien District, An Giang province

(Figure 1). During the flood season (commonly from August to November, with the exact timing depending on the upstream flow of the Mekong River and operation of Tha La dam and Tra Su dam), three small areas were selected to examine sediment deposition. Due to water flow from the Tha La Dam and the Tra Sa Dam, the areas were designated as follows: Area 1 (upstream), Area 2 (behind the Melaleuca forest), and Area 3 (downstream) (Figure 1). The upstream area receives water from the Tha La and Tra Su sub-canals; the behind-forest area receives water from the Tha La Canal and the 1/5 sub-canal; and the downstream area receives water from the Tra Su Canal and the Ranh sub-canal (Figure 1). In this study, the aim was to compare the quantity and quality of sediment among field types within each area and across areas.

At each area, sediment deposition between natural flooded fields as control fields and flood-based farming fields was compared. A natural flood field refers to a rice field where, after harvesting, farmers plow the rice stubble and then leave the field to be naturally inundated, without carrying out any farming activities during the flood season. The three flood-based farming fields include: ratoon rice cultivation combined with natural fish storage, ratoon rice cultivation combined with fish farming, and lotus cultivation combined with fish farming. Ratoon rice cultivation combined with natural fish storage is a farming system in which farmers set up fishing nets around the ratoon rice fields to retain naturally occurring fish, which are then harvested when the floodwater recedes at the end of the flood season. In this system, the natural fish is supplemented with feed sources from the ratoon rice. Ratoon rice cultivation combined with fish farming is a system in which farmers enclose ratoon rice fields with nets and release fingerlings into them. During the flood season, the fish are nourished not only by supplementary industrial feed but also by the ratoon rice. Lotus cultivation combined with fish farming is a system in which farmers also use nets to enclose the lotus fields and then release fingerlings into the fields. During the flood season, the fish are fed with supplementary industrial feed. In addition, during lotus cultivation, farmers also apply urea and compound NPK fertilizers (Figure 2).

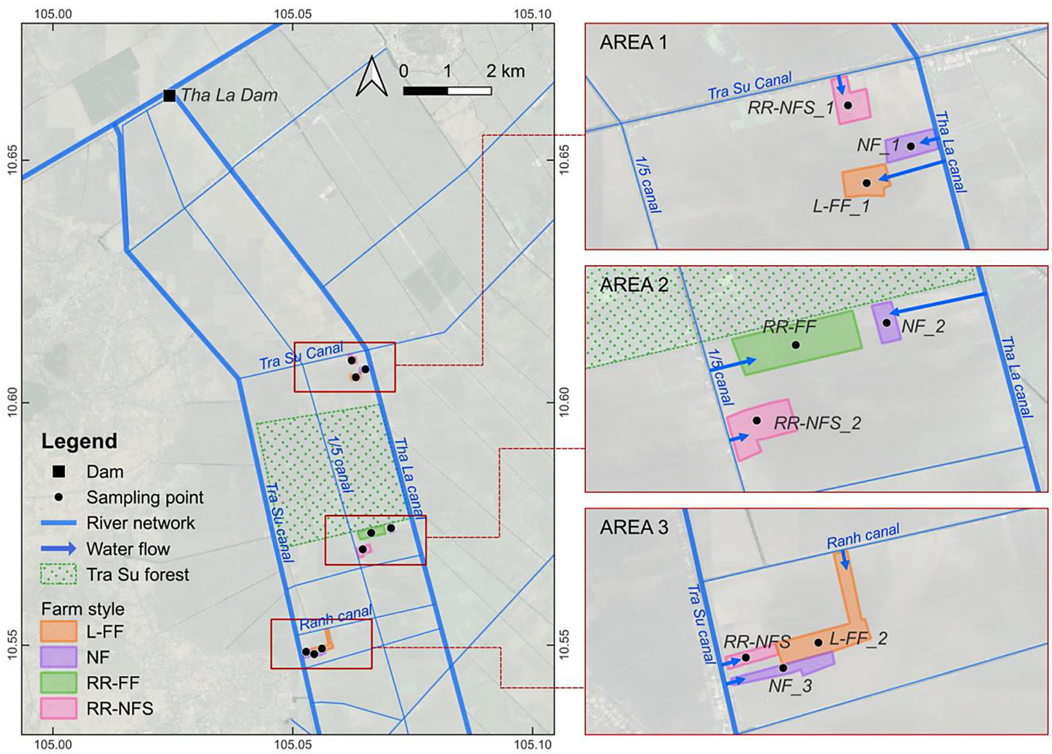

Figure 1. Sampling locations in various flood-based farming fields

Note: "L-FF" denotes a field for lotus cultivation combined with fish farming; "NF" refers to a natural flood field; "RR-FF" denotes a field for ratoon rice cultivation combined with fish farming; and "RR-NFS" refers to a field for ratoon rice cultivation combined with natural fish storage.

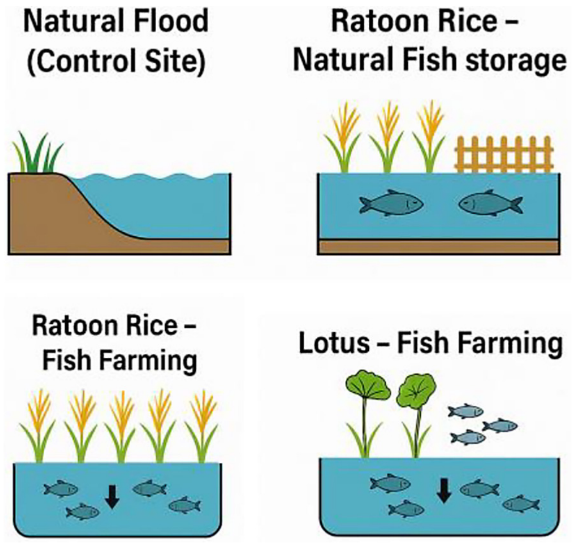

Figure 2. The flood-based farming fields in the research areas

Sediment sampling

Sediment traps were selected as net traps designed based on the study of Phung et al. (2017), with modifications. The sediment trap was constructed using a square iron frame (*Φ*8 mm) with an area of 0.025 m². The frame was covered and reinforced with thick fabric (Figure 3).

Sediment traps were installed in the fields from 7th September 2024 and collected on 23ed November 2024 (Table 1). In each field, traps were set at three positions arranged diagonally. At each position, two traps were placed side by side. Before trap installation, an open field area of approximately 4 m² was cleared (removing surface vegetation). A square polyethylene plastic sheet of about 0.64 m² was then laid on the ground and fixed at the four corners with short bamboo stakes. Long bamboo poles were also used to mark and secure the trap positions. One day, after placing the polyethylene plastic sheets, the sediment traps were gently set on top of the sheets to avoid disturbing the water, which could affect sediment deposition inside the traps. At the time of trap placement, water depth at the positions ranged from 5 to 15 cm. When the water depth in the fields decreased to less than 5 cm, the sediment traps were retrieved. The traps were removed carefully to avoid sediment loss. For the traps with water remaining on top, both water and accumulated sediments were transferred into plastic bags. The samples were then transported to the laboratory for further analysis.

In the laboratory, all sediments and water collected from each trap were transferred into a basin. The sediments adhering to the trap fabric were rinsed off with distilled water. The sediment samples were then air-dried under laboratory room temperature conditions. To accelerate water removal from the basins containing samples, excess water was regularly siphoned out using a plastic pipette. The samples were subsequently dried under laboratory conditions prior to processing for the determination of sediment quantity and quality.

Determination of sediment mass and quality

After air-drying under laboratory conditions, the sediments were homogenized manually. The entire sample was then oven-dried at 50 °C until a constant weight was reached in order to determine dry mass. After determining dry weight, the samples were used for particle-size analysis to identify texture, and chemical analyses, including pH, electrical conductivity (EC, µS/cm), organic matter (%OM), total nitrogen (%TN), ammonium (mg/kg NH_4^+-N), nitrate (mg/kg NO_3^--N), total phosphorus (%TP), available phosphorus

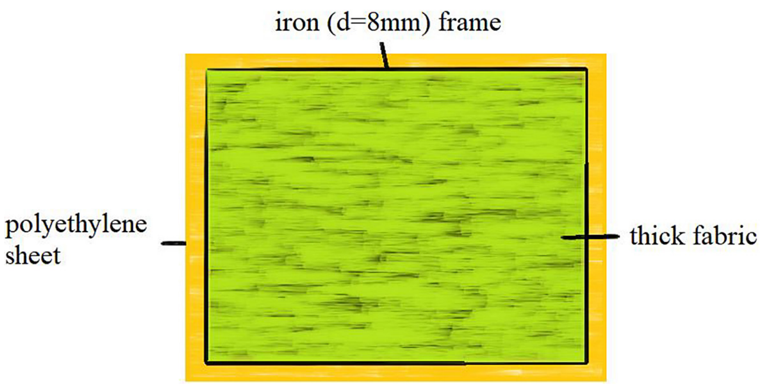

Figure 3. Structure of the sediment trap modified from Phung et al. (2017)

Table 1. Study locations and sediment trap positions during the flood season

Area	Place	Field type	Field code	Estimated area (ha)	Estimated distance from nearest canal to field (Figure 1)
1-Upstream (estimated inlet canal length from Tha La dam to this area: 7.8 km)	Van Giao village, Tinh Bien district	Natural flood (NF)	NF_1	2.0	Adjacent to Tha La canal
		Ratoon rice - Natural fish storage (RR-NFS)	RR-NFS_1	2.8	Adjacent to Tra Su sub-canal
		Lotus - Fish farming (L-FF)	L-FF_1)	3.0	280 m from Thala canal
2-Behind forest (estimated inlet canal length from Tha La dam to this area: 11.8 km)	Van Giao village, Tinh Bien district	Natural flood	NF_2	1.8	890 m from Thala canal
		Ratoon rice - Natural fish storage	RR-NFS_2	7.0	270 m from 1/5 sub-canal
		Ratoon rice – Fish farming	RR_FF	11	Adjacent to 1/5 sub-canal
3-Downstream (estimated length of main canal from Tra Su dam to this area: 13.2 km)	Vinh Trung village, Tinh Bien district	Natural flood	NF_3	2.0	Adjacent to Tra Su canal
		Ratoon rice - Natural fish storage	RR-NFS_3	13	Adjacent to Tra Su canal
		Lotus - Fish farming	L-FF_3	6.0	Adjacent to Ranh sub-canal

Note: NF = Natural flood; RR-NFS = Ratoon rice – Natural fish storage; RR-FF = Ratoon rice – Fish farming; L-FF = Lotus – Fish farming. Distances indicate the approximate distance from each field to the nearest input canal or sub-canal. “Upstream,” “Behind forest,” and “Downstream” denote the relative positions of the areas within the floodplain system.

(mg/kg P_2O_5), total potassium (%TK), and exchangeable potassium (mg/kg K_2O).

For pH and EC, the samples were extracted with distilled water at a 1:5 soil-to-solution ratio. The pH of the extracts was measured using a portable pH meter (HM-3IP, TOA, DKK, Japan), and EC was determined using a portable EC meter (CM-3IP, TOA, DKK, Japan). Sediment texture was determined using the hydrometer method (based on Vietnamese National Standard TCVN 5294:1995). Organic matter was analyzed using the Walkley–Black method (TCVN 9294:2012). Total nitrogen was measured by the Kjeldahl method (TCVN 6498:1999). Ammonium-N and nitrate-N were extracted with 2M KCl, and analyzed using the indophenol blue colorimetric method (TCVN 8557:2010) and the Cd reduction–Griess colorimetric method (TCVN 6180:1996), respectively. Total phosphorus was analyzed after wet digestion with concentrated H_2SO_4–$HClO_4$ and determined colorimetrically with the molybdenum blue method (TCVN 8940:2011). Available phosphorus was extracted using the Bray-1 method and determined colorimetrically by the molybdenum blue method. Total potassium was determined after NaOH/Na_2CO_3 fusion and measured by atomic absorption spectrophotometry (AAS). Exchangeable potassium was extracted with 1N NH_4OAc and determined by AAS.

At each sampling position, two traps were installed, and the sediments from the two traps were combined into one composite sample, because the amount of sediment was insufficient for individual quality analyses. At each field, three sampling points were established, and the mean values of sediment quality parameters were calculated from these three points; except for sediment texture, for which only one value was obtained per field due to the limited amount of sediment.

Data processing method

SPSS version 20.0 software was used to compare the mean values of variables, including sediment quantity and quality parameters between areas and field types. One-way ANOVA was applied when sample variances were homogeneous. In the cases where sample variances were not homogeneous, the non-parametric Kruskal–Wallis H test was employed.

RESULTS AND DISCUSSION

Quantitative assessment of sediment deposition

Comparison of sediment deposition among the research areas

In this study, the sediment mass at Area 1 (upstream) (Mean ± SD = 5.81 ± 1.70 g/m²×d) was the highest, followed by Area 2 (downstream)

(3.55 ± 0.28 g/m²×d) and Area 3 (behind the Melaleuca forest) (4.34 ± 0.76 g/m²×d). The differences in sediment mass among the three areas were statistically significant ($p < 0.05$) (Figure 4). The values observed in this study are comparable to the previous findings in the Mekong Delta but somewhat lower than the sediment deposition reported in floodplain fields before the construction of large upstream reservoirs. For instance, Phung et al. (2017) measured daily sediment deposition rates ranging from 8–12 g/m²×d in districts of Chau Phu, Phu Tan, Cho Moi, and Thoai Son, An Giang province (not Tinh Bien district) during flood seasons (2013–2016), which were notably higher than those recorded here. Manh et al. (2015) highlighted that the sediment delivery to floodplains in the Mekong Delta has decreased by 50–60% in recent decades due to hydropower development. The obtained results are consistent with the decreasing trend of sediment availability documented by Kummu et al. (2010), who estimated that more than half of the Mekong's sediment load could be retained by upstream dams by 2030. The relatively low deposition rates found in the downstream and behind-Melaleuca-forest areas in this study further support the notion that local hydraulic conditions, vegetation barriers, and reduced flood connectivity play a critical role in limiting sediment delivery to agricultural fields [Hung et al., 2014; Noe and Hupp, 2005]. These comparisons suggest that the current level of sediment deposition in the studied floodplain fields is already insufficient to fully compensate for soil nutrient losses under intensive cultivation. This underscores the urgent need to integrate sediment-based nutrient budgets into land and water management strategies in the Mekong Delta.

Comparison of sediment deposition among field types

In the upstream area, the sediment deposition rate in the NF_1 field (7.86 ± 0.87 g/m²×d) was significantly higher than in the F-FF_1 field (5.19 ± 0.93 g/m²×d) and the RR-NFS_1 field (4.39 ± 0.25 g/m²×d) ($p < 0.05$) (Figure 5). However, no significant difference in sediment deposition was found between the F-FF_1 and RR-NFS_1 fields ($p > 0.05$). In the behind-Melaleuca-forest area, the differences in sediment deposition rate among the surveyed fields were not statistically significant ($p > 0.05$), with values of 3.73 ± 0.42 g/m²×d, 3.49 ± 0.21 g/m²×d, and 3.43 ± 0.16 g/m²×d for the NF_2, RR-NFS_2, and F-FF_2 fields, respectively. In the downstream area, the sediment deposition rate in the NF_3 field (5.20 ± 0.32 g/m²×d) was significantly higher than in the F-FF_3 field (4.04 ± 0.48 g/m²×d) and the RR-NFS_3 field (3.79 ± 0.48 g/m²×d) ($p < 0.05$). However, no significant difference was found between the L-FF_3 and RR-NFS_3 fields ($p > 0.05$) (Figure 5). The conducted study is the first to investigate sediment deposition in flood-based farming models. These flood-based farming systems generate income for local communities. However, from the perspective of sediment

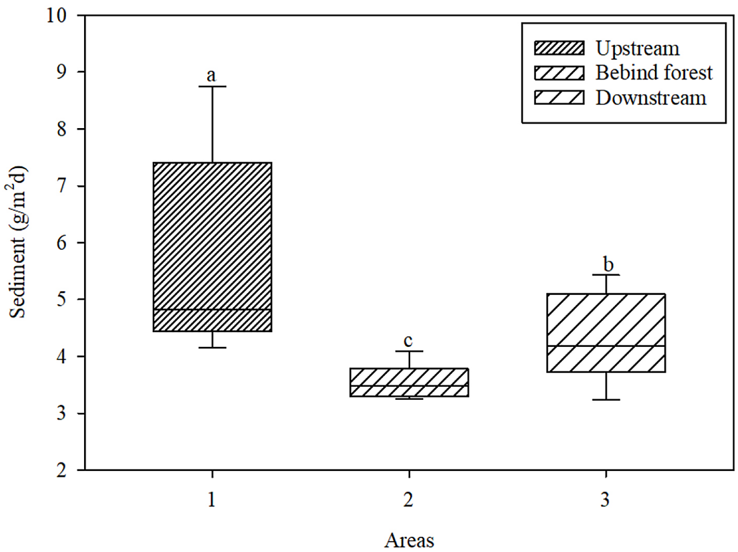

Figure 4. Sediment deposition rates with significant differences among areas

Note: bars with different letters (a, b, c) indicate significant differences at the 95% confidence level.

dynamics, the level of sediment deposition in flood-based farming models was lower than that in natural floodplain fields. The fields with ratoon rice and lotus cultivation may reduce sediment deposition because the standing plants at the field margins obstruct floodwaters, preventing sediment from entering the inner parts of the fields (where the traps were installed), particularly during the early stages of flooding.

Within the same model type, the sediment deposition rate in the NF fields across different areas showed a similar trend to the overall area comparison results: the highest deposition occurred in the upstream area, followed by the downstream area, and then the area behind the Melaleuca forest. For the RR-NFS fields, the sediment deposition rate in the upstream area was higher than that in the area behind the Melaleuca forest, while no significant differences were found between the upstream and downstream areas, nor between the downstream and behind-Melaleuca-forest areas. For the L-FF fields, the differences in sediment deposition rate between the upstream and downstream areas were not significant (Figure 5).

These findings indicate that the upstream area receives greater sediment deposition, which can be explained by its direct exposure to river flows carrying high suspended sediment concentrations during the flood season. In contrast, downstream and forest-protected areas typically experience lower sediment deposition due to reduced flow velocity and sediment trapping by vegetation. Sediment deposition was lowest in the behind-Melaleuca-forest area, as the forest obstructs the flood flows carrying sediment from the upstream sediment source. In addition, the fields that receive water from secondary canals tended to have lower sediment deposition because floodwaters entered these canals later than the main channels. The fields in the downstream area also had lower sediment deposition compared to the upstream area, which can be explained by the delayed arrival of floodwaters, resulting in less water (and sediment) entering the fields than in the upstream zone. The conducted study also monitored field water levels in the three areas (Figure 6). The results showed that water levels in the upstream area were higher than those in the behind-Melaleuca-forest and downstream areas. This provides the main explanation for the differences in sediment accumulation among the areas.

Quality assessment of sediment depositio

Sediment texture

The results show that deposited sediment across the three study areas was consistently classified as clay loam, with clay as the dominant fraction (~60%), moderate silt (~31–34%), and a relatively low proportion of sand (<10%). Statistical analysis indicated no significant differences among upstream, behind-forest, and downstream

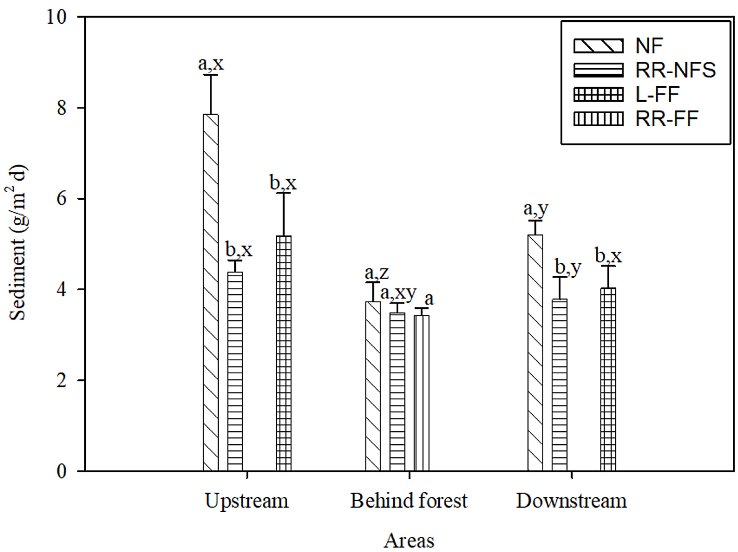

Figure 5. Sediment deposition rates in different field types across study areas

Note: For the same area, bars with different letters (a, b, c) indicate significant differences at the 95% confidence level. For the same field type, bars with different letters (x, y, z) indicate significant differences at the 95% confidence level.

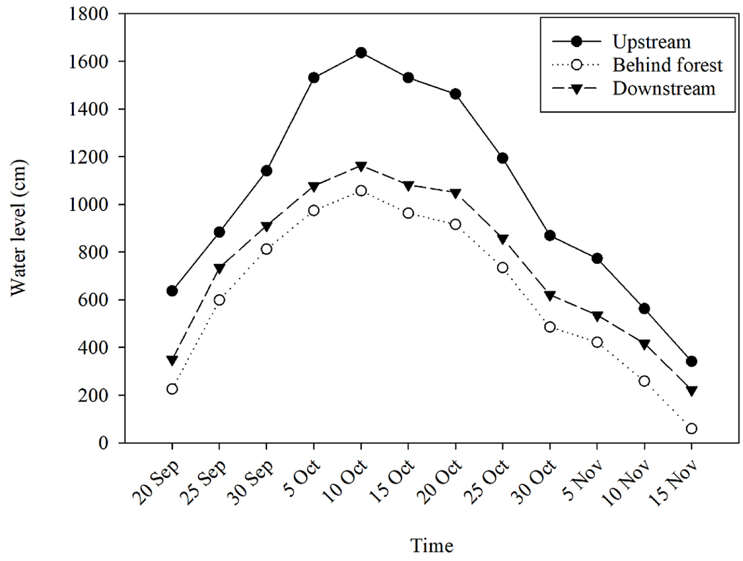

Figure 6. Monitored water levels in fields across study areas

areas ($p > 0.05$). Compared to previous studies, the obtained findings are consistent with Phung et al. (2017), who reported that floodplain sediments in the An Giang province inside and outside dike systems were also classified as clay loam, with contents of 58–65% and sand contents <10%. From a soil fertility perspective, the relatively high clay fraction in Mekong sediments may promote cation exchange capacity and nutrient retention, reinforcing the importance of organic matter inputs to sustain soil productivity [Chapman et al., 2016]. Therefore, maintaining flood connectivity while promoting organic matter accumulation is critical for balancing the physical and chemical functions of sediments in flood-based farming systems (Table 2).

pH, EC, and OM of sediments

In the study area, the sediment pH was 5.5 ± 0.2, indicating slightly acidic conditions. No significant differences in pH values were observed among the study areas, among field types within the same area, or among field types of the study areas ($p > 0.05$) (Table 3). Similar pH values have been reported in the Mekong Delta floodplains, where sediments generally range from weakly acidic to neutral due to prolonged inundation and organic matter decomposition [Phung et al., 2017; Toan et al., 2018].

The sediment EC was 0.17 ± 0.11 mS/cm. The low EC values (< 0.3 mS/cm) across all sampling areas indicate that the sediments were of very low salinity. No significant differences in EC were found among areas, among field types within areas, or among field types of the study areas (Table 3). This result is consistent with earlier studies in the Vietnamese Mekong Delta, which found that flood-borne sediments are typically fresh, with salinity levels rarely exceeding 0.5 mS/cm, except in coastal zones where saline intrusion occurs [Hung et al., 2014; Manh et al., 2015].

The sediment OM content was relatively high (9.57 ± 1.09%), suggesting good accumulation of organic matter. This result highlights the benefit of seasonal flood-borne sediment deposition in rice fields, which can replenish soil organic matter depleted by continuous rice cultivation. No significant differences in OM were found among areas, among field types within the same area, or among field types of the study areas (Table 3). At the area level, significant differences ($p < 0.05$) were only detected in specific cases: in the upstream area, between the NF_1 field and RR-NFS_1 field; in the behind-forest area, between the RR-FF_2 field and the NF_2 and RR-NFS_2 fields. However, no significant differences were observed among field types in the downstream area ($p > 0.05$). These differences appeared irregular and did not follow a clear pattern, suggesting that farming model type is not a determinant factor for variation in OM content. This OM value is higher than those reported in several earlier studies in the Mekong Delta, which typically range between 5–8% [Phung et al., 2017; Luu et al., 2010]. The elevated OC content highlights the beneficial role of seasonal sediment deposition in replenishing soil organic matter depleted by

Table 2. Sediment texture (% clay, % silt, and % sand) in different field types across study areas

Area	Field type	% clay	% silt	% sand
Upstream	NF_1	63.1	32.0	4.9
	RR-NFS_1	62.3	32.1	5.6
	L-FF_1	60.9	30.4	8.7
	Mean±SD	62.1±1.1	31.5±1.0	6.4±2.0
Behind forest	NF_2	60.2	34.2	5.6
	RR-NFS_2	59.8	33.9	6.3
	RR-FF_2	61.2	34.3	4.5
	Mean±SD	60.4±0.7	34.1±0.2	5.5±0.9
Downstream	NF_3	63.8	31.3	4.9
	RR-NFS_3	61.7	33.3	5.0
	L-FF_3	54.8	35.6	9.6
	Mean±SD	60.1±4.7	33.4±2.2^x	6.5±2.7
Differences between areas		ns	ns	ns

Note: "ns" denotes no significant difference.

continuous rice cultivation. Previous research has emphasized that flood-borne sediments contribute not only mineral nutrients but also particulate and dissolved organic matter that can improve soil fertility as well as support long-term sustainability of flood-based farming systems [Chapman et al., 2016; Kummu and Varis, 2007].

Nutrients in sediments

Nitrogen in sediments

The sediment TN content across the study areas showed little variation, ranging from 0.287–0.421% (0.351 ± 0.043%). No significant differences in TN were found among the areas. Within the upstream area, TN values in the RR-NFS_1 and L-FF_1 fields were significantly higher than in the NF_1 field ($p < 0.05$), while the difference between RR-NFS_1 and L-FF_1 was not significant ($p > 0.05$). In the behind-forest area, TN in the RR-FF_2 field was significantly higher than in the NF_2 and RR-NFS_2 fields ($p < 0.05$), whereas NF_2 and RR-NFS_2 did not differ significantly ($p > 0.05$). In the downstream area, TN in the L-FF_3 field was significantly higher than in the RR-NFS_3 field ($p < 0.05$), and TN in the RR-NFS_3 field was significantly higher than in the NF_3 field ($p < 0.05$). The relatively narrow range of TN observed in this study is consistent with values previously reported for flood-borne sediments in the Vietnamese Mekong Delta, typically ranging from 0.2–0.5% [Phung et al., 2017; Luu et al., 2010]. The relatively uniform TN content across study areas indicates that seasonal floods distribute nitrogen fairly evenly across the landscape, although localized differences among field types suggest that farming practices play a role in nitrogen retention.

The NH_4^+-N content of sediments varied widely among the study areas, ranging from 4.53–47.96 mg/kg (21.27 ± 13.48 mg/kg). No significant differences in NH_4^+-N were found among areas ($p > 0.05$). Within the upstream area, NH_4^+-N in the L-FF_1 field was significantly higher than in the RR-NFS_1 field ($p < 0.05$), and NH_4^+-N in the RR-NFS_1 field was significantly higher than in the NF_1 field ($p < 0.05$). In the behind-forest area, NH_4^+-N in the RR-FF_2 field was significantly higher than in the RR-NFS_2 field ($p < 0.05$), and NH_4^+-N in the RR-NFS_2 field was significantly higher than in the NF_2 field ($p < 0.05$). Similarly, in the downstream area, NH_4^+-N in the L-FF_3 field was significantly higher than in the RR-NFS_3 field ($p < 0.05$), and NH_4^+-N in the RR-NFS_3 field was significantly higher than in the NF_3 field ($p < 0.05$). Ammonium nitrogen concentrations were highly variable, reflecting the dynamic processes of organic matter mineralization and ammonification in floodplain environments. The tendency for L-FF (lotus–fish) and RR-FF (ratoon rice–fish) fields to accumulate higher NH_4^+-N compared to NF fields is likely linked to the supplemental nitrogen inputs from fish feed and chemical fertilizers applied to lotus, as well as contributions from fish excreta. Similar findings have been reported in integrated rice–fish systems in Bangladesh and Cambodia, where

Table 3. The pH, EC, and OM of sediment in different field types across study areas

Area	Field types	pH	EC (mS/cm)	OM (%)
Upstream	NF_1	5.6±0.0^{a}	0.16±0.01^{a}	8.93±0.30^{ab}
	RR-NFS_1	5.6±0.0^{a}	0.20±0.01^{a}	10.54±0.55^{a}
	L-FF_1	5.8±0.0^{a}	0.20±0.01^{a}	10.05±0.02^{b}
	Mean±SD	5.7±0.1^{x}	0.18±0.02^{x}	9.84±0.83^{x}
Behind forest	NF_2	5.3±0.2^{a}	0.04±0.00^{a}	8.36±0.75^{b}
	RR-NFS_2	5.4±0.2^{a}	0.04±0.00^{a}	9.01±0.23^{b}
	RR-FF_2	5.6±0.2^{a}	0.04±0.00^{a}	10.78±0.31^{a}
	Mean±SD	5.4±0.2^{x}	0.04±0.00^{x}	9.38±1.25^{x}
Downstream	NF_3	5.7±0.2^{a}	0.25±0.02^{a}	9.92±1.37^{a}
	RR-NFS_3	5.2±0.2^{a}	0.30±0.02^{a}	8.53±1.55^{a}
	L-FF_3	5.6±0.1^{a}	0.33±0.03^{a}	10.02±0.81^{a}
	Mean±SD	5.5±0.3^{x}	0.29±0.04^{x}	9.49±0.83^{x}
Differences between areas (n=3)		ns	ns	ns
Differences in the same field type among areas (n = 3)		ns	ns	ns

Note: Means followed by different letters differ significantly at $p < 0.05$ (lowercase a–c within areas; x–z across areas).

sediments and soils under aquaculture–rice rotations showed elevated ammonium levels relative to rice monocultures [Ahmed and Garnett, 2010; Joffre and Bosma, 2009].

The NO_3^--N content of sediments also exhibited large variability, ranging from 28.14–79.29 mg/kg (49.76 ± 17.65 mg/kg). The NO_3^--N values in the upstream area were significantly higher than those in the behind-forest and downstream areas ($p < 0.05$), whereas no significant difference was found between the behind-forest and downstream areas ($p > 0.05$). Across areas, the trends in NO_3^--N among the field types were generally similar to those observed for NH_4^+-N**.** Nitrate nitrogen (NO_3^--N) values were highest in the upstream fields and significantly lower in the behind-forest and downstream areas. This gradient aligns with hydrological studies in the Mekong Delta showing that floodwaters entering upstream areas are more oxygenated, favoring nitrification, resulting in more nitrate reduced [Hung et al., 2014]. The similarity between NO_3^--N and NH_4^+-N trends across field types highlights the interplay between hydrology in controlling nitrogen forms in deposited sediments.

The elevated nitrogen levels in integrated systems (RR-FF, L-FF) compared to natural floodplain fields suggest that multi-functional land-use models may enhance nutrient retention in sediments, potentially improving soil fertility for subsequent crops. The nitrogen dynamics observed in this study underscore the dual role of flood-borne sediments and integrated farming practices in shaping soil fertility in the Mekong Delta. While seasonal sediment deposition ensures a baseline supply of nitrogen, integrated systems such as rice–fish and lotus–fish farming contribute additional nitrogen inputs that can be beneficial for crop productivity.

Phosphorus in sediments

The sediment TP content of sediments across the study areas showed little variation, ranging from 0.010 to 0.029% (0.021 ± 0.007%). Overall, the TP levels were low, reflecting the phosphorus-poor nature of the deposited sediments. TP in the upstream area was significantly higher than in the behind-forest and downstream areas ($p < 0.05$), whereas no significant difference was found between the behind-forest and downstream areas ($p > 0.05$). Within the upstream area, TP in the sediments of the L-FF_1 field was significantly higher than in the RR-NFS_1 and NF_1 fields ($p < 0.05$), while no significant difference was found between RR-NFS_1 and NF_1 ($p > 0.05$). In the behind-forest area, TP in the RR-FF_2 and RR-NFS_2 fields was significantly higher than in the NF_2 field ($p < 0.05$), but the difference between RR-FF_2 and RR-NFS_2 was not significant ($p < 0.05$). In the downstream area, TP in the L-FF_3 field was significantly higher than in the RR-NFS_3 field ($p < 0.05$), and TP in the RR-NFS_3 field was significantly higher than in the NF_3 field ($p < 0.05$). The low levels of total phosphorus observed in this study reflect the generally phosphorus-poor nature of flood-borne sediments in the Mekong Delta. Similar findings have been reported by Phung et al. (2017), who found TP values typically below 0.03% in An Giang floodplain sediments, and by Luu et al. (2010) in Cambodian floodplains. This highlights a potential limitation of Mekong sediments in terms of replenishing phosphorus stocks for agriculture, despite their contributions of nitrogen and organic carbon. Within each area, the tendency for higher TP in integrated systems, such as L-FF and RR-FF compared to NF fields suggests that the quaculture feed and chemical fertilizers used in lotus cultivation contribute additional phosphorus inputs to the sediments. This pattern is consistent with the earlier reports from integrated rice–fish systems in Bangladesh and Cambodia, where fish feed residues and pond mud recycling increased soil P availability [Ahmed and Garnett, 2010; Joffre and Bosma, 2009].

The available phosphorus content of sediments also showed a narrow range, from 0.041–0.990 mg/kg (0.449 ± 0.383 mg/kg). No significant differences in P_2O_5 were detected among areas ($p > 0.05$). The distribution pattern of P_2O_5 among field types in the upstream and behind-forest areas was similar to that of TP. In the downstream area, P_2O_5 in the L-FF_3 field was significantly higher than in the RR-NFS_3 and NF_3 fields ($p < 0.05$), while the difference between RR-NFS_3 and NF_3 was not significant ($p > 0.05$). The P_2O_5 narrow range and low concentrations further reinforce the conclusion that the flood-borne sediments in the Mekong are relatively poor in readily available phosphorus. This limitation is agronomically important because phosphorus is a key nutrient often limiting rice yields in the Mekong Delta [Syers et al., 2008].

Overall, the distribution of phosphorus across fields and areas resembled the patterns observed for nitrogen, which may be explained by similar factors, such as nutrient inputs from fish feed, chemical fertilization in lotus fields, and organic matter contributions from crop residues and aquaculture activities. Overall, the distribution patterns of both TP and P_2O_5 mirrored those of nitrogen, suggesting that integrated farming practices (lotus–fish, rice–fish) enhance nutrient deposition through external inputs, while natural floodplain fields remain nutrient-poor. These findings emphasize the dual role of seasonal flood sediments: while they contribute organic matter and nitrogen, their phosphorus content is relatively low and may not be sufficient to offset crop phosphorus removal. Consequently, farmers may need to rely on external phosphorus fertilization to sustain yields, particularly in the fields without aquaculture integration.

Potassium in sediments

The TK content of sediments across the study areas showed little variation, ranging from 3.47–3.99% (3.77 ± 0.16%). TK in the behind-forest area was significantly lower than in the other two areas ($p < 0.05$), while no significant difference was found between the upstream and downstream areas ($p > 0.05$). Across the three areas, no significant differences in TK were observed among the field types, except in the upstream area where TK in the L-FF_1 field was significantly higher than in the other two fields ($p < 0.05$). The relatively stable range of total potassium observed in this study confirms that the flood-borne sediments in the Mekong Delta are naturally rich in potassium. These values are in line with previous studies in the An Giang and Dong Thap provinces (upstream Mekong Delta, which also reported the TK levels above 3% in deposited sediments during flood seasons [Phung et al., 2017; Toan et al., 2018]. Compared to nitrogen and phosphorus, potassium was found in much higher concentrations, suggesting that the Mekong River floodplain sediments are a particularly important source of this nutrient. The significantly higher TK in the L-FF fields compared to other field types likely reflects direct potassium inputs from the fertilizer applied to lotus crops. This aligns with the previous findings that integrated rice–fish or rice–lotus systems often exhibit elevated soil potassium levels due to external inputs and recycling of organic matter [Ahmed and Garnett, 2010].

The available potassium content of sediments varied widely, ranging from 554.3–1258.4 mg/kg (788.9 ± 240.5 mg/kg). No significant differences in K_2O were found among areas. Within the upstream and downstream areas, K_2O in the L-FF fields was significantly higher than in the RR-FF and NF fields ($p < 0.05$), while the difference between RR-FF and NF was not significant ($p > 0.05$). In the behind-forest area, K_2O in the RR-FF_2 field was significantly higher than in the RR-NFS_2 and NF_2 fields ($p < 0.05$). The elevated K_2O values in the L-FF fields may be attributed to the potassium fertilizer applied to lotus, which subsequently accumulated in the sediments. The available potassium showed a much wider variation, indicating that while the total potassium pool is relatively stable, its bioavailable fraction is highly dynamic and influenced by field management. The particularly high K_2O levels in L-FF fields highlight how localized farming practices can strongly affect nutrient distribution in sediments. Similar patterns have been observed in Bangladesh and Cambodia, where integrated farming systems increased available potassium in paddy soils through fertilizer application and decomposition of aquatic biomass [Joffre and Bosma, 2009].

Overall, the potassium levels in sediments were much higher compared to nitrogen and particularly phosphorus. This finding indicates that flood-borne sediments provide a substantial potassium supply for rice cultivation, thereby reducing the need for potassium fertilizer application during the early growth stages of rice. Such contributions are especially important for the winter–spring rice crop following the flood season in the Mekong Delta. From an agronomic perspective, the abundant potassium content in sediments has direct implications for rice cultivation in the Mekong Delta. Potassium is a critical nutrient for rice growth, particularly in improving lodging resistance, water-use efficiency, and grain filling. The substantial potassium input from flood-borne sediments reduces the requirement for chemical fertilizer application in the early stages of the winter–spring rice crop, thereby lowering production costs for farmers. This nutrient subsidy is especially important in the context of intensive triple-cropping systems, where soil nutrient depletion is a major concern [Syers et al., 2008].

The findings of this research provide important insights for improving the management of flood-based agriculture in the Vetnamese Mekong Delta. The clear spatial differences in sediment deposition among upstream, behind-forest, and downstream areas emphasize the need to maintain hydrological connectivity that enables sediment and nutrient inflow to fields. Adaptive dyke operation that allows controlled flooding could help restore natural sediment delivery and enhance soil fertility. The results also suggest that flood-borne sediments contribute significant nitrogen and potassium inputs but remain poor in phosphorus, indicating that supplemental phosphorus is essential to balance soil nutrients. Integrated models, such as ratoon rice–fish and lotus–fish systems, further enhance nutrient retention through recycling of fish feed and organic matter, showing potential for scale up these model. Overall, strengthening sediment monitoring and promoting nature-based, integrated floodplain management can support both soil fertility and flood-based livelihoods under declining sediment supply in the Mekong Delta (Table 4).

Table 4. Nutrient contents (TN, NH_4^+-N, NO_3^--N, TP, P_2O_5, TK, K_2O) of sediments across field types and study areas

Area	Field type	TN (%N)	NH_4^+-N (mg/kg)	NO_3^--N (mg/kg)	TP (%P_2O_5)	P_2O_5 (mg/kg)	TK (%K_2O)	K_2O (mg/kg)
Upstream	NF_1	0.305±0.027^{b}	5.19±0.68^{c}	17.78±0.40^{c}	0.028±0.010^{b}	0.075±0.008^{b}	3.86±0.09^{b}	652.6±16.5^{b}
	RR-NFS_1	0.348±0.021^{a}	25.38±2.51^{b}	22.14±4.96^{b}	0.030±0.001^{b}	0.144±0.038^{b}	3.85±0.16^{b}	699.7±134.0^{b}
	L-FF_1	0.384±0.013^{a}	56.06±0.88^{a}	102.82±0.64^{a}	0.045±0.004^{a}	1.010±0.214^{a}	4.11±0.07^{a}	1327.4±102.7^{a}
	Mean±SD	0.345±0.039^{x}	28.87±25.62^{x}	47.58±7.89^{y}	0.034±0.010^{x}	0.410±0.521^{x}	3.94±0.15^{x}	893.23±376.7^{x}
Behind forest	NF_2	0.306±0.020^{b}	4.72±0.15^{c}	29.48±0.68^{c}	0.010±0.000^{b}	0.059±0.006^{b}	3.59±0.06^{a}	577.9±24.1^{b}
	RR-NFS_2	0.343±0.017^{a}	23.14±1.35^{b}	30.82±4.09^{b}	0.020±0.005^{a}	0.777±0.095^{a}	3.67±0.21^{a}	636.5±37.9^{b}
	RR-FF_2	0.382±0.019^{a}	30.04±1.48^{a}	43.53±9.40^{a}	0.026±0.001^{a}	0.793±0.096^{a}	3.74±0.14^{a}	989.5±33.4^{a}
	Mean±SD	0.344±0.038^{x}	19.30±13.09^{x}	34.61±7.76^{y}	0.019±0.008^{y}	0.543±0.420^{x}	3.66±0.07^{z}	734.61±222.7^{x}
Downstream	NF_3	0.304±0.017^{c}	5.10±0.54^{c}	56.65±1.75^{c}	0.018±0.001^{c}	0.061±0.018^{b}	3.86±0.07^{a}	645.4±10.2^{b}
	RR-NFS_3	0.354±0.006^{b}	24.05±1.05^{b}	62.97±3.89^{b}	0.023±0.001^{b}	0.131±0.022^{b}	3.86±0.11^{a}	672.0±16.5^{b}
	L-FF_3	0.415±0.007^{a}	40.59±6.64^{a}	75.09±3.70^{a}	0.028±0.002^{a}	0.874±0.105^{a}	3.90±0.09^{a}	1212.2±76.9^{a}
	Mean±SD	0.358±0.055^{x}	23.25±17.76^{x}	64.91±9.37^{x}	0.023±0.005^{y}	0.355±0.451^{x}	3.87±0.02^{y}	843.21±319.8^{x}
Differences between areas		ns	ns	$p < 0.05$	$p < 0.05$	ns	$p < 0.05$	$p < 0.05$

Note: Means followed by different letters differ significantly at $p < 0.05$ (lowercase a–c within areas; x–z across areas).

CONCLUSIONS

Sediment deposition was significantly higher in the upstream area than in the behind-forest and downstream areas, confirming the role of hydrological connectivity in sediment delivery. Sediments were classified as clay loam, relatively homogeneous in texture across areas, with slightly acidic pH, low salinity, and high organic carbon. Nitrogen content was moderate and enhanced in integrated farming models (ratoon rice-fish farming, lotus-fish farming), while phosphorus was consistently low, indicating a potential fertility constraint. Potassium was abundant in all areas, representing a major nutrient subsidy from flood-borne sediments for rice-based systems. Integrated farming models (rice–fish, lotus–fish) contributed additional nutrient inputs (particularly nitrogen and potassium), though patterns varied irregularly across areas. This study provides the first comparative evidence on both the quantity and quality of flood-borne sediments across multiple flood-based farming models in the upstream Mekong Delta. The findings contribute important scientific insights for designing the nature-based solutions that sustain soil fertility, optimize integrated farming systems, and enhance the resilience of local livelihoods under declining sediment inputs.

Strengthen monitoring programs of sediment quantity and quality under changing hydrology and dam development to provide the information on adaptive agricultural strategies.

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