frontiers | Frontiers in Agronomy

TYPE Original Research
PUBLISHED 14 June 2024
DOI 10.3389/fagro.2024.1397474

OPEN ACCESS

EDITED BY
Stéphane Cordeau,
INRAE, UMR Agroécologie, France

REVIEWED BY
Jiban Shrestha,
Nepal Agricultural Research Council, Nepal
Sharif Ahmed,
International Rice Research Institute (IRRI), Philippines
Sopialena Sopialena,
Mulawarman University, Indonesia

*CORRESPONDENCE
Md Amirul Islam
ma.islam@uni-bonn.de

RECEIVED 07 March 2024
ACCEPTED 24 May 2024
PUBLISHED 14 June 2024

CITATION
Islam MA, Pariyar S, Krupnik TJ and Becker M (2024) Changing trends in crop management practices and performance attributes of rice-based systems of coastal Bangladesh. *Front. Agron.* 6:1397474.
doi: 10.3389/fagro.2024.1397474

Changing trends in crop management practices and performance attributes of rice-based systems of coastal Bangladesh

Md Amirul Islam [1,2*], Shyam Pariyar [1], Timothy J. Krupnik [2] and Mathias Becker [1]

[1]Department of Plant Nutrition, Institute of Crop Science and Resource Conservation, University of Bonn, Bonn, Germany, [2]International Maize and Wheat Improvement Center (CIMMYT), Sustainable Agrifood Systems (SAS) Program, Dhaka, Bangladesh

Climate change affects changes in rice-based systems of coastal Bangladesh. Both external pressures and system-immanent attributes influence farmers' adoption of new production practices, leading to the emergence of new land use patterns. Field and household surveys quantified recent and emerging change trends in crop yields and associated intensification-related practices in representative rice-based systems, using a diachronic approach (comparing the years 2011 and 2021). We analyzed 240 rice-producing farms, representing three rice-based cropping systems, namely extensive rice-fallow rotations, intensified irrigated rice double rotations, and diversified rice-mungbean rotations. The study sites contrasted favorable biophysical conditions (climate, soil type, water source and quality, soil fertility) in the Barishal district, and marginal (unfavorable biophysical environments) conditions at Patuakhali district in coastal Bangladesh. Soil fertility attributes were assessed at both study sites. The type, the extent, and the pathways of recent changes differed between locations, systems and seasons. We observed significant increases in aggregated yield (across crops and seasons), in individual crop yields, and in economic yields at both the marginal and the favorable sites. Crop yields varied widely (rice: 3.0–7.8 t ha^{-1}, mungbean: 0.4–1.5 t ha^{-1}), and rice yield was higher in dry than in the wet season. Farmers' adoption of intensification practices started earlier in the marginal study area, but the extent of the changes was larger at favorable sites. Most prominent was the mechanization of tillage operations and an increased use of mineral fertilizers, with the largest changes observed in irrigated rice and in dry season mungbean. Such site-, system-, and season-specific assessments will permit identifying drivers of change and can inform the assessment of potential future patterns of land system changes.

KEYWORDS

diversification, intensification, *Oryza sativa*, salinity, system shifts, *Vigna radiata*

1 Introduction

Crop production in the coastal area is vulnerable to changing climate. Their unique geographical and economic attributes exacerbate negative consequences of climate change, where rising sea water levels can lead to increased saltwater intrusion, land salinization, and declining crop yields (Clarke et al., 2015). These processes negatively affect food production and farmers' income (Aryal et al., 2020), and increasingly challenge the required doubling of the food supply by 2050 (Bahar et al., 2020).

Like most of its neighboring countries, Bangladesh relies heavily on agriculture and is characterized by high population densities. About 31% of total land area of Bangladesh is located in the coastal zone, where 27% of the population lives below the poverty line (Mainuddin et al., 2014). The geographical features of this region exhibit a greater degree of diversity and dynamism than commonly acknowledged, encompassing landscapes such as piedmonts, river valleys, tidal and estuarine floodplains, elevated blocks, and hilly terrains (Roncoli et al., 2016; Brammer, 2017). Additionally, this area experiences higher instability compared to other regions of the country, attributed to the significant discharge of sediment through the Meghna estuary, resulting in shoreline dynamics and alterations in land use and land cover (Chowdhury and Sikder, 2024). Crop production in this area is increasingly constrained by soil salinity, poor governance of fresh water resources, and by climate vulnerabilities (Bernier et al., 2016), particularly during the dry season (Emran et al., 2022). These critical attributes limit the land use intensification that is required to meeting a growing food demand, leading to large shares of the available cropland area being abandoned or left seasonally fallow (Krupnik et al., 2017). In addition, socio-political changes, the poor resource endowment of smallholders, improper use of agrochemicals, and declining soil fertility negatively affect the predominant rice-based production systems (Alam et al., 2021). Recent spikes in input prices, limited opportunities to earn off-farm income, and reduced returns from remittances further constrain farmers' adaptive capacity, and increasingly limit on-farm investments (Alam et al., 2013).

Farmers respond to these emerging challenges by modifying their production systems and associated agronomic practices. The sustainable intensification of rice-based systems may entail different approaches and pathways, as a function of the marginality of site conditions and the on-farm resource endowment, leading to the emergence of diverse patterns of land systems. Strategies of intensification comprise not only the intensity of land use (double or multiple cropping) but concern all steps in the production process from varietal choice, land preparation, crop establishment the use of agrochemicals and crop harvest (Krupnik et al., 2017). This has entailed recent increases in the use of improved crop varieties and of agrochemicals (Al Mamun et al., 2021), adoption of laborsaving technologies (Krupnik et al., 2022), nutrient management options (Islam et al., 2024) and irrigation methods (Schulthess et al., 2019). While rainfed wet season rice is grown on much of the available cultivable land of rural Bangladesh (Bhattacharya et al., 2019), cropping intensification by growing irrigated rice during the dry season (Krupnik et al., 2017) requires available irrigation water supplies which is limited (Gaydon et al., 2021). A shift toward less water-demanding upland crops during the dry season, such as mungbean, soybean and vegetables, may offer the possibility for land use intensification by diversifying the crop portfolio (Assefa et al., 2021; Emran et al., 2022), without exacerbating the depletion of ground- and surface-water resources (CIAT and World Bank, 2017). However, such strategies require cultivation techniques, agronomic practices and nutrients inputs that are not available as of now, and their applicability may differ with the marginality or favorability of the site. In addition, most diversification strategies tend to be more labor- and knowledge-intensive, and require market access and well-developed value chains (Aravindakshan et al., 2020). Thus, crop diversification may be restricted to peri-urban settings and to farms with a favorable resource endowment.

The recognition of such location-specific differences will permit identifying measures and targeting interventions for accelerating system-specific transitions towards sustainable intensification and diversification in coastal areas of Bangladesh and beyond. However, little is known about the manifestation of practices and regarding rates of adoption of new technology options in southern Bangladesh.

We hypothesized that changes in the adoption of agronomic management practices towards intensifying land systems differ between favorable and marginal environments reflecting famers' adaptive capacity to system-specific transitions in coastal Bangladesh, and emerging intensification of land systems mainly expands towards dry season crops. The objectives of the study are i) to quantify change trends in performance attributes of rice-based production systems and associated agronomic practices in the past 10 years (2011 vs. 2021), and ii) to assess farmers' perceived constraints for adopting intensification-related production strategies at two distinct sites in coastal Bangladesh. We demonstrate for the first time the on-going trends in land system changes, applying a diachronic analysis (comparing recent past and present states) to farms in coastal rice-based systems of Bangladesh.

2 Materials and methods

2.1 Site attributes and prevailing cropping systems

To identify transitions in land use and cropping practices in coastal Bangladesh, we selected two districts in the division of Barishal, representing the climatic and edaphic conditions typically encountered in coastal delta regions. They represent priority research areas or key intervention zones of the national research program, with data being available regarding biophysical conditions and socio-economic household attributes. The study regions in Barishal and Patuakhali districts are located between 90.3 and 90.4°E and between 22.4 and 22.8°N. Both districts belong to same agro-ecological zone of the "sub-humid tropical lowland" with similar lengths of growing periods of 180–209 days (https://gaez-services.fao.org/) and are characterized as Equatorial Monsoon (Am) or Equatorial Savannah (Aw), according to the Köppen-Geiger (Kottek et al., 2006).

The average monthly maximum and minimum temperature almost similar in both sites. While the maximum temperature ranges from 24°C (January) to 33°C (April/May) in Barishal site and 25°C (January) to 34°C (April) in Patuakhali site. The minimum temperature ranges from 12°C (January) to 26°C (June) in Barishal site and 13°C (January) to 27°C (June) in Patuakhali site. The relative humidity is constantly high in both sites with 74% (March) to 88% (July), and 75% (February/March) to 90% (July) in Barishal and Patuakhali sites, respectively. Annual rainfall varies between the sites with ~1900 mm in Barishal and ~2500 mm in Patuakhali site. In addition, rainfall varies between the seasons with ~90% rainfall occurred in wet season in both sites (Figures 1A, B).

However, the study areas contrast in terms of edaphic attributes. While both are dominated by clay-textures alluvial Gley- or Fluvisols (Huq and Shoaib, 2013) and are well endowed with plant available P (~44 mg kg^{-1}) and K (58–101 mg kg^{-1}), the "marginality" of soils in Patuakhali district is informed by salt water intrusion during high tide and resulting soil salinity in the dry season of 4.9 dSm^{-1}. In addition, organic C (1.0%) and total N contents (0.1%) are much lower than at the favorable Barishal site with 1.4% C and 0.2% N (Table 1). These soil attributes are based on analyses of composite topsoil (0–20 cm) samples, collected from seven sampling points along a diagonal of each field. When farmers had different plots of same crop rotation, soil sampling was performed from a largest plot of that particular rotation. These soil sample were collected at the end of dry season (April–May, 2022) followed by air drying. The samples were analyzed in the laboratory of the Institute of Crop Science and Resource Conservation at the University of Bonn, Germany.

The prevailing cropping patters are determined by the seasonality of rainfall, the access to irrigation water from either surface resources or the shallow aquifer, and by opportunities for commercialization (market access) and production risks (soil salinity). Farmers at both sites cultivate transplanted lowland rice during the monsoon (wet) season, covering 60–67% of the total arable land area. In the dry season, farmers can opt for leaving the land to fallow (extensive production system) or for cultivating irrigated crops (intensified or diversified production systems). The latter may comprise either lowland rice (irrigated rice double cropping on 33% of the land area) or high-value and often perishable legumes or vegetables (Bangladesh Bureau of Statistics–BBS, 2023). This

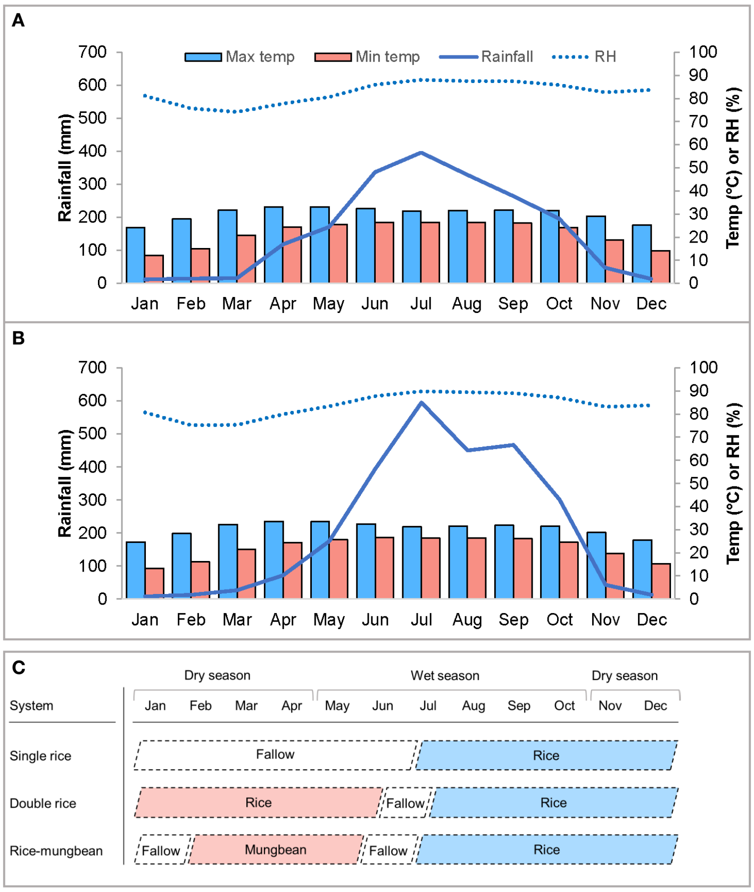

FIGURE 1
Monthly climatic patterns in Barishal (favorable site, **A**) and Patuakhali (marginal site, **B**) in coastal Bangladesh. The climate data represent the monthly average of 15 years (2008–2022) (Source: Bangladesh Bureau of Statistics). Temp, temperature (°C); RH, relative humidity (%); max, maximum; min, minimum. Annual crop calendar under different cropping systems **(C)** (Source: Agriculture Information Service, Bangladesh).

TABLE 1 Selected soil attributes at the favorable (Barishal district) and marginal sites (Patuakhali district) in coastal Bangladesh.

Soil attributes	Sites		*P value*
	Favorable (*n* = 30)	Marginal (*n* = 30)	
pH (H_2O)	5.3 ± 0.2	4.8 ± 0.1	0.018
Electric conductivity ($dS\ m^{-1}$)	0.9 ± 0.1	4.9 ± 0.5	0.000
C_{org} (%)	1.4 ± 0.1	1.0 ± 0.0	0.000
N_{tot} (%)	0.2 ± 0.0	0.1 ± 0.0	0.001
C:N ratio	9.4 ± 0.2	8.9 ± 0.2	0.029
P_{Olsen} ($mg\ kg^{-1}$)*	44.8 ± 0.9	43.9 ± 0.9	0.503
K ($mg\ kg^{-1}$)*	57.8 ± 0.4	101.2 ± 0.8	0.000

*CAL method (Schüller, 1969).
Values represent means ± standard error of mean. P values denote significance levels between sites, according to Tukey's test, sample size (n) = 30.

diversified cropping system is exemplified by the most frequently encountered rice-mungbean rotation (Figure 1C). Thus, the predominant cropping patterns at both study sites (districts) encompass: (1) Rice-Fallow (one single crop rainfed or irrigated wet season rice – extensive system); (2) Double Rice (irrigated rice cultivated during both the dry and the wet seasons – intensive system); and (3) Rice-Mungbean (wet season rice being followed by an upland crop – diversified system). However, the relative spatial extent of these systems differs by the marginality of site conditions. Thus, in Patuakhali (marginal site), the extensive single rice system with land left to fallow or used as grazing ground during the dry season covers 16% of the total cultivable land. Due to water-limitations and high soil salinity during the dry season, the rice double cropping (intensive system) is restricted to only 2% of the arable land area. Rice-upland crop rotation (diversified system) cover 36% of the cultivable land, with a predominance of mungbean as the dry season component crop (Department of Agricultural Extension – DAE, 2023). In contrast, at the favorable site in Barishal, single rice occupies 14%, double rice 11%, and mixed cropping 13% of the arable land area. The remaining 48–52% of the arable land area at both sites are cultivated to jute, fruit trees or other perennials and plantation crops.

2.2 Field survey and data collection

To address our research objectives, we combined (1) primary data collection, gathered through a diachronic household survey as outlined in Becker et al. (2023), and (2) secondary data sources obtained from the Bangladesh Bureau of Statistics (BBS). The diachronic household survey was conducted during in March and April 2022 at both locations using semi-structured survey questionnaires. Farmers were identified randomly from census-based lists of households. Farmer's verbal consent was obtained prior to each interview. Participation in the study was voluntary, with only farmers expressing interest and willingness to respond being included.

From the resulting sub-sample, we selected 40 households each, applying either extensive rice single cropping, irrigated rice double cropping, or rice-mungbean rotations at both the marginal and the favorable sites, resulting in 120 farmers per site and a total of 240 farmers across sites. This selection was done with support of field officers from the Department of Agricultural Extension. The questionnaire-based survey assessed changes in agronomic practices and crop yields during the past decade, comparing 2021 with 2011. The data for 2011 were collected as recall. The structured interviews were conducted by well-trained enumerators (university graduates), addressing the household heads. Questions assessed past and current agronomic practices applied in wet season rice, and, where applicable, in the cultivation of dry season rice and mungbean. All data were recorded either at the farmer's residence or in the field. In addition, composite topsoil samples (0–20 cm) were collected from seven sampling points along a diagonal of each field for subsequent laboratory analyses.

Table 2 provides a detailed breakdown of eleven intensification-related agronomic practices applied in the three contrasting cropping systems. We measured current (farmers' records) and estimated past (remembered) crop yields. Exact field sizes were obtained by walking around each plot with a GPS device. Subsequently, the possibly less reliable past crop yields were compared with relevant national statistics to confirm accuracy and consistency. Furthermore, the economic yield, accounting for both wet and dry season crops, was calculated considering the

TABLE 2 Intensification-related cropping practices in coastal Bangladesh.

Practices	Description
Cropping system (rotation)	Wet season rice – fallow Rice double cropping Rice–mungbean rotation
Genotype	Traditional vs. modern high-yielding or hybrid varieties
Soil tillage	Animal plow vs. power tiller and/or tractor
Harvest	Manual vs. reaper/combine harvester
Organic amendments	Application of farm yard manure and return of rice straw
Mineral N fertilizer	Application rates of urea
Recommended mineral N rates	2011 – WS rice: 45 $kg\ ha^{-1}$, DS rice: 120 $kg\ ha^{-1}$, mungbean: 18 $kg\ ha^{-1}$ 2021 – WS rice: 90 $kg\ ha^{-1}$, DS rice: 180 $kg\ ha^{-1}$, mungbean: 18 $kg\ ha^{-1}$
Mineral N fertilizer split	Single application vs. split of basal and top-dressed N
Non–N fertilizer	Application of P, K, S, Zn fertilizer (sole or in combination)
Weed control	Manual weeding vs. herbicide use
Pest control	Insecticide use
Disease control	Fungicide use

Recommended doses of mineral fertilizers are based on the national fertilizer recommendation guides for the year 2011 and 2021 of the Bangladesh Agriculture Research Council (BARC). WS, wet season; and DS, dry season.

market price at the respective year's harvest time as per reported by Bangladesh Bureau of Statistics (Bangladesh Bureau of Statistics – BBS, 2014, 2023). For international comparison, exchange rates were applied based on the Bangladesh Bank Forex Department, with 1 Euro = 105.46 BDT (Bangladesh Taka) in 2011 and 1 Euro = 100.96 BDT in 2021.

2.3 Data analysis and visualization

Survey and field data were transferred to digital spreadsheets and cleaned, following a plausibility check. The aggregate level of land use intensification was expressed first at the level of the individual farmer. It was calculated as the cumulative share of intensification practices been applied, ranging from 0% (no intensification practice adopted) to 100% (all eleven intensification-related practices adopted). Subsequently, the percentage shares of farmers adopting specific agronomic practices (qualitative or categorical data) were used for change detection analysis between years (2011 vs. 2021) within each category, comprising sites (favorable vs. marginal), seasons (dry vs. wet season) and crops. Quantitative data were analyzed following a test of normality of data distribution by Shapiro-Wilk test. For non-normally distributed data, such as the grain yield at the favorable site, the non-parametric Mann-Whitney U test was used to detect difference between groups. In the case of normally distributed data, we applied a homogeneity test (Levene's test). While homogenous data were subjected to one-way ANOVA and mean separation by Tukey's test, significance levels of heterogeneous data were compared using Welch's test. All data were analyzed using SPSS Statistics Version 27.

Changes in productivity attributes and the type of adopted practices were additionally visualized using a cluster heat map approach (modified after Wilkinson and Friendly, 2009).

3 Results

Farmers in coastal Bangladesh have intensified their crop management practices in the past ten years. This intensification is reflected in larger areas used for food crop cultivation, in growing shares of farmers cultivating during the dry season, but also in modifying crop agronomic practices, which has been associated with higher outputs and general increases in various system performance attributes. However, the type, the extent, and the speed of the observed changes differ by season and by the marginality of site conditions as shown in the subsequent sections.

3.1 Land systems and land use intensity

The cropped land in Barishal District of coastal Bangladesh covers some 270,000 ha and is dominated to 94–98% by rice or rice-based cropping systems (Supplementary Table S1). The rice area covers 150,000 ha at the favorable and 203,000 ha at the marginal sites (Figure 2A). Based on the national statistics from 2014 and 2021 (no data available from 2011), we observe a slight expansion of the total cropped area from 158,000 to 163,000 ha at the favorable and a slight decline from 212,000 to 204,000 ha at the marginal sites.

However, substantial changes were observed regarding the land use intensity. Thus, the extensive single rice system with dry season fallow declined from 29,000 to 22,000 ha at the favorable and from

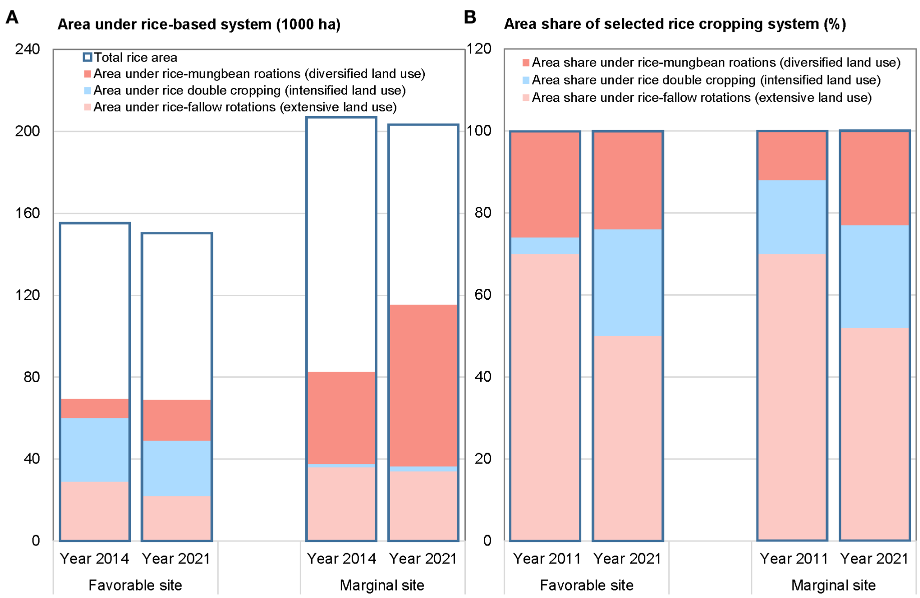

FIGURE 2
Land uses and recent change trends in rice-based cropping systems in Barishal (favorable site) and Patuakhali (marginal site) of coastal Bangladesh. **(A)** Data from Bangladesh Bureau of Statistics, Department of Agricultural Extension (2014 and 2021) expressed in 1000 ha; **(B)** Own survey data (2011 and 2021) considering the three main rice-based cropping systems extensification, intensification, and diversification of rice-based cropping systems expressed as percentage share of the total land (n = 120 farmers).

36,000 to 34,000 ha at the marginal sites between 2014 and 2021. On the other hand, land use has intensified by replacing the dry season fallow by either irrigated rice (intensification) or by mungbean and other upland crops (diversification). Thus, the share of irrigated rice double cropping has decreased from 31,000 to 27,000 ha at the favorable, and increased from 2,000 to 2,600 ha at the marginal sites. Rice mungbean rotations are more prominent at the marginal (79,000 ha) than the favorable sites (20,000 ha). Their share has nearly doubled between 2014 and 2021 at both sites, reaching 13 and 38% of the total rice-based land area at the favorable and marginal sites, respectively. The importance of other rice-based land uses (wheat, vegetables) has declined and was gradually replaced by intensification (double rice) or diversification (rice-mungbean) options.

This shift in land use from extensive single rice to intensive rice double cropping or diversified rice-mungbean rotations was even more pronounced in the limited subsample of 120 farmers in the own survey (Figure 2B). Thus, we observed declines in extensive single rice cropping from 70 to 50% of the surveyed farmers at the favorable and from 71 to 52% at the marginal sites between 2011 and 2021. Conversely, the share with intensified land use by irrigated double cropping of rice has increased from 2011 to 2021 by 22 and 8%, at the favorable and marginal sites, respectively. Diversification by adopting rice-mungbean rotations has increased by 13% of all surveyed farmers at the marginal site. However, at the favorable site, a further expansion of dry season crop growth was not visible, at least at our survey sites, and the share of crop diversification remained constant at around 25%.

3.2 Intensification-related agronomic practices

Crop production practices constantly change, and are an expression of farmers' adaptive capacity to respond to external pressures or changing needs. Agronomic practices may be adopted (1) in view of increasing yields or partial factor productivity of purchased inputs, or (2) to reduce labor demand. They may comprise the use of modern high-yielding genotypes, the use and efficient management of external inputs, and the mechanization of diverse operation steps. In the rice-based production systems of coastal Bangladesh, we observed differential trends in cropping intensification between sites, seasons and component crops. The aggregate level of land use intensification was calculated at the cumulative level of the farmer adopting any number of the eleven predefined intensification practices within component crops and among sites and are presented thereafter. Subsequently, we present changes in farmers adopting individual intensification practices between 2011 and 2021, differentiating marginal and favorable sites.

3.2.1 Aggregate changes and trends

When aggregating adoption rates across all eleven intensification-related land use and cropping practices, the mean intensification level across farmers in the sample was very low in 2011. It reached a mean of only 4% of adopted intensification practices at the favorable and about 22% at the marginal site. The level of intensification in 2011 was generally higher at the marginal than at the favorable sites and it increased by about 20% in the last decade, irrespective of the site, reaching aggregate levels of intensification of 42 and 56% at the favorable and the marginal sites, respectively. The rate of adoption of intensification-related practices (differences between 2011 and 2021) was much lower in (rainfed) wet than in (irrigated) dry season rice, but was generally higher at the marginal that at the favorable site (Figure 3). The largest recent increases in adopting intensification practices were observed in mungbean, with 30% increase at the favorable and with only 18% at the marginal site. Across crops, intensity of cropping in 2021 was more in the dry than in the wet season, and generally more at the marginal than at the favorable site. However, the highest rates of adoption were observed at the favorable site, reaching aggregate levels of intensification of nearly 50% in mungbean and in dry season rice.

3.2.2 Intensification-related practices

A separation of these aggregate change trends by individual agronomic practices (percentage share of farmers adopting a giving practice) provides a more differentiated pattern of land use intensification (Figure 4). Among the agronomic practices, largest levels of recent adoption were observed with mechanizing the land preparation (>90% of all farmers adopting tractor tillage), followed by the use of mineral N fertilizers (68%), of insecticides (62%), and of non-N fertilizers (60%). Largest rates of change occurred at the favorable site, with increases in the adoption of mineral N fertilizers by 67%, of tractor tillage by 62%, of non-N fertilizers by 52%, and of high-yielding genotypes by 36%. While starting at a much higher level of intensification in 2011, the rates of change never exceeded

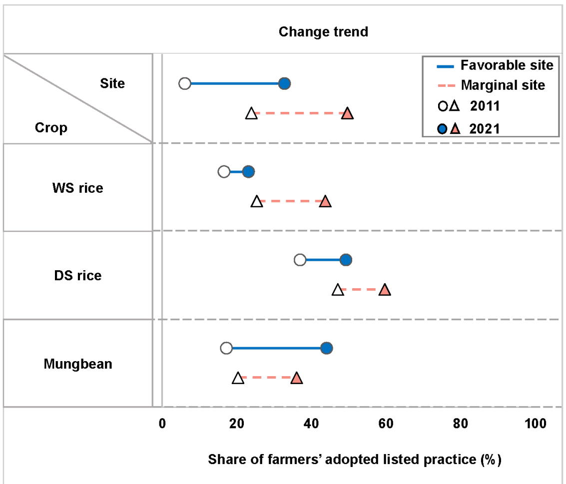

FIGURE 3
Aggregated change across intensification related crop agronomic practices between 2011 and 2021 at favorable and marginal sites in coastal Bangladesh, differentiated by component crops (rice and mungbean). The aggregate level of land use intensification was calculated as the cumulative share of intensification practices been applied, ranging from 0% (no intensification practice adopted) to 100% (all eleven intensification-related practices adopted) (WS, wet season; DS, dry season).

the 30% increase in any of the practices at the marginal site. Practices that were not or hardly adopted during the past decade concern mainly the favorable site and comprise harvest by combine harvester, the application of organic amendments, and use of herbicides and fungicides.

On the other hand, the use of pesticides reached 32, 37, and 76% of all farmers applying herbicides, fungicides and insecticides, respectively in 2021 at the marginal site, where farmers reported pests and disease being the main production constraints. It was also only at the marginal site that pests and diseases were perceived to be associated with land use intensification, affecting mainly the dry season crops of rice and mungbean (data not presented). A further differentiation of adoption levels and rates of change for individual component crops is presented in the Supplementary Materials (Supplementary Table S2).

3.3 Crop performance attributes

The main reason for adopting intensification-related agronomic practices is an increase in performance attributes, including grain and economic yields and the partial factor productivity (input use efficiency) of fertilizers and labor. The grain yields of all crops (wet season rice, dry season rice and dry season mungbean) have increased in the past 10 years, irrespective of the site. This implied increases in the yield of wet season rice from 2.2 in 2011 to 2.9 t ha^{-1} in 2022 (+30%). During the same time, the yield of dry season rice increased from 2.9 to 4.8 t ha^{-1} (+60%) und that of mungbean from 0.6 to 0.9 t ha^{-1} (+40%).

The resulting aggregate changes (cumulative yield of all component crops) were similar between marginal and favorable sites, and the increase from 2011 to 2022 was highly significant ($P<0.001$). Thus, cumulative yields increased from 1.9 to 2.8 t ha^{-1} at the marginal and from 2.0 to 2.9 t ha^{-1} at the favorable site (Figures 5A, B). However, yields tended to be more variable at the marginal (coefficients of variation – CV of >55%) than at the favorable site (CV of 45–49%). With a grain yield of 5.5 t ha^{-1}, irrigated dry season rice was not only the highest-yielding component crop but also to one showing the largest yield increase in the past 10 years (+64% at the marginal and +93% at the favorable site) and the lowest between-field yield variability (CV~15%). Location-specific differences in yield increases and yield

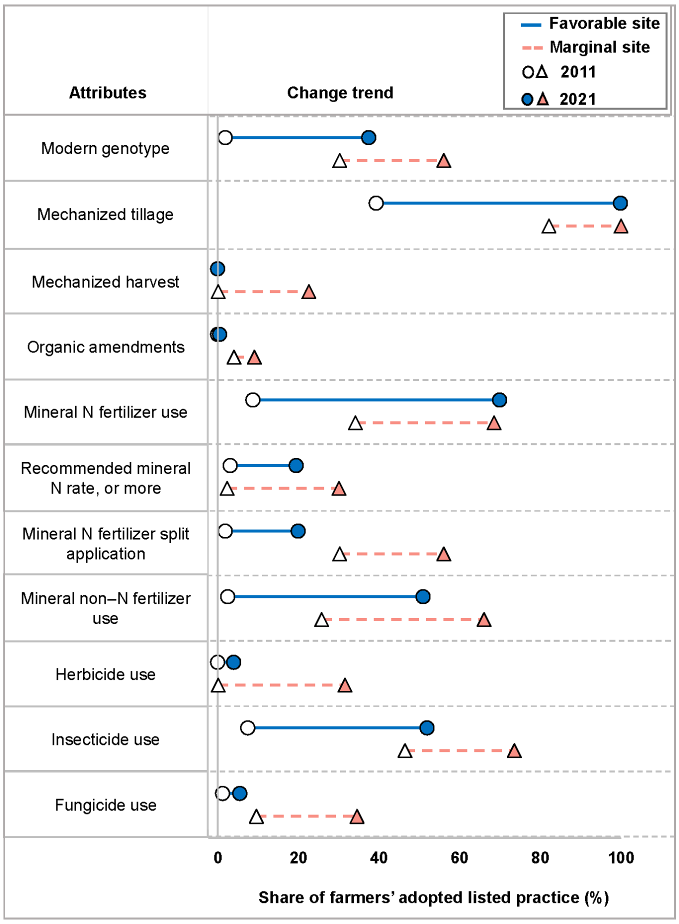

FIGURE 4
Change trends in in intensification related crop agronomic practices, comparing between favorable and marginal sites in both past (year 2011) and present (year 2021) in coastal Bangladesh.

variabilities of wet season rice and mungbean were less pronounced (Figures 5C, D). The national statistics of these particular sites showed diverse change trends (Supplementary Table S3). The yield of dry season rice increased in both site i.e., 3.9 to 4.1 t ha^{-1} (+2.9%) in favorable site and 2.5 to 3 t ha^{-1} (+19%) in marginal site. However, while mungbean yield increased 23% (0.8–1.1 t ha^{-1}) in favorable site but decreased 28% (0.7–0.5 t ha^{-1}) in marginal site. Counter wise, wet season rice increased 20% (1.7–2.1 t ha^{-1}) in marginal site while favorable site showed decreased trend (−8%, 2.1–1.9 t ha^{-1}).

The monetary revenue generated by farmers from the three production systems highlights the benefits of system diversification, particularly of land use intensification by rice double cropping (Figures 5E, F). Thus, double rice provided ~2,200 € ha^{-1} year^{-1}, while rice-mungbean yielded ~1,300 € and single wet season rice only ~750 € ha^{-1} year^{-1}. The substantial increase in revenues from 2011 to 2022 from both diversified (rice-mungbean) and intensified cropping (double rice) was partially an effect of modest yield increases, but particularly the result of more farmers shifting from single rice to multiple cropping (increase from 5–50% adopters in 2011 to >80% adopters in 2022).

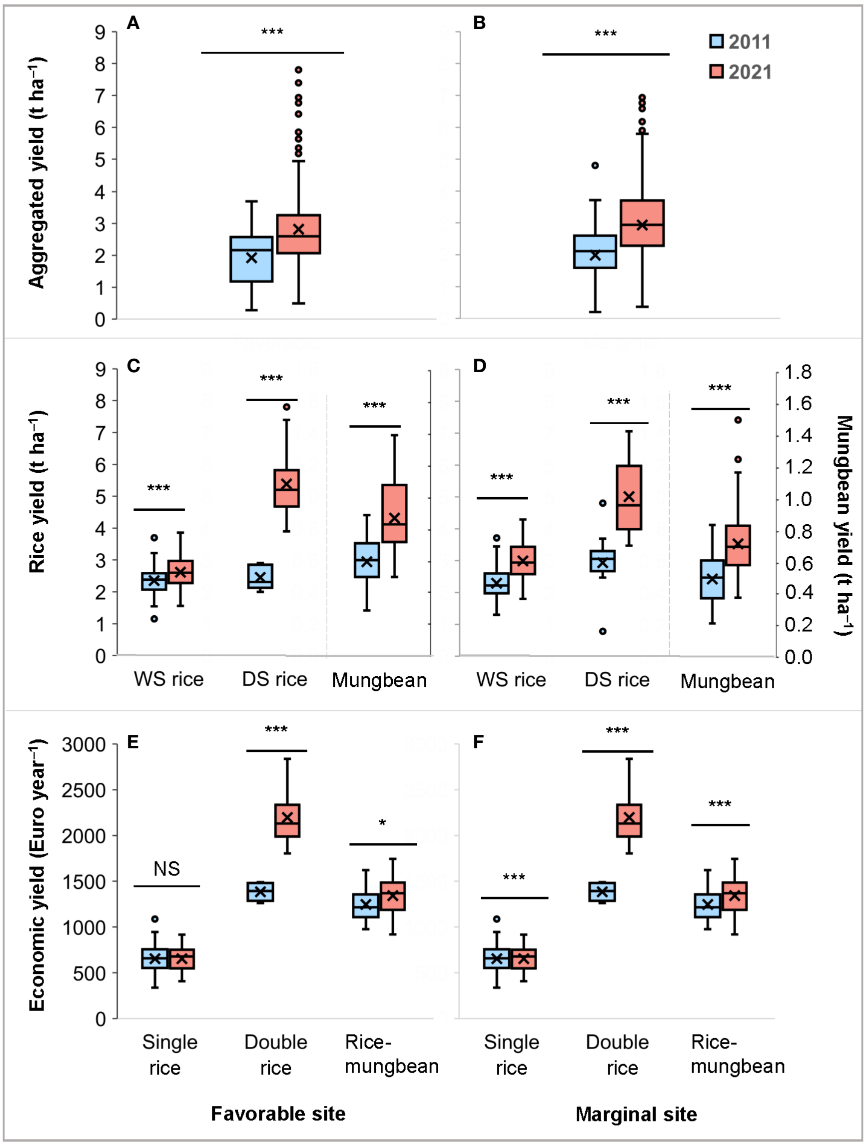

FIGURE 5
Grain yields (1) aggregated across component crops **(A, B)**, (2) of individual crops **(C, D)**, and (3) expressed as monetary revenue (economic yield) of the production systems **(E, F)**, differentiated by site attributes (marginal vs. favorable site) and between past and present (2011 vs. 2021). ***, * significance level at 0.001, 0.05. Primary and secondary Y-axes **(C, D)** denote grain yields of rice and of mungbean, respectively. The economic yield was calculated as the cumulative revenue from component crops based on harvested amounts and the produce values at the respective year's market prices by Bangladesh Bureau of Statistics (BBS) and currency exchange rates as per Foreign exchange of Bangladesh Bank. Inflation was adjusted using respective year consumer price index as indicated by BBS. WS, wet season; DS, dry season; NS, non-significant.

3.4 Patterns of change

The above-reported observed changes in intensification-related agronomic practices and in crop yields between 2011 and 2021 are summarized and visually illustrated by a cluster heat map (Figure 6). While most practices and performance attributes showed increasing trends in the past 10 years (red color), some labor-intensive operations such as tillage, harvest, and the application of organic amendments either showed decreasing trends (blue color) or remained largely unchanged. The intensity of change (as illustrated by the darker colors) was higher at the favorable than at the marginal sites, and was more pronounced during the dry than the wet season, and the associated component crops.

The adoption of modern genotype has increased at both sites, but was higher in dry than in wet season crops. Largest changes were apparent for the adoption of labor saving strategies, with a pronounced shift from animal to tractor tillage, and from manual to machine harvesting, particularly at the favorable site. Practices such as the use and the split application of mineral N fertilizers increased at all sites and in all component crops, but tended to be highest in irrigated dry season rice and mungbean. Pesticide use increased most at the marginal site, particularly in dry season crops. Overall, grain yields increased during the past 10 years, and the extent of yield increases reflect the rates of adopting intensification-related agronomic practices.

4 Discussion

4.1 Determinants of land system change

Land use and crop production systems continuously change. The general trend is a move towards system intensification, which concerns the application of practices to meet changing human needs, while contributing to resilience and sustainability of landscapes (Rockström et al., 2017). Intensification can comprise conversions among land use categories but also intensity changes within these categories (Levers et al., 2018). The extent of intensification can refer to land expansion, the intensification of agronomic practices, the substitution of land and labor by capital investments (mechanization and agrochemical uses), or production strategies that increase the use efficiency of inputs or production factors (mechanization, multiple split application of mineral N). Besides intensification, further strategies e.g., crop rotation, agroecology, agroforestry, livestock integration, community based approach etc., may concern the diversification of the crop portfolio or the adoption of conservation practices.

Land systems are subject to exogenous pressure from global incidence such as demographic growth, climate change, the globalization of value chains, and transnational policy changes, which are generally considered drivers of change (Foley et al., 2005). However, such exogenous pressures do not solely determine changes of social-ecological systems, and the availability of technological innovations and system-inherent determinants may additionally influence system transformation dynamics (Peel et al., 2016). Innovations such as modern genotypes, mechanization, and the provision of IT services have been shown to boost crop production or to modify land systems, and to shape the intensity, the trajectories, and the types of emerging patterns of land use (Becker and Angulo, 2019). In addition, the biophysical site conditions (marginality) and the households' resource endowment (wealth status) determine farmers' adaptive capacity and hence the extent and direction of expected changes (Struik and Kuyper, 2017). Thus, location factors and farm/farmer characteristics interact differentially with economic, technological, demographic, institutional, and sociocultural processes, and shape the transformation of production systems (Becker et al., 2023). In the present study, we illustrated the differential transformation (pathways of change) and emerging land systems (patterns of

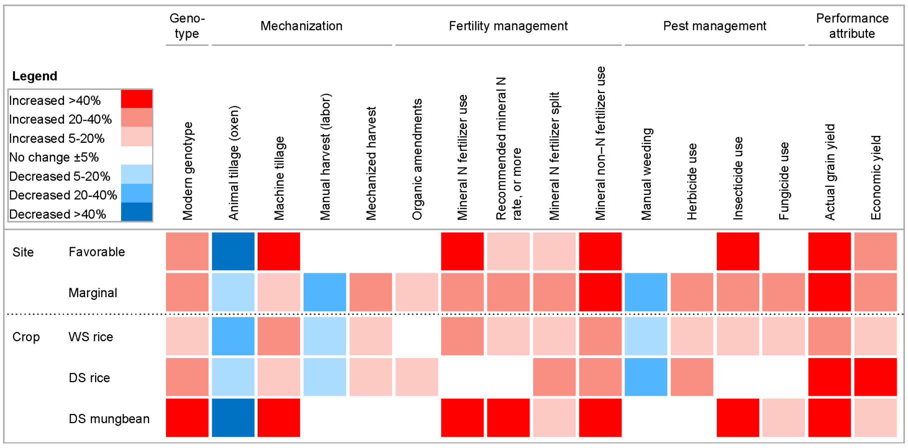

FIGURE 6
Change detection of intensification-related agronomic practices and associated grain yields at favorable or marginal sites in different component crops (wet season rice, dry season rice, and mungbean) and seasons in coastal Bangladesh. The intensity of colors visualizes the extent of observed changes, with ±5% indicating no change (white), 5–20 and 20–40% increase (light and dark red) and with 5–20 and 20–40% decline (light and dark blue). WS, wet season; DS, dry season. Sample size: favorable (n = 120), marginal (n = 120).

change) at both favorable and marginal rice production sites of coastal Bangladesh.

4.2 Change trends in cropping systems of Bangladesh

In recent years, Bangladesh has experienced notable changes in its cropping systems and land use trends, partially driven by population pressure, climate change, and government initiatives (Timsina et al., 2018; Islam et al., 2021). One of the prominent features of Bangladesh's agriculture is its diversity in cropping systems (Nasim et al., 2018). The majority of the cultivated land in Bangladesh is dedicated to rice-based cropping systems, serving as the primary contributor to the country's food security (Bangladesh Bureau of Statistics – BBS, 2023). Our study reveals that rice-based systems occupy >90% of the net (actual) cropped area at both the favorable and the marginal sites (Figure 2, Supplementary Table S1). A key driving force of the observed land use trends is related to policy intervention by the government, emphasizing the aim of achieving food security through intensification and diversification, particularly in the coastal zone of Bangladesh (Assefa et al., 2021). We can differentiate three rice-growing seasons namely the wet season (rainfed rice), the dry season (irrigated rice) and the spring season (partially irrigated rice). Particularly wet and dry season rice (and to a much lesser extent the spring season rice) contributors to total production. The main cropping system in coastal Bangladesh is the single rice system, where wet season rice is followed by an extended, partially grazed fallow period during the dry season. The area of this extensive single rice cropping system is decreasing, and the fallow vegetation is being replaced by either low-input crops such mungbean and lathyrus (Schulthess et al., 2019) at rural sites, and by high-input and high-value vegetable crops at peri-urban sites (Manickam et al., 2023). However, the dominant government strategy to increase cropping intensity in coastal Bangladesh has been the promotion and development support of irrigated dry-season rice (Al Mamun et al., 2021). This included policies that enhance the access to loans, the promotion of technologies to efficiently manage mineral N fertilizers, improved access to superior-grade seeds from both the public and the private sectors, and technological advancements by breeding research for site-adapted high-yielding genotypes (Emran et al., 2022). The implications of such interventions were also noticeable in the present study, where we observed a substantial increase in dry season crop production, irrespective of site conditions. Similar results were also reported from other studies in Southeast Asia (Becker et al., 2023). The observed system diversification by inclusion of mungbean in the rotations will require similar efforts and the development of new salinity- and drought-tolerant genotypes, particularly for the marginal sites (Schulthess et al., 2019).

However, these intensification strategies may frequently be constrained by water shortage and by soil and water salinity, increasing the risk of crop losses for smallholder farmers. This risk of failing returns to their investments, prevent or reduce farmers' willingness to adopt intensification practices (Roth et al., 2023). Reducing production risks and achieving sustainable intensification can only be achieved by developing irrigation infrastructure and improving water management approaches (Krupnik et al., 2017). These may be combined with no-till soil cultivation, green manure application, and the adoption of high-value crop-based rotations (Mandal et al., 2022). Finally, a further intensification may be possible by including additional short-cycled crops in either the pre- or the post-rice cropping niches that may further increase farm productivity and farmers' income (Malik et al., 2017). Such strategies, may involve the inclusion of pre-rice green manure legumes (Becker et al., 2007), of pre-rice mungbean (Ro et al., 2016), or of post-rice vegetables (Shrestha et al., 2020), as reported from other areas in South and Southeast Asia.

4.3 Change trends in agronomic practices

4.3.1 Modern genotypes

Several crop management practices in the rice-based systems of coastal Bangladesh have changed, leading to their intensification. Thus, the adoption of modern genotypes has increased, but it was higher at the favorable than at the marginal site, and it concerned primarily dry season crops (Figure 4; Supplementary Table S2). This observed trend is confirmed by historical data from the Bangladesh Bureau of Statistics (2011–2023), indicating recent adoption rates of modern genotypes increasing during for both seasons, but reaching >54% in dry season rice. Comparable trends were reported in Cambodia, Myanmar and the Philippines, where large-scale adoption of modern genotypes benefitted mainly the dry season crop in intensive double rice system (Becker et al., 2023). Farmers residing in marginal sites have embraced modern crop varieties, possibly in reaction to the difficulties presented by salinity intrusion, prompting a shift towards tolerant crop types (Billah et al., 2017). Conversely, farmers in non-saline regions adopt such varieties as a component of diversification and adaptation tactics aimed at mitigating risks in crop cultivation (Sarker et al., 2022). Nevertheless, the pace of adopting modern genotypes fluctuates due to a multifaceted interaction among environmental factors, socioeconomic circumstances, and governmental policies (Lassoued et al., 2018).

4.3.2 Mechanization

Emerging labor shortages and increasing labor costs are key determinants of farmers' investing in the mechanization of tillage, weeding and harvest operations (Becker et al., 2023). Also in Bangladesh, like in most other rice-based systems of South and Southeast Asia (Hossen et al., 2020; Becker et al., 2023), we observed an increased use of machinery. Our results revealed that all interviewed farmers have recently adopted the use of machine tillage at both study sites (Figure 4). However, the rate of increase was higher at the favorable than at the marginal site, where the use of tractors was already four times higher in 2011 (Bangladesh Bureau of Statistics – BBS, 2014, 2023). In addition, even at the marginal site only 4% of farming households own tillers or tractors, while the vast majority of farmers (89%) opt to rent machinery for soil tillage (Diao et al., 2020).

In contrast to tillage operations, and also in contrast to favorable sites in coastal Cambodia (Becker et al., 2023), the mechanization of the rice harvest is much lower in coastal Bangladesh, where it was largely restricted to the marginal site, while harvesters were mostly absent and rice is still being harvested manually at the favorable site (Figure 4; Supplementary Table S2). Apart from the high price of combine harvesters, machine harvesting of mungbean is additionally constrained by its uneven maturation and pod-shattering. Similarly, the use of drilling machines for direct seeding of rice or for the mechanical establishment of mungbean is low, despite notable benefits for the evenness of crop establishment and for labor savings (https://csisa.org/accelerating-adoption-of-direct-seeded-rice-in-bangladesh-and-nepal/). On the other hand, the potential for mechanizing crop establishment and harvest as high, also at the favorable site, as indicated by large numbers of government-supported and internationally-funded agricultural mechanization projects across the country (Rahman et al., 2021).

4.3.3 Fertility management

A significant number of farmers recently opted for applying increasing quantities of inorganic fertilizers, particularly at sites with poor availability of organic amendments. On the other hand, the overall application of farmyard manure has increased at both sites, with higher application rates at the marginal than at the favorable site (Figure 4). This difference between sites is informed by larger numbers of livestock owned, and hence by large amounts of manure being available at the marginal site. Such relationships between livestock ownership and herd sizes (in addition to the availability of labor for manual manure application) on the decision to apply manure have also been shown for rice-based systems in Cambodia and Myanmar (Becker et al., 2023). In addition, recent increases in fertilizer prices and the untimely availability of mineral fertilizers induce farmers to look for alternatives, and further stimulate the use of organic amendments (compost, farm-yard manure, and rice straw) for soil fertility management. However, even for adopters, the use of farmyard manure is no stand-alone strategy, and it is in most cases combined with using mineral (both N and non-N sources). Application rates of mineral N need to increase (Bijay-Singh et al., 2022), while also non-N fertilizers (mainly P, K and Zn) must be increasingly applied in the coming decade (Penuelas et al., 2023) to meet the growing food demand. Given recent price spikes, partially related to the Russia-Ukraine war, and potentially undesired environmental side-effects (Snapp et al., 2023), particularly the mineral N fertilizers need to be used more efficiently. Measures to increase the efficiency of applied mineral N comprise not exceeding the recommended rates and the multiple splitting of the N application in view of improving the supply-demand synchrony (Hegde et al., 2007). They may also involve integrated fertility management strategies, combining organic and inorganic sources to optimize fertilizer use (Snapp et al., 2023). In the present study, the number of farmers that apply mineral N at recommended rate and in serval split doses was low in the past and has recently increased to around 20%. However, >60% of the farmers in Bangladesh still apply less than the recommended rate and do so only by one single basal application, irrespective of the site (Figure 4). This result is similar to the study by Islam et al. (2022) where they reported that small holder farmers practicing single or double rice applied less than the recommended dose of mineral N, K and other micro nutrients. However, this observation contrasts with other regions in Southeast Asia, where high N rates and multiple split applications predominate the fertilizer management in rice-based systems (Becker et al., 2023). Moreover, the introduction of modern genotype, unbalanced use of fertilizer, and challenges in water supply led to an increase in fertilization over time (Bell et al., 2015).

4.3.4 Pest and disease management

The number and intensity of biotic stress events (weed, insects and pests) have increased at both the favorable and the marginal sites, inducing farmers to increasingly adopted control measures (Figure 4). While not being considered to be a main production constraint in 2011, weeds today are causing significant yield losses in Bangladesh (Ahmed et al., 2021) and are perceived key constraints throughout the coastal region. Control strategies involve manual weeding and application of herbicides. Particularly in labor-scarce environments, herbicide-based weed control has more than doubled in the past decade (Bangladesh Bureau of Statistics – BBS, 2023). Similarly, the perceived importance of insect pests has significantly increased, with most prominent problems being the yellow stem borer, the green leafhopper, the case worm, and field crickets (Morshed et al., 2023). We observed largest shares of farmers applying insecticides at the marginal (saline) site, and more so in the wet than in the dry seasons (Figure 4, Supplementary Table S2). Salinity is a universal threat for crop plants and will have negative impact on their yield. To recover the yield loss, farmers apply more fertilizers, particularly nitrogen, which can indeed cause more insect abundance in rice production (Rashid et al., 2017). Farmers may overestimate losses caused by insects, leading to the application of more insecticides despite poor productivity gains (Heong et al., 2015). Additionally, it has been reported that the abundance of insects in rice fields in Bangladesh was higher in wet season (July–December) (Morshed et al., 2023). In addition to intensified (near permanent) land use, particularly shifts in climate patterns and more frequent of extreme weather events have contributed to the increased prevalence of various rice diseases (Mousumi et al., 2023), with the rice double cropping system at the marginal site being most vulnerable to disease outbreaks (mainly rice blast – *Magnaporte griseae* and bacterial blight). In consequence, the use of all pesticides combined has increased 5-fold during the past 25 years (Bangladesh Bureau of Statistics – BBS, 2023), with increasing associated risks for biodiversity and human health (Sarker et al., 2021). However, in the absence of effective alternative solutions, a substantial reduction in pesticide use in rice-based systems appears unrealistic at present.

4.4 Past, present (and future) system performance

System performance is crucial for agricultural sustainability, food security and the well-being of farming communities, and crop yields are one of the main indicators of the overall performance of cropping systems. In the present study, yields of both rice and non-rice crops have significantly increased in the past decade, with largest yields but also largest income gains in dry season rice (Figure 5) as also reported elsewhere (Raghu et al., 2016; Al Mamun et al., 2021). Thus, the intensive irrigated double rice system provided the largest economic yield as reported earlier in other regions in Bangladesh (Assefa et al., 2021; Emran et al., 2022). However, particularly dry season rice has highest demands for applied nutrients and particularly for water. With emerging water limitations for dry season cultivation, modified sowing dates and innovations for more efficient irrigation water management are urgently required (Gaydon et al., 2021).

Low productivity of rice and non-rice crops in the past were associated with the predominating subsistence orientation, high labor inputs in the absence of mechanization options, and the widespread use of traditional (non-input-responsive) crop cultivars (Becker et al., 2023). At present, rice-based systems in Bangladesh have started to intensify, involving double or multiple cropping (near permanent land use) and the widespread and increasing adoption of laborsaving technologies (mainly mechanization), and to a lesser extent improved plant nutrient and soil fertility management practices (Shew et al., 2019; Becker et al., 2023). Such interventions combined with the introduction of high-yielding and hybrid rice varieties have the potential to increase overall crop production in the coastal zone, with particularly dry season crop cultivation being expected to become the main contributor towards meeting the growing food demand (Mainuddin et al., 2021).

Improved soil fertility management and nutrient supply (both from organic and mineral sources) are essential for increasing crop production as shown before and from several other areas in South and Southeast Asia (Becker et al., 2023). However, in the absence of timely-available mineral fertilizers (also non-N sources) and poor agronomic management of such inputs (e.g., N splitting) there is only poor synchrony of nutrient supply and crop nutrient demand and input use efficiencies remain low (Panwar et al., 2019). Thus, future performance of rice-based systems in coastal Bangladesh must increase and substantial transformations (beyond those reported here for the past decade) will be needed. Despite an uncertainty on past data used in this study, where past data were collected based on recalling individual memory and perceived information, the diachronic approach was already used as an alternative to panel data collected in different time series for data scarce regions (Becker et al., 2023). The limitation of the study is that the temporal scope of this study is relatively short (a decade) and further studies on the long-term data collection might be needed to reveal longer-term trends and patterns in farmers' adaptation strategies to changing climate and production practices. Besides that, our study reveals that the adoption of modern genotypes, advanced technologies and proper fertility management strategies might play pivotal roles for achieving the required sustainable intensification of rice-based systems in both Barishal and Patuakhali districts, and potentially to other adjacent coastal regions in Bangladesh.

4.5 Conclusion and future perspectives

Rice-based agriculture in Bangladesh has undergone significant transformations in the last decade. The coastal regions were predominantly dedicated to extensive subsistence-oriented rice production during the wet season in the past, but they are potential prime intervention areas for future sustainable intensification.

We observed recent land use intensity changes, mainly by dry season cropping of irrigated rice or mungbean. In addition, we see emerging changes in the adoption of agronomic management practices towards intensifying land systems in both favorable and marginal environments. Major emerging practices concern the adoption of modern high-yielding genotypes, the mechanization of tillage and harvest operations, and an increased use of mineral fertilizers. Intensification-associated production constraints gaining importance concern biotic stressors such as weeds, pests and diseases, and soil fertility decline in both areas. Intensification of land systems appears possible mainly by further expanding dry season crop uses. This requires investments in irrigation infrastructure for dry season rice in the marginal, salt-effected areas, and a more efficient use of available green and blue water resources for diversified upland cropping, particularly in favorable areas.

With emerging labor and water shortages and imbalanced fertilizer use, research and development must provide stress-adapted genotypes and management practices increasing the use efficiency of applied mineral fertilizers by improving nutrient supply-demand synchronies. In the policy arena, interventions that improve farmers' linkages to input and output markets and fostering the adoption of mechanization will pave the way for agricultural transformation and the large-scale intensification of land systems.

The present study also showed that diachronic surveys are suitable for identifying recent processes and likely drivers of change, while heat maps of change are a simple tool contributing to elaborate and visualize emerging patterns of change in coastal Bangladesh.

Web resources

https://gaez-services.fao.org/, accessed Nov 2023. https://csisa.org/accelerating-adoption-of-direct-seeded-rice-in-bangladesh-and-nepal/, accessed Nov 2023.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MAI: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. SP: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Project administration. TK: Conceptualization, Methodology, Supervision, Writing – review &

editing. MB: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing, Project administration.

Funding

The authors declare financial support was received for the research and publication of this article. The research activities were financed by the Academy for International Agricultural Research (ACINAR). ACINAR is commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ), and is being carried out by ATSAF e.V. Germany (ATSAF Grant ID 70210) on the behalf of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Germany.

Conflict of interest

Author TK was employed by International Maize and Wheat Improvement Center (CIMMYT).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2024.1397474/full#supplementary-material.

References

Ahmed, S., Kumar, V., Alam, M., Dewan, M. R., Bhuiyan, K. A., Miajy, A. A., et al. (2021). Integrated weed management in transplanted rice: Options for addressing labor constraints and improving farmers' income in Bangladesh. *Weed Technol.* 35, 697–709. doi: 10.1017/wet.2021.50

Alam, M. J., Al-Mahmud, A., Islam, M. A., Hossain, M. F., Ali, M. A., Dessoky, E. S., et al. (2021). Crop diversification in rice-based cropping systems improves the system productivity, profitability and sustainability. *Sustainability.* 13, 6288. doi: 10.3390/su13116288

Alam, M. M., Karim, M. R., and Ladha, J. K. (2013). Integrating best management practices for rice with farmers' crop management techniques: A potential option for minimizing rice yield gap. *Field Crops Res.* 144, 62–68. doi: 10.1016/j.fcr.2013.01.010

Al Mamun, M. A., Nihad, S. A. I., Sarkar, M. A. R., Aziz, M. A., Qayum, M. A., Ahmed, R., et al. (2021). Growth and trend analysis of area, production and yield of rice: A scenario of rice security in Bangladesh. *PloS One* 16, e0261128. doi: 10.1371/journal.pone.0261128

Aravindakshan, S., Krupnik, T. J., Groot, J. C. J., Speelman, E. N., Amjath-Babu, T. S., and Tittonell, P. (2020). Multi-level socioecological drivers of agrarian change: Longitudinal evidence from mixed rice-livestock-aquaculture farming systems of Bangladesh. *Agric. Syst.* 177, 102695. doi: 10.1016/j.agsy.2019.102695

Aryal, J. P., Sapkota, T. B., Khurana, R., Khatri-Chhetri, A., Rahut, D. B., and Jat, M. L. (2020). Climate change and agriculture in South Asia: Adaptation options in smallholder production systems. *Environ. Dev. Sustain.* 22, 5045–5075. doi: 10.1007/s10668-019-00414-4

Assefa, Y., Yadav, S., Mondal, M. K., Bhattacharya, J., Parvin, R., Sarker, S. R., et al. (2021). Crop diversification in rice-based systems in the polders of Bangladesh: Yield stability, profitability, and associated risk. *Agric. Syst.* 187, 102986. doi: 10.1016/j.agsy.2020.102986

Bahar, N. H. A., Lo, M., Sanjaya, M., Van Vianen, J., Alexander, P., Ickowitz, A., et al. (2020). Meeting the food security challenge for nine billion people in 2050: What impact on forests? *Glob. Environ. Change* 62, 102056. doi: 10.1016/j.gloenvcha.2020.102056

Bangladesh Bureau of Statistics – BBS (2014). *Yearbook of agricultural statistics – 2012, 24th series* (Dhaka, Bangladesh: Statistics and Informatics Division (SID), Ministry of Planning, Government of the People's Republic of Bangladesh). Available online at: https://bbs.gov.bd/site/page/3e838eb6-30a2-4709-be85-40484b0c16c6/- (Accessed 16.10.2023).

Bangladesh Bureau of Statistics – BBS (2023). *Yearbook of agricultural statistics-2022. 34th series* (Dhaka, Bangladesh: Bangladesh Bureau of Statistics (BBS). Statistics and Informatics Division (SID). Ministry of Planning. Government of the People's Republic of Bangladesh). Available online at: https://bbs.gov.bd/site/page/3e838eb6-30a2-4709-be85-40484b0c16c6/- (Accessed 16.10.2023).

Becker, M., and Angulo, C. (2019). The evolution of lowland rice-based production systems in Asia: Historic trends, determinants of change, future perspective. *Adv. Agron.* 157, 293–327. doi: 10.1016/BS.AGRON.2019.04.003

Becker, M., Asch, F., Maskey, S. L., Pande, K. R., Shah, S. C., and Shrestha, S. (2007). Effects of transition season management on soil N dynamics and system N balances in rice–wheat rotations of Nepal. *Field Crops Res.* 103, 98–108. doi: 10.1016/j.fcr.2007.05.002

Becker, M., Clavero, R., Maung, Z. N., Khin, O. M., Kong, S., Men, P., et al. (2023). Pathways and determinants of changing nutrient management in lowland rice-based systems of Southeast Asia. *Agron. Sustain. Dev.* 43, 79. doi: 10.1007/s13593-023-00932-6

Bell, A. R., Bryan, E., Ringler, C., and Ahmed, A. (2015). Rice productivity in Bangladesh: What are the benefits of irrigation? *Land Use Policy* 48, 1–12. doi: 10.1016/j.landusepol.2015.05.019

Bernier, Q., Sultana, P., Bell, A. R., and Ringler, C. (2016). Water management and livelihood choices in southwestern Bangladesh. *J. Rural Stud.* 45, 134–145. doi: 10.1016/j.jrurstud.2015.12.017

Bhattacharya, J., Saha, N. K., Mondal, M. K., Bhandari, H., and Humphreys, E. (2019). The feasibility of high yielding aus-aman-rabi cropping systems in the polders of the low salinity coastal zone of Bangladesh. *Field Crops Res.* 234, 33–46. doi: 10.1016/j.fcr.2019.01.007

Bijay-Singh, B., Bilal, H. M., and Aziz, T. (2022). Nitrogen use efficiency in crop production: issues and challenges in South Asia. *Nitrogen Assessment: Pakistan as Case-Study*, ed. T. Aziz, A. Wakeel, M. A. Watto, M. Sanaullah, M. A. Maqsood and A. Kiran (Academic Press), 127–148. doi: 10.1016/B978-0-12-824417-3.00009-5

Billah, M., Latif, M. A., Hossain, N., and Uddin, M. S. (2017). Evaluation and selection of salt tolerant hybrid maize under hydroponics culture. *Res. Crops.* 18, 481–489. doi: 10.5958/2348-7542.2017.00084.5

Brammer, H. (2017). Bangladesh's diverse and complex physical geography: implications for agricultural development. *Int. J. Environ. Sci.* 74, 1–27. doi: 10.1080/00207233.2016.1236647

Chowdhury, P., and Sikder, M. B. (2024). Shoreline dynamics in the reserved region of meghna estuary and its impact on lulc and socio-economic conditions: a case study from nijhum dwip, Bangladesh. *J. Coast. Conserv.* 28, 1. doi: 10.1007/s11852-023-01000-7

CIAT and World Bank (2017). Climate-smart agriculture in Bangladesh. In: *CSA country profiles for asia series* (Washington, D.C., USA: International Center for Tropical Agriculture (CIAT); World Bank). Available online at: https://alliancebioversityciat.org/publications-data/climate-smart-agriculture-Bangladesh (Accessed 21.10.2023).

Clarke, D., Williams, S., Jahiruddin, M., Parks, K., and Salehin, M. (2015). Projections of on-farm salinity in coastal Bangladesh. *Environ. Sci. Process Impacts.* 17, 1127–1136. doi: 10.1039/C4EM00682H

Department of Agricultural Extension – DAE. (2023). Annual agricultural statistics of Barishal and Patuakhali district. *Ministry of Agriculture. Government of the People's Republic of Bangladesh.*

Diao, X., Takeshima, H., and Zhang, X. (2020). *An evolving paradigm of agricultural mechanization development: how much can Africa learn from Asia?* (Washington D.C., USA: International Food Policy Research Institute). doi: 10.2499/9780896293809

Direct seeded rice (DSR) adoption. Available at: https://csisa.org/accelerating-adoption-of-direct-seeded-rice-in-bangladesh-andnepal/. Accessed Nov 2023.

Emran, S. A., Krupnik, T. J., Aravindakshan, S., Kumar, V., and Pittelkow, C. M. (2022). Impact of cropping system diversification on productivity and resource use efficiencies of smallholder farmers in south-central Bangladesh: a multi-criteria analysis. *Agron. Sustain. Dev.* 42, 78. doi: 10.1007/s13593–022-00795–3

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science.* 309, 570–574. doi: 10.1126/science.1111772

Gaydon, D. S., Radanielson, A. M., Chaki, A. K., Sarker, M. M. R., Rahman, M. A., Rashid, M. H., et al. (2021). Options for increasing Boro rice production in the saline coastal zone of Bangladesh. *Field Crops Res.* 264, 108089. doi: 10.1016/j.fcr.2021.108089

Hegde, D. M., Babu, S. S. N., Qureshi, A. A., and Murthy, I. Y. L. N. (2007). Enhancing nutrient use efficiency in crop production – A review. *Indian J. Agron.* 52, 261–274. PISSN: 0537–197X.

Heong, K. L., Escalada, M. M., Chien, H. V., and Delos Reyes, J. H. (2015). "Are there productivity gains from insecticide applications in rice production?," in *Rice planthoppers*. Eds. K. Heong, J. Cheng and M. Escalada (Springer, Dordrecht). doi: 10.1007/978–94-017–9535-7_9

Hossen, M. A., Talukder, M. R. A., Al Mamun, M. R., Rahaman, H., Paul, S., Rahman, M. M., et al. (2020). Mechanization status, promotional activities and government strategies of Thailand and Vietnam in comparison to Bangladesh. *AgriEngineering* 2, 489–510. doi: 10.3390/agriengineering2040033

Huq, S. M. I., and Shoaib, J. U. M. (2013). "Soil classification," in *The soils of Bangladesh. World soils book series*, vol. 1. (Springer, Dordrecht, The Netherlands). doi: 10.1007/978–94-007–1128-0_1

Islam, M. S., Bell, R. W., Miah, M. A. M., and Alam, M. J. (2022). Farmers' fertilizer use gaps relative to government recommendations in the saline coastal zone of the Ganges Delta. *Agron. Sustain. Dev.* 42, 59. doi: 10.1007/s13593–022-00797–1

Islam, S. M. M., Gaihre, Y. K., Islam, M. N., Jahan, A., Sarkar, M. A. R., Singh, U., et al. (2024). Effects of integrated nutrient management and urea deep placement on rice yield, nitrogen use efficiency, farm profits and greenhouse gas emissions in saline soils of Bangladesh. *Sci. Total Environ.* 909, 168660. doi: 10.1016/j.scitotenv.2023.168660

Islam, S., Ma, M., Hossain, M. N., Ganguli, S., and Sarker, M. N. I. (2021). Temporal evaluation of climate change on land use and land cover changes in the Southeastern region of Bangladesh from 2001 to 2016. *Climate Vulnerability and Resilience in the Global South: Climate Change Management*, ed. G. M. M. Alam, M.O. Erdiaw-Kwasie, G.J. Nagy and W. L. Filho (Cham: Springer), 509–525. doi: 10.1007/978–3-030–77259-8_26

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift.* 15, 259–263.

Krupnik, T. J., Hossain, M. K., Timsina, J., Gathala, M. K., Sapkota, T. B., and Yasmin, S. (2022). Adapted conservation agriculture practices can increase energy productivity and lower yield-scaled greenhouse gas emissions in coastal Bangladesh. *Front. Agron.* 4. doi: 10.3389/fagro.2022.829737

Krupnik, T. J., Schulthess, U., Ahmed, Z. U., and McDonald, A. J. (2017). Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential. *Land Use Policy.* 60, 206–222. doi: 10.1016/j.landusepol.2016.10.001

Lassoued, R., Smyth, S. J., Phillips, P. W. B., and Hesseln, H. (2018). Regulatory uncertainty around new breeding techniques. *Front. Plant Sci.* 9. doi: 10.3389/fpls.2018.01291

Levers, C., Schneider, M., Prishchepov, A. V., Estel, S., and Kuemmerle, T. (2018). Spatial variation in determinants of agricultural land abandonment in Europe. *Sci. Total Environ.* 644, 95–111. doi: 10.1016/j.scitotenv.2018.06.326

Mainuddin, M., Alam, M. M., Maniruzzaman, M., Kabir, M. J., Mojid, M. A., Hasan, M. M., et al. (2021). Yield, profitability, and prospects of irrigated Boro rice cultivation in the North-West region of Bangladesh. *PloS One* 16, e0250897. doi: 10.1371/journal.pone.0250897

Mainuddin, M., Kirby, M., Chowdhury, R. A. R., Sanjida, L., Sarker, M. H., and Shah-Newaz, S. M. (2014). *Bangladesh Integrated Water Resources Assessment supplementary report: land use, crop production, and irrigation demand* (Australia: CSIRO). CSIRO: EP141373. doi: 10.4225/08/584af225e7355

Malik, A. I., Nasim, M., Flower, K., Hossain, M. A., Rahman, M. S., Anwar, B., et al. (2017). Cropping system intensification: vegetable pea can replace fallow between rainfed monsoon rice and irrigated spring rice. *J. Agric. Sci.* 155, 1287–1298. doi: 10.1017/S0021859617000351

Mandal, S., Sarangi, S. K., Mainuddin, M., Mahanta, K. K., Mandal, U. K., Burman, D., et al. (2022). Cropping system intensification for smallholder farmers in coastal zone of West Bengal, India: A socio-economic evaluation. *Front. Sustain. Food Syst.* 6. doi: 10.3389/fsufs.2022.1001367

Manickam, R., Kaur, D. P., Vemula, A., Rathore, A., Unkovich, M., Bellotti, W., et al. (2023). Diversifying vegetable production systems for improving the livelihood of resource poor farmers on the East Indian Plateau. *Front. Sustain. Food Syst.* 7. doi: 10.3389/fsufs.2023.966376

Morshed, M. N., Al Mamun, M. A., Nihad, S. A. I., Rahman, M. M., Sultana, N., and Rahman, M. M. (2023). Effect of weather variables on seasonal abundance of rice insects in southeast coastal region of Bangladesh. *J. Agric. Food Res.* 11, 100513. doi: 10.1016/j.jafr.2023.100513

Mousumi, M. A., Paparrizos, S., Ahmed, M. Z., Kumar, U., Uddin, M. E., and Ludwig, F. (2023). Common sources and needs of weather information for rice disease forecasting and management in coastal Bangladesh. *NJAS: Impact Agric. Life Sci.* 95, 2191794. doi: 10.1080/27685241.2023.2191794

Nasim, M., Shahidullah, S., Saha, A., Muttaleb, M., Aditya, T., Ali, M., et al. (2018). Distribution of crops and cropping patterns in Bangladesh. *Bangladesh Rice J.* 21, 1–55. doi: 10.3329/brj.v21i2.38195

Panwar, A. S., Shamim, M., Babu, S., Ravishankar, N., Prusty, A. K., Alam, N. M., et al. (2019). Enhancement in productivity, nutrients use efficiency, and economics of rice-wheat cropping systems in India through farmer's participatory approach. *Sustainability* 11, 122. doi: 10.3390/su11010122

Peel, D., Berry, H. L., and Schirmer, J. (2016). Farm exit intention and wellbeing: A study of Australian farmers. *J. Rural Stud.* 47, 41–51. doi: 10.1016/j.jrurstud.2016.07.006

Penuelas, J., Coello, F., and Sardans, J. (2023). A better use of fertilizers is needed for global food security and environmental sustainability. *Agric. Food Secur.* 12, 5. doi: 10.1186/s40066–023-00409–5

Raghu, P. T., Aravindakshan, S., Rossi, F., Krishna, V., Baksh, E., and Miah, A. A. (2016). "A biophysical and socioeconomic characterization of the cereal production systems of Northwest Bangladesh," in *Cereal systems initiative for South Asia project, phase III* (CIMMYT, Dhaka, Bangladesh).

Rahman, M. M., Ali, M. R., Oliver, M. M. H., Hanif, M. A., Uddin, M. Z., Hasan, T. U., et al. (2021). Farm mechanization in Bangladesh: A review of the status, roles, policy, and potentials. *J. Agric. Food Res.* 6, 100225. doi: 10.1016/j.jafr.2021.100225

Rashid, M. M., Ahmed, N., Jahan, M., Islam, K. S., Nansen, C., Willers, J. L., et al. (2017). Higher fertilizer inputs increase fitness traits of Brown Planthopper in rice. *Sci. Rep.* 7, 4719. doi: 10.1038/s41598–017-05023–7

Ro, S., Becker, M., and Manske, G. (2016). Effect of phosphorus management in rice–mungbean rotations on sandy soils of Cambodia. *J. Soil Sci. Plant Nutr.* 179, 481–487. doi: 10.1002/jpln.201600043

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., et al. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio.* 46, 4–17. doi: 10.1007/s13280–016-0793–6

Roncoli, C., Crane, T., and Orlove, B. (2016). Fielding climate change in cultural anthropology. in *Anthropology Climate Change: From Encounters to Actions*, ed. S. Crate and M. Nutall (Left Coast Press), 87–115. doi: 10.4324/9781315434773–9

Roth, C. H., Cosijn, M., Carter, L., Chakraborty, A., Das, M., Hamilton, S. H., et al. (2023). Overcoming barriers to social inclusion in agricultural intensification: reflections on a transdisciplinary community development project from India and Bangladesh. *Community Dev. J.* 59 (1), 87-107. doi: 10.1093/cdj/bsad005

Sarker, A., Islam, T., Rahman, S., Nandi, R., and Kim, J.-E. (2021). Uncertainty of pesticides in foodstuffs, associated environmental and health risks to humans—a critical case of Bangladesh with respect to global food policy. *Environ. Sci. pollut. Res.* 28, 54448–54465. doi: 10.1007/s11356–021-16042–3

Sarker, U. K., Kaysar, M. S., Uddin, M. R., Hossain, M. A., Hassan, S., and Hassan, M. M. (2022). Exploring farmers' Insight on cropping pattern for sustainable crop production in char area of Bangladesh. *Sustainability (Switzerland)* 14, 1745. doi: 10.3390/su14031745

Schüller, H. (1969). Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. *Z. für Pflanzenernährung und Bodenkunde* 123, 48–63. doi: 10.1002/jpln.19691230106

Schulthess, U., Ahmed, Z. U., Aravindakshan, S., Rokon, G. M., Kurishi, A. S. M. A., and Krupnik, T. J. (2019). Farming on the fringe: Shallow groundwater dynamics and irrigation scheduling for maize and wheat in Bangladesh's coastal delta. *Field Crops Res.* 239, 135–148. doi: 10.1016/j.fcr.2019.04.007

Shew, A. M., Durand-Morat, A., Putman, B., Nalley, L. L., and Ghosh, A. (2019). Rice intensification in Bangladesh improves economic and environmental welfare. *Environ. Sci. Policy.* 95, 46–57. doi: 10.1016/j.envsci.2019.02.004

Shrestha, S., Becker, M., Lamers, J. P. A., and Wimmer, M. A. (2020). Boron and zinc fertilizer applications are essential in emerging vegetable-based crop rotations in Nepal. *J. Soil Sci. Plant Nutr.* 183, 439–454. doi: 10.1002/jpln.202000151

Snapp, S., Sapkota, T. B., Chamberlin, J., Cox, C. M., Gameda, S., Jat, M. L., et al. (2023). Spatially differentiated nitrogen supply is key in a global food–fertilizer price crisis. *Nat. Sustain.* 6, 1268–1278. doi: 10.1038/s41893–023-01166-w

Struik, P. C., and Kuyper, T. W. (2017). Sustainable intensification in agriculture: the richer shade of green: A review. *Agron. Sustain. Dev.* 37, 39. doi: 10.1007/s13593–017-0445–7

Timsina, J., Wolf, J., Guilpart, N., van Bussel, L. G. J., Grassini, P., van Wart, J., et al. (2018). Can Bangladesh produce enough cereals to meet future demand? *Agric. Syst.* 163, 36–44. doi: 10.1016/j.agsy.2016.11.003

Wilkinson, L., and Friendly, M. (2009). The history of the cluster heat map. *Am. Stat.* 63, 179–184. doi: 10.1198/tas.2009.0033