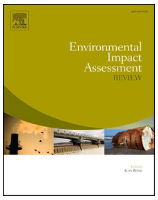
Environmental Impact Assessment Review 106 (2024) 107503

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar



Are rice systems sustainable in Sri Lanka? - A case of Deduru Oya reservoir irrigation scheme

M.M.J.G.C.N. Jayasiri [a,b,*], N.D.K. Dayawansa [c], Karin Ingold [d], Sudhir Yadav [a,e,**]

[a] *Sustainable Impact Platform, International Rice Research Institute, Los Baños, Philippines*
[b] *Postgraduate Institute of Agriculture, University of Peradeniya, Sri Lanka*
[c] *Faculty of Agriculture, University of Peradeniya, Sri Lanka*
[d] *University of Bern, Switzerland*
[e] *Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, St. Lucia 4072, QLD, Australia*

ARTICLE INFO

Keywords:
Sustainability indicators
Spatial variability
Rice farm diversity
Pressure points
Sustainable rice platform

ABSTRACT

Sustainable rice systems play a crucial role in achieving sustainable development goals, particularly in countries like Sri Lanka that heavily rely on paddy production. The study aims to examine the economic, social, and environmental sustainability gaps of a rice production system at various spatial scales using the Sustainable Rice Platform (SRP) framework v2.1 and identify interventions that can address these gaps. Data for the study was collected through a structured questionnaire, which incorporated the 12 performance indicators of the SRP framework, including profitability, labor productivity, grain yield, water productivity, nutrient use efficiency, biodiversity, greenhouse gas emission, food safety, health and safety, child labor and youth engagement, and women empowerment. The survey was conducted over two consecutive cropping seasons, in 2019 dry and 2019/2020 wet seasons, in selected paddy fields representing three topo-sequences within the Deduru Oya irrigation project in Sri Lanka. The study's findings revealed that the rice systems' profitability ranges from 475 ± 45 to 642 ± 59 USD/ha across seasons and topo-sequences, and a yield gap of approximately 33% was observed. Substantial exploitable gaps were observed in labor productivity (67%–77%) and water productivity (58%–68%). Additionally, there was significant variability in nutrient use efficiency and greenhouse gas emissions due to variations in water management practices. The social sustainability of rice systems has received lower scores, particularly for health safety and women empowerment. The study attributed most of the economic and environmental sustainability gaps in the agricultural practices of cultivators, while various socio-political and cultural factors influenced the social sustainability gaps. This study offers valuable insights to policymakers and practitioners in countries with extensive rice systems, aiding their efforts toward achieving sustainable development goals.

1. Introduction

Fast-growing population, depletion of natural resources, and climate change are exerting immense pressure on food demand worldwide. In most Asian countries, including Sri Lanka, ensuring the sustainability of rice-based systems is an important aspect of addressing these challenges and achieving food security. The rice production systems need to be profitable (economic sustainability), provide societal benefits (social sustainability) with a minimal negative impact on the environment (environmental sustainability). Globally, more attention has been paid to economic outcomes (e.g., grain yields) rather than a holistic approach encompassing multiple domains of sustainability. Furthermore, a major limitation of most studies is their focus on plot- or farm-level analyses with relatively little attention to spatial heterogeneity, which is critical for scaling interventions (Ricciardi et al., 2020).

Paddy cultivation holds significant importance in Sri Lanka, as 15%

Abbreviations: SRP, Sustainable Rice Platform; SRP-PI, Sustainable Rice Platform Performance Indicator; WP, Water Productivity; NUE, Nitrogen-Use Efficiency; PUE, Phosphorus-Use Efficiency; GHG, Green House Gas; SECTOR, Source-selective and Emission-adjusted GHG CalculaTOR for Cropland; USD, United States Dollars.

[*] Corresponding author at: Sustainable Impact Platform, International Rice Research Institute, Los Baños, Philippines.
[**] Corresponding author at: Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, Australia.
E-mail address: sudhir.yadav@uq.edu.au (S. Yadav).

https://doi.org/10.1016/j.eiar.2024.107503
Received 2 March 2023; Received in revised form 29 March 2024; Accepted 30 March 2024

of the country's land is dedicated to paddy production (DOA, 2019). Sri Lanka's paddy production has averaged 4.18 million metric tons of paddy over ten years (2013–2022) (DCS, 2024). However, the rice production systems in the country face various challenges due to climate and other stresses (Ratnasiri et al., 2019; Wickramasinghe et al., 2023). Therefore, understanding sustainability gaps in Sri Lankan rice production systems is crucial for achieving sustainable development goals. While several studies have been carried out in Sri Lanka on the performance of rice production systems but without a holistic approach to the economic, social, and environmental dimensions of sustainability. Several studies (Kadupitiya et al., 2022; Amarasingha et al., 2015) reported high potential paddy land productivity levels of 6–8 t/ha; however, the average national land productivity was 4.05 t/ha, during the period 2015–2019 (DCS, 2021) highlighting relatively large yield gaps. In addition, the total nitrogen loss from paddy farming in Sri Lanka is high with 70% of applied urea being lost (Sirisena et al., 2001), indicating poor nitrogen use efficiency and risks of water pollution.

Fertilizer and pesticide pollution is evident in the Deduru Oya basin of Sri Lanka (Jayasiri et al., 2022a). Furthermore, the potential ecotoxicological impacts of applied pesticide use such as risks of amphibian growth by Diazinon, insect mortality by Fipronil, and fish reproduction risk by Diazinon, have also been reported in the same basin (Jayasiri et al., 2021). Using fertilizers, pesticides and herbicides can cause human, ecotoxicological, and environmental (e.g., carbon, nitrogen, and water footprints) impacts (Arunrat et al., 2022; Toolkiattiwong et al., 2023). The water productivity of the most intensive paddy farming areas in Sri Lanka, Polonnaruwa, and Gal Oya schemes are reported within the range of 0.22–0.44 kg/m^3 (Devkota et al., 2019; Bandara, 2003). However, these figures are still on the lower side compared to the global range of 0.15–0.60 kg/m^3 (Cai and Rosegrant, 2003). The gaps in land productivity, nutrient management, pesticide use, and water productivity indicate needed improvements in economic and environmental sustainability dimensions. Although, contamination of rice grains by toxic substances like heavy metals is not reported in Sri Lanka (Navarathna et al., 2021), it is important to note that long-term ingestion of contaminated foods containing harmful substances, even at low concentrations below the threshold, can have potential health consequences (Liu et al., 2020).

All these facts provide evidence of overall sustainability gaps in Sri Lankan rice systems, and most studies have focused on one or two domains of sustainability and have not examined rice systems comprehensively. To our knowledge, there have been no attempts to utilize a comprehensive framework to examine the economic, environmental, and social sustainability aspects of Sri Lankan rice production systems on a spatial scale to comprehend sustainability assessment. Understanding the sustainability gaps at various scales in rice production systems and recommending potential solutions to address these gaps are important for addressing the emerging challenges to rice systems in Sri Lanka. Therefore, the objectives of this study were as follows; 1) to apply the Sustainable Rice Platform (SRP) framework to understand the major sustainability gaps of a rice production system at plot-to-basin scale and 2) to propose the potential interventions to address these gaps.

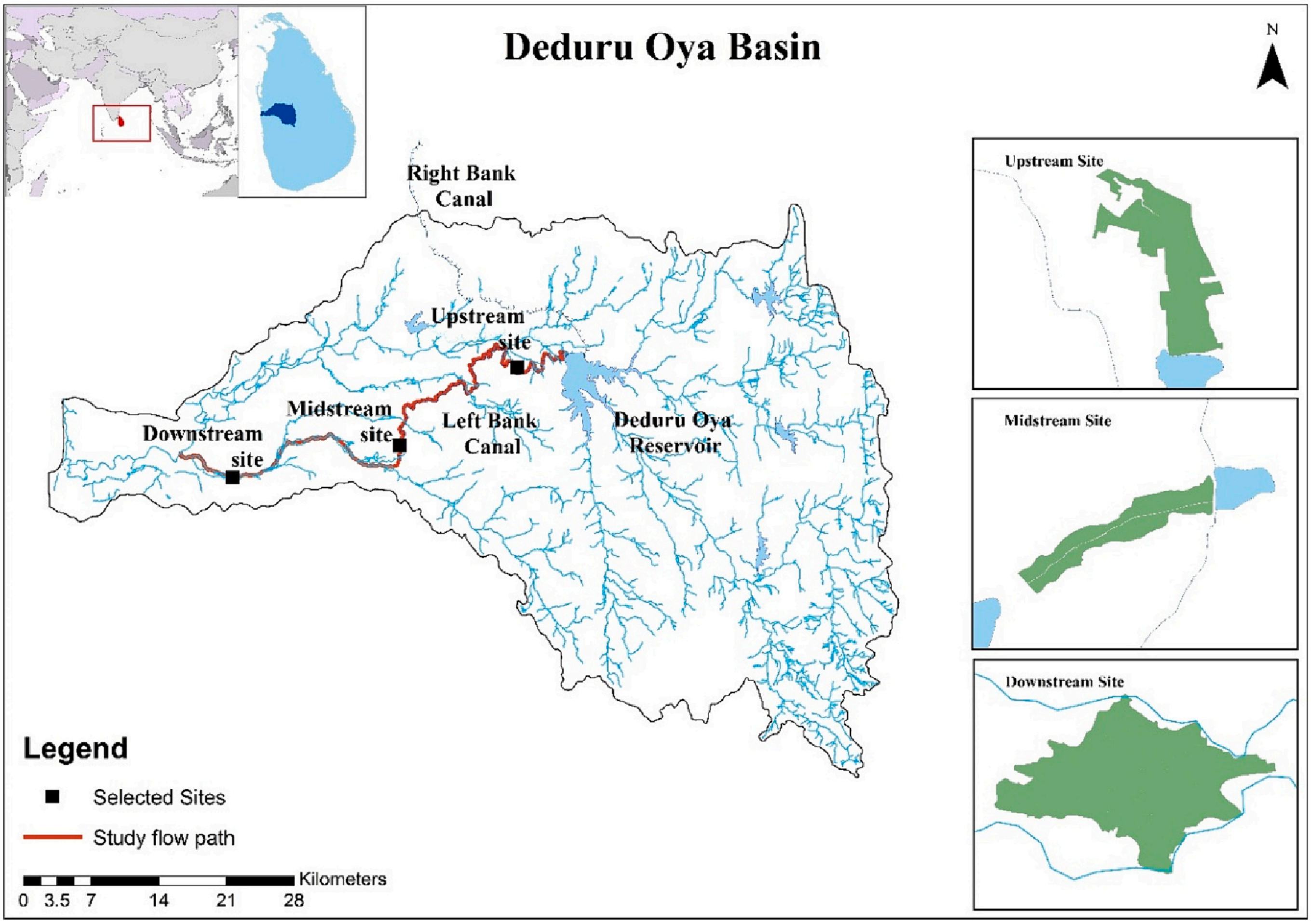


Fig. 1. Study sites within the Deduru Oya River basin.

2. Methodology

2.1. Study area

The study was conducted in the Deduru Oya river basin, the fourth largest river basin, and a major rice growing area in Sri Lanka (Fig. 1). We did not opt for the first two largest basins due to their complexity with trans basin diversion projects. The third largest basin was not selected due to lack of paddy cultivation within the basin. The climate of the basin area is characterized by dry weather, low rainfall, high evapotranspiration and low humidity. The monthly average temperature of the basin is 25–30 °C with the highest potential evapotranspiration occurring in August. The average annual rainfall of the basin is 1648 mm, and varies between 1100 mm and 2600 mm. The Deduru Oya reservoir is the main reservoir of the basin, which has a capacity of 75 million m^3 and supplies water to a command area of 11,115 ha. Paddy cultivation dominates agriculture in the basin, including the command area of the Deduru Oya reservoir project. Vegetables, coconuts, and other field crops are also grown in the basin.

This study was conducted in the left bank canal area of the Deduru Oya reservoir irrigation scheme. Three paddy tracts (a contagious piece of paddy land and associated components like irrigation canals) were selected to represent each of the upstream, midstream, and downstream sections of the basin. The selected upstream (7°42′31.71″N; 80°13′23.38″E) and midstream (7°37′58.09″N; 80° 6’48.31″E) sites are directly fed by the left bank canal of the Deduru Oya reservoir irrigation project and cover 13 and 7 ha of land area, respectively. Water released from the left bank canal flows into *Kolamunu Oya*, a tributary of the Deduru Oya river. The downstream site (7°36′7.14″N; 79°57′28.04″E) is a 34 ha of paddy field that receives water through pumping from the *Kolamunu Oya*.

There are generally four rainfall seasons in Sri Lanka, including two monsoons: the northeast (December–February) and southwest monsoons (May–September) and two inter-monsoonal seasons (March–April and October–November). *Maha* (can be referred as the wet season; October–February) and *Yala* (dry season; March–September) seasons, the two major cropping seasons in Sri Lanka, are well-aligned with these rainfall seasons. Typically, the paddy is cultivated in these two seasons every year.

2.2. Sustainable rice platform (SRP) framework

The SRP is an independent association involved with holistic multistakeholders More than 100 public and private bodies, international organizations, and research institutes are involved as partners. SRP offers a range of tools to promote sustainable rice cultivation, including SRP Performance Indicators (SRP-PIs) to measure the impact of current practices through the lens of sustainability. In this study, SRP-PI version 2.1 was used to assess the sustainability of the rice system. The SRP framework consists of 12 performance indicators, i.e. profitability, labor productivity, grain yield, water productivity (WP), nitrogen-use efficiency (NUE), phosphorus-use efficiency (PUE), biodiversity, greenhouse gas (GHG) emission, food safety, health and safety, child labor and youth engagement, and women empowerment (SRP, 2020). Most of the indicators were specified with multiple assessing measurements at three scales—basic, intermediate, and advanced—allowing a choice based on the level of accuracy necessary as well as the availability of resources and data. The SRP framework has been applied to the rice production system assessment in several countries (Devkota et al., 2019; Devkota et al., 2020; Arouna et al., 2021; Devkota et al., 2022). It is a relatively simple, versatile, conceptually clear framework that includes economic, social, and environmental considerations and performs well in data-poor situations. Generally, these indicators are utilized to comprehend the scenarios at the field level and draw comparisons across various geographical locations. This approach facilitates understanding variations both within a field (or intra-topo sequential) and between different fields across landscapes.

2.3. Sampling sites and land profiling

The three selected study sites (paddy tracts) were chosen out of 30 randomly surveyed sites across the Deduru Oya irrigation project representing upstream, midstream, and downstream areas of the project. The study sites were mapped using an unmanned aerial survey and data was digitized to prepare plot-level boundary maps. Additionally, three focus group discussions were organized involving all relevant farmers to gather information about land profiles, including plot tenancy and ownership status. Based on the feedback from farmers on the ownership of plots, a contiguous piece of paddy land consisting of one or more paddy plots cultivated by the same cultivator was defined as a “paddy parcel” for this study. A farmer may be cultivating one or more parcels within the same paddy tract.

2.4. Interview-based questionnaire survey

A structured questionnaire (Annex S1) was prepared following the SRP performance indicators version 2.1 (SRP, 2020). The questionnaire was drafted to gather demographic data and farming information such as; cultivated areas, varieties, all the agricultural inputs and their costs, irrigation water depths and durations, harvested quantities, and grain selling price. The questionnaire was translated into the local language and carried out as a paper-based interview questionnaire to collect data on two cropping seasons, the 2019 dry and the 2019/2020 wet seasons. The paddy parcel was considered the data collection units and interviews were conducted with the cultivator of the land (rather than the landowner). The questionnaire survey was carried out in three selected representative paddy tracts from each of the topo-sequence (up-, mid-, and downstream segments) and the total farmer population of the selected three paddy tracts ($n = 84$) was considered for the survey consisted of 41 cultivators from upstream, 23 from midstream, and 20 from downstream. A total of 54 ha of area was covered under this study, including 13 ha in upstream, 7 ha in midstream and 34 ha in downstream. The collected data were used to assess the SRP–PIs.

2.5. Data analysis

All the used equations to compute SRP performance indicators are presented in annex S2. The SRP performance indicators of each site were used to understand the sustainability gaps and compare inter- and intratopo-sequence differences.

The profitability was determined using the average selling price of all paddy parcels (Arouna et al., 2021). This approach was adopted to exclude market dynamics and focus solely on rice production systems. All monitory data were collected in Sri Lankan Rupees and then converted into United States Dollars (USD) using a conversion rate of 183.63 (as of February 28, 2020). As the hiring of mechanization services appeared as a common practice, the cost of hiring machinery was also considered for all the farmers, including those who own the machine (due to limited information on capital and depreciation costs, model of machinery, and date of purchase). The labor productivity was computed using the information on hired labor only; because the hired labor is reported with significant productivity issues compared to family labor (Akite et al., 2022; Darpeix et al., 2014; Chowdhury, 2016).

The grain yield reported by farmers was considered at 20% grain moisture content (based on experts' consultation) and was adjusted to 14% (based on SRP manual instructions). The rainfall was not considered for WP calculations considering that the rainfall distribution over three sites was similar (Fig. S1), and the variation in the water input through rainfall to individual parcels was negligible compared to the variation of receiving water from irrigation. The GHG emission was computed by the Source-selective and Emission-adjusted GHG CalculaTOR for Cropland (SECTOR) model (Wassmann et al., 2019). For social indicators such as food safety, health and safety, child labor, and youth engagement, as well as women's empowerment, ordinal data were collected and computed as percent of responses were based on scorecards included in the SRP framework.

Establishing a sustainability target is crucial for discerning the critical junctures within a sustainable agri-food system. Various methods exist for setting baselines and targets for indicators, such as external benchmarks, farm survey percentiles, and theoretical modeling (Chavez et al., 2013; Devkota et al., 2020; Saito et al., 2021). While external targets aid macro-level policy and research, local data percentiles effectively address agro-environmental variations. Consequently, this study used the top decile method to examine intra-field variations.

To calculate the yield gaps, farmers were categorized into three groups based on grain yield obtained and they were top decile (top 10%), middle deciles (middle 80%), and bottom decile (bottom 10%). The exploitable yield gap was calculated as the difference between the mean grain yield of the top decile and the average grain yield of the total population. The exploitable yield gap percentage was calculated by dividing the exploitable yield gap by the mean yield of the top decile (Arouna et al., 2021). The exploitable gaps of the first six indicators were calculated similarly.

Distribution of the grain yield, NUE, PUE, and WP across paddy parcels were mapped to identify potential trends over resource use. Different software, including Minitab 17, R, and ArcMAP 10.5 were used for data analysis and plotting of graphs and maps.

3. Results

3.1. Demography of the study area

The farming community across all the study sites is predominately elderly, with an average age of 56 ± 13 in the upstream and 51 ± 10 in the midstream. However, the downstream farming community is comparatively younger, averaging 44 ± 13 years. All surveyed farmers, except one, had formal education, with 95–100% of farmers receiving primary education, while 9–27% of the farmers received education up to the university entrance class level (highest class in Sri Lankan schools). The downstream farmers are more educated compared to the other two. Out of the total surveyed farmers, only 6% were women. The midstream site showed the highest women participation in farming at 13%, while the downstream site has no women farmers. The majority of the farmers cultivate their lands except for some tenant farmers; 5% in the upstream and 32% in the downstream site.

3.2. Calculation of SRP indicators and understanding the sustainability of each topo sequence

The twelve SRP indicators were studied to understand and compare the sustainability status of the up-, mid-, and downstream paddy fields. The descriptive statistics of each SRP performance indicator at each study site are shown in Table S1 and presented in Fig.s 2 and 3.

3.2.1. Profitability

The downstream parcels obtained the highest mean profitability (Table S1) in both seasons. In contrast to the other two sites, a higher proportion of parcels has achieved the mean profitability in the downstream sites (Fig. 2a and b). The highest standard error values were observed in the midstream site compared to the other two sites, in both dry (566 ± 62 USD/ha) and wet seasons (403 ± 78 USD/ha). In the midstream site, harvest was lower, with greater variability observed during the wet season, which could be indicative of water management issues. There were 12.7%, 10.4%, and 1.9% of the parcels in up-, mid-, and downstream sites, respectively, with negative profitability. The overall exploitable gaps in profitability were 49%, 52%, and 36% in each upstream, midstream, and downstream sites, respectively.

3.2.2. Labor productivity

The highest mean labor productivity was observed in the upstream site in both dry (360 ± 69 USD/ha/day) and wet (331 ± 54 USD/ha/day) seasons and with the least variation compared to the other two sites (Table S1). In up- and midstream paddy tracts, the highest labor productivity was observed in the dry season, while in the downstream site,

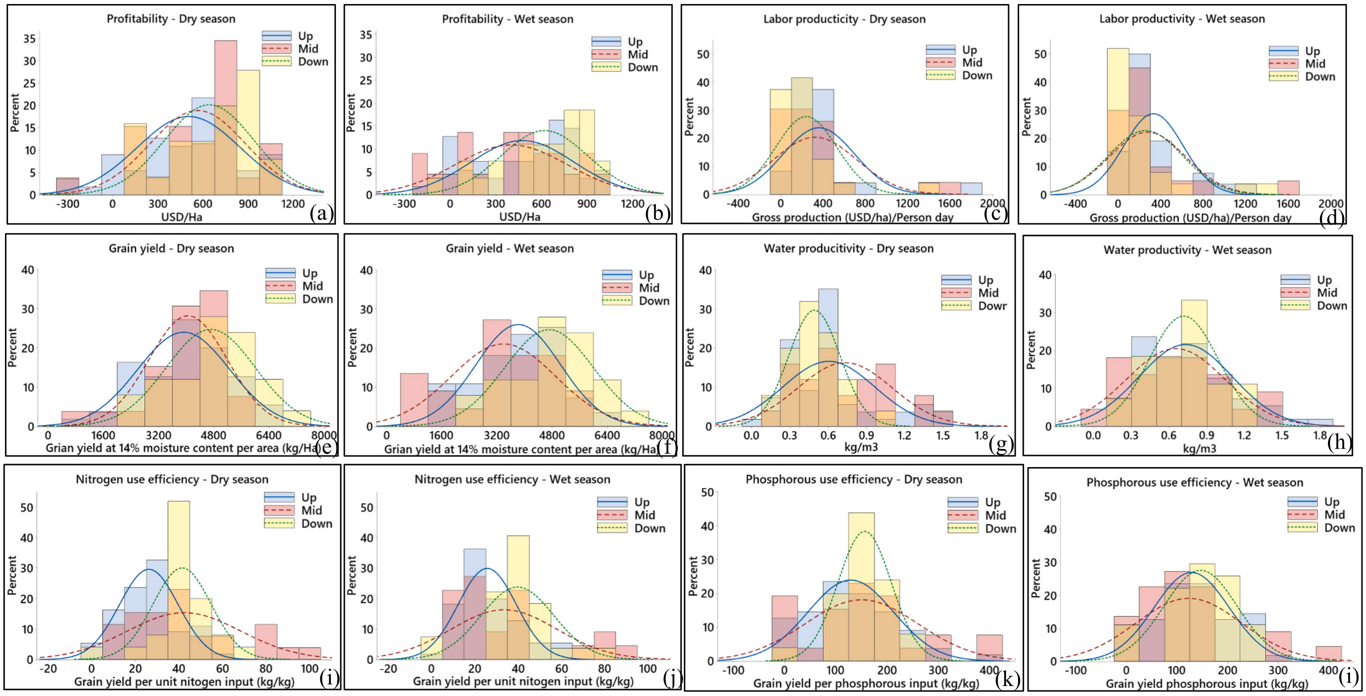


Fig. 2. Sustainability Rice platform indicators in three survey sites; Profitability in the dry (a) and wet season (b), Labor productivity in the dry (c) and wet season (d), Grain yield in the dry (e) and wet season (f), Water productivity in the dry (g) and wet season (h), Nitrogen use efficiency in the dry (i) and wet season (j), and Phosphorous use efficiency in the dry (k) and wet season (l).

it was in the wet season (Fig. 2c and 3d). This may be due to dense weed growth, as observed in the fields, and a high number of irrigation cycles (as per data obtained from the questionnaire survey), which results in a greater demand for labor leading to lower labor productivity. Furthermore, there is a significant need for improvement in labor productivity, as evidenced by the exploitable labor productivity gaps of 69%, 77%, and 76% in the upstream, midstream, and downstream sites, respectively.

3.2.3. Grain yield

The mean grain yield of the downstream site (4717 and 4506 kg/ha in dry and wet seasons) was reported higher than both the up- and midstream (Table S1; Fig. 2e and f). The mean yields of upstream (3926 and 3818 kg/ha in dry and wet seasons) and midstream (4059 and 3395 kg/ha in dry and wet seasons) sites were less than the national average (4500 kg/ha). Though the average grain yield in downstream was higher than the national average, a high standard error was observed, especially in the dry season, which may be due to water availability variation across the paddy tract. The lowest grain yield was reported from midstream in the wet season, which may be attributed to a water management issue. Overall, a considerable exploitable yield gap of 33% was computed as an average of all three sites with a maximum (35%) in the upstream and lowest (32%) in the downstream.

3.2.4. Water productivity (WP)

In the dry season, the mean WP values were 0.60 ± 0.05, 0.73 ± 0.07, and 0.49 ± 0.04 kg/m^3 for up-, mid- and downstream sites, respectively, while it was 0.73 ± 0.05, 0.65 ± 0.08 and 0.72 ± 0.05 kg/m^3 in the wet season, respectively (Table S1). The midstream site had the highest standard error in both seasons, indicating highly variable water management practices and a water management problem at the site. Despite having the highest grain yield, less WP was observed downstream in the dry season, an indication of excess irrigation application. However, the downstream showed the least standard error in both seasons, demonstrating relatively less variation in water management practices across seasons.

In terms of spatial scale, the proportion of area coverage with WP equal to or higher than the mean WP was higher in downstream compared to the other two sites (Fig. 2g and h). The exploitable WP gap was calculated to be 68%, 67% and 58% in up-, mid-, and downstream sites, respectively. Therefore, significant attention is required to improve WP across all three sites need.

3.2.5. Nitrogen use efficiency (NUE)

Compared to the other two sites, the downstream site showed the highest mean NUE (43 ± 2 in the dry season and 43 ± 3 in the wet season), which was nearly doubled the NUE observed at upstream (Table S1, Fig. 2i and j). Mean NUE was least in the upstream paddy field (27 ± 2 in the dry season and 26 ± 2 in the wet). Also, the lowest NUE was observed in the upstream site, compared to the other sites, which were 2–8 times higher. The midstream showed the highest standard error, and the fattened distribution curve demonstrated highly diverse nutrient management practices across parcels, probably linked with varying water management practices. Midstream site exhibited the highest exploitable NUE gap (58%) followed by upstream (49%) and downstream (39%).

3.2.6. Phosphorous use efficiency (PUE)

The highest average PUE (283 ± 20) was observed at the midstream site in the dry season. Surprisingly, the same site had the lowest PUE 142 ± 9 in the wet season, indicating inconsistency of nutrient management across seasons. The midstream site had highly varying phosphorous management practices in both seasons (Table S1; Fig. 2k and l). These observations in the midstream site were probably owing to a water management issue in the wet season. On the other hand, when examining the minimum PUE values, the upstream site had the lowest PUE in both seasons, with the other two sites showing PUE values 2–6 times higher. A similar trend was observed for the minimum NUE, which could

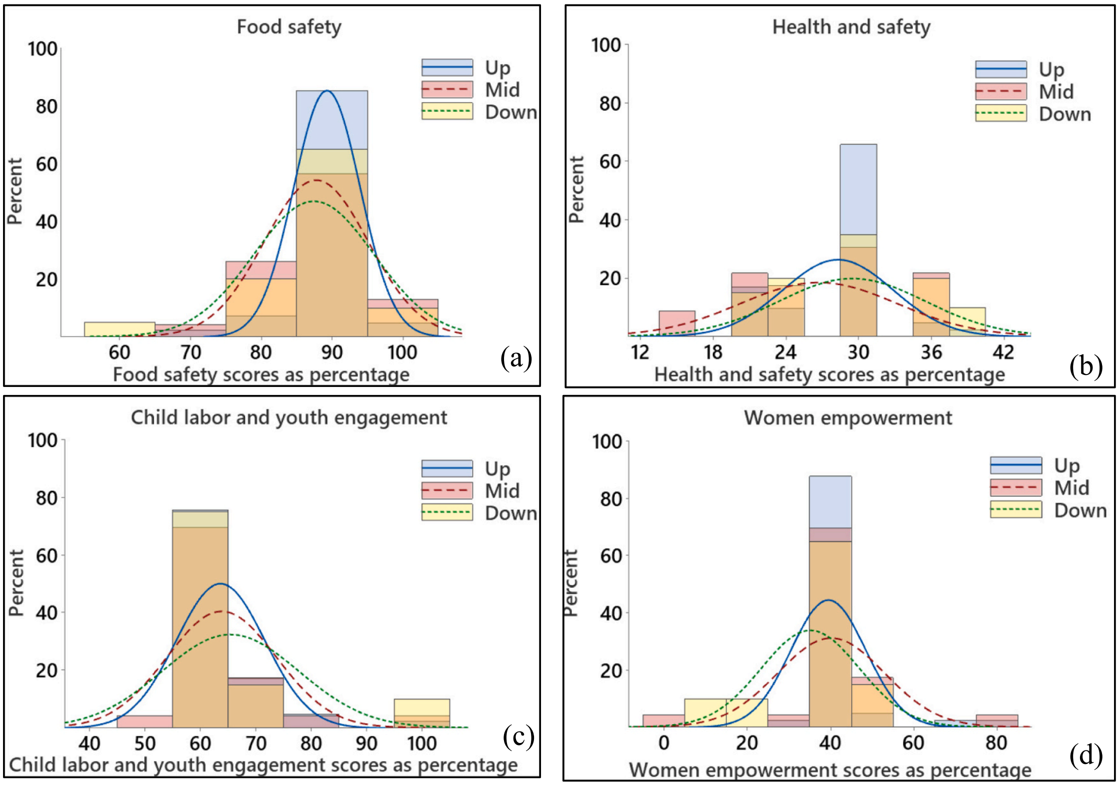


Fig. 3. Scorecard-based sustainability performance indicators (a) Food safety, (b) Health and safety, (c) Child labor and youth engagement, and (d) Women empowerment in three survey sites.

be related to water stagnation in the parcels due to improper leveling in the upstream site. Furthermore, the midstream site showed the highest exploitable PUE gap (56%) followed by the upstream (45%) and downstream (32%). The downstream site showed comparatively consistent PUE in both dry (163 ± 8) and wet (165 ± 11) seasons, which might be one of the reasons for the high grain yield.

3.2.7. Number of pesticide applications

Downstream farmers applied a higher number of pesticide applications per season, with a mean of 5, which was more than double the numbers for up- and midstream sites (Table S1). The frequency of pesticide application observed in upstream and midstream sites matches the previously reported frequency (2) in the same climatic zone of Sri Lanka (Dissanayake et al., 2019).

3.2.8. Greenhouse gas emission

The GHG emissions from each parcel showed comparable results in the upstream and downstream areas, and varied between 0.19 ± 0.02–0.26 ± 0.03 equivalent weight of carbon dioxide per unit grain yield (Table S1). Among sites, the emission and the variability of GHG emission were highest in midstream, especially in the wet season (0.36 ± 0.07). This indicates a significant variation in agricultural practices, such as water management, which contributes to GHG emissions.

3.2.9. Social indicators

All three sites achieved almost similar mean scores for the social indicators. However, the upstream site had a higher number of respondents reaching the mean scores compared to the other two sites (Fig. 3).

Regarding food safety, the mean scores were consistently above 87.5%, with a median of 90% across all sites (Table S2). In the upstream area, 35% of the respondents achieved the mean score for food safety, while this percentage dropped below 13% for both the mid- and downstream areas (Fig. 3a). Overall, no respondent scored below 60% for food safety. These figures indicate relatively fewer gaps, whether real or perceived, in terms of food safety. In terms of health and safety practices, none of the three sites demonstrated satisfactory scores, with average scores falling below 30%. Health and safety practices received highly variable responses (Fig. 3b), suggesting that most farm workers do not adhere to safe health measures. The response regarding child labor and youth inclusion also exhibited a high level of variability (Fig. 3c). The mean values of child labor and youth inclusion were 64% for the up- and mid-stream and slightly higher (66%) in the downstream. The mean scores for women empowerment were 40% for the up- and mid-stream and 35% for the downstream sites. Only 18% of respondents in the upstream area achieved the average score for women empowerment, while this percentage remained below 8% in the mid- and downstream segments (Fig. 3d).

3.3. Variation of selected indicators across parcels

The trend and potential causes for spatio-temporal variability of different SRP indicators are discussed in this section. Grain yield per unit area, nutrient use efficiency, and WP maps of the upstream, midstream and downstream sites are presented in Figs. 4, 5, and 6, respectively. Parcel-wise input application maps of all three sites (nitrogen input,

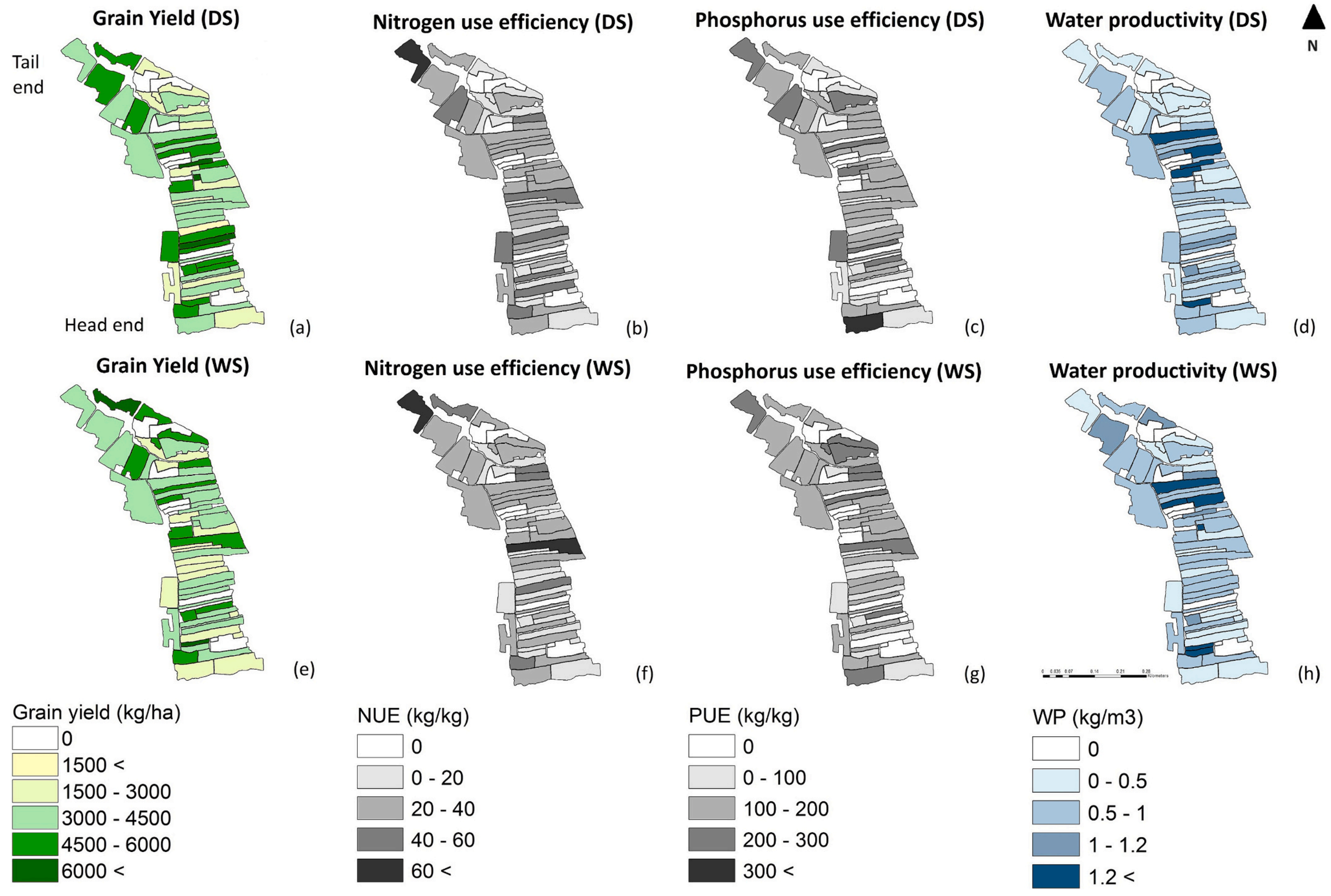


Fig. 4. Spatial distribution of performance indicators in upstream of Deduru Oya irrigation scheme for (a) Grain yield in dry season, (b) Nitrogen use efficiency in dry season, (c) Phosphorous use efficiency in dry season, (d) Water productivity in dry season, (e) Grain yield in wet season, (f) Nitrogen use efficiency in wet season, (g) Phosphorous use efficiency in wet season, (h) Water productivity in wet season.

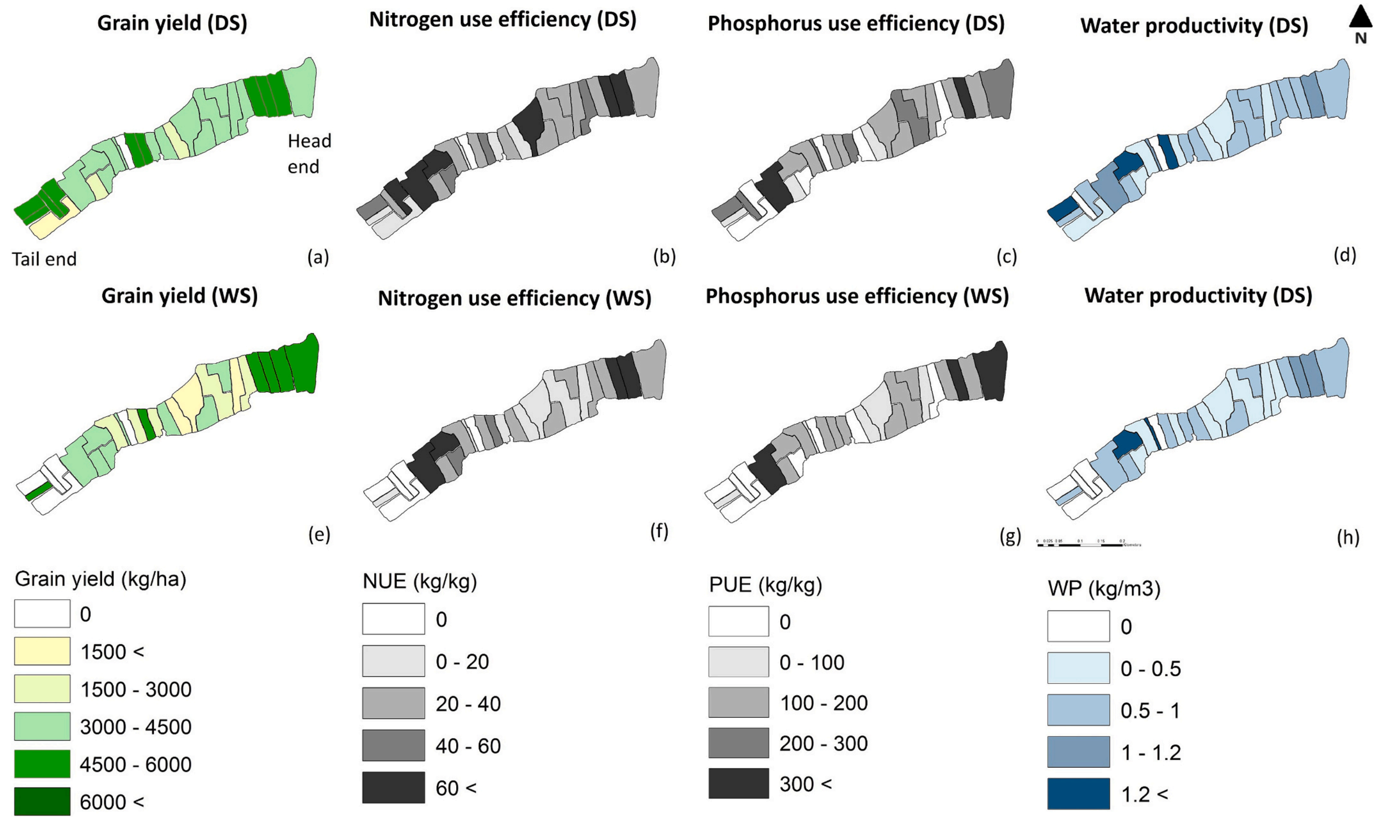


Fig. 5. Spatial distribution of performance indicators in midstream of Deduru Oya irrigation scheme for (a) Grain yield in dry season, (b) Nitrogen use efficiency in dry season, (c) Phosphorous use efficiency in dry season, (d) Water productivity in dry season, (e) Grain yield in wet season, (f) Nitrogen use efficiency in wet season, (g) Phosphorous use efficiency in wet season, (h) Water productivity in wet season.

phosphorous input, water height, and pesticide application) are presented in Supplementary materials (Fig. S3–S5).

The parcels with high grain yields (above the national average, 4500 kg/ha) were randomly dispersed across the paddy tracks in up- and midstream sites (Fig. 4a, 5e, 6a, and e). On the contrary, at downstream, the parcels with higher yields were concentrated towards the tail end (Fig. 6a and e), possibly due to the significant undulation towards the head-end, which often resulted in water logging. The grain yield was higher in the dry than in the wet season at all three sites, which is consistent with the national average in the respective year; 4896 kg/ha in the dry season and 4531 kg/ha in the wet season (DCS, 2021).

Excessive nitrogen application was a common practice across the sites. In the upstream parcels, approximately 70% of them applied urea above the recommended dose, with not a single parcel adhering to the recommended nitrogen levels (Fig. S3a and S3d). In fact, in 5% of the upstream parcels, nitrogen applications exceeded three times the recommended amount in both seasons. Overapplication of nitrogen in the upstream area could explain the low NUE (Fig. 4b and f), indicating a risk of nitrogen loss. In the midstream site, nitrogen was overapplied in half of the parcels (Fig. S4a and S4d), with only 4% sticking to the recommended nitrogen levels. In the downstream site, recommended nitrogen input was applied to 22% and 28% of the cultivated paddy parcels in the dry and wet seasons, respectively (Fig. S5a and S5d).

Irrespective of seasons, overapplication of phosphorus was observed in 42–58% of parcels across all sites. Compared to nitrogen applications, a higher proportion of land was applied with the recommended dose of phosphorus. The recommended quantities of phosphorus were applied to 24% and 27% of paddy parcels in the upstream (Fig. S3b, and S3e), 23% and 27% of paddy parcels in the midstream (Fig. S4b, and S4e), and 33% and 33% of paddy parcels in the downstream (Fig. S5b, and S5e) during the dry and wet seasons, respectively.

Water depths varied across upstream and midstream sites in both seasons, indicating different water management practices by farmers (Fig. S3c, S3f, S4c, S4f, S5c, S5f). In the wet season, water depth showed less variability in downstream parcels, likely due to well-distributed rainfall and fewer irrigation events. In contrast, water depths varied across downstream parcels in the dry season, remaining higher compared to the wet season within the same site. The other two sites rarely experienced irrigation with water inputs above 1200 mm in both seasons. The lower WP in the dry season for the downstream site (Fig. 6d) indicated a high waste of irrigated water.

3.4. *Correlation analysis*

Table 1 presents the correlation between grain yield versus inputs and input use efficiencies. The grain yield showed the highest significant correlation coefficient with WP, NUE, and PUE respectively. The WP of the downstream site is highly correlated with the grain yield in the wet season.

4. Discussion

4.1. *Sustainability dynamics in the rice system*

The sustainability dimensions were dynamic spatially and temporally. The downstream site showed highest sustainability in dry season in terms of all the economic and environmental SRP-PIs (7 indicators) except pesticide application. On other hand, midstream site showed least sustainability in wet season over same 7 indicators. Labor productivity, water productivity, greenhouse gas emission and health safety can be identified as pressure points in all the study sites (Fig. 7).

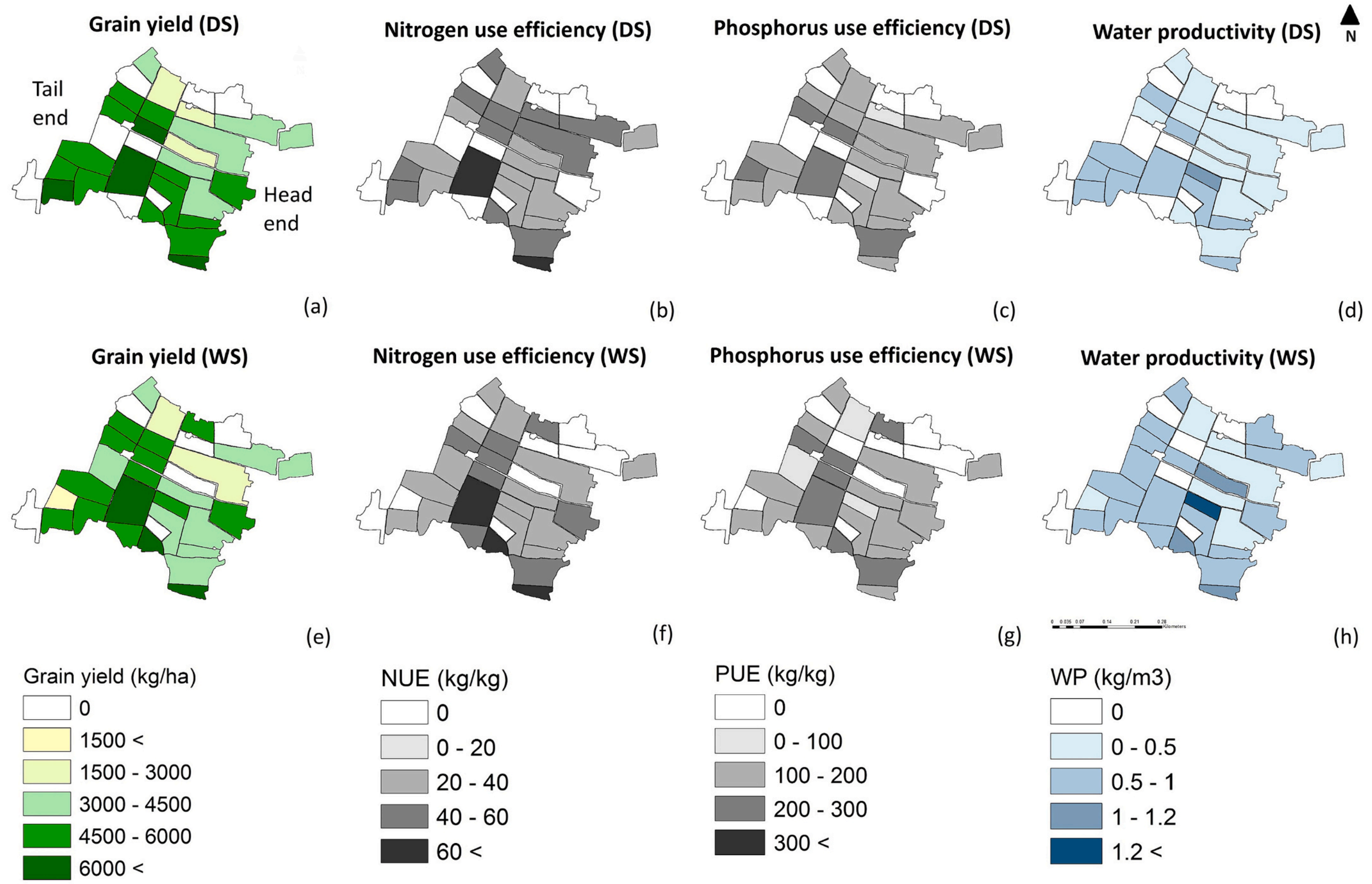


Fig. 6. Spatial distribution of performance indicators in downstream of Deduru Oya irrigation scheme for (a) Grain yield in dry season, (b) Nitrogen use efficiency in dry season, (c) Phosphorous use efficiency in dry season, (d) Water productivity in dry season, (e) Grain yield in wet season, (f) Nitrogen use efficiency in wet season, (g) Phosphorous use efficiency in wet season, (h) Water productivity in wet season.

Table 1
Correlation among grain yield versus inputs and input use efficiencies.

Correlation matrices	Pearson correlation coefficient - Dry season			Pearson correlation coefficient - Wet season		
	Upstream	Midstream	Downstream	Upstream	Midstream	Downstream
Grain yield vs. urea application	0.011 (*p* = *0.937*)	0.047 (*p* = *0.821*)	0.394 (*p* = *0.051*)	0.063 (*p* = *0.647*)	0.159 (*p* = *0.480*)	0.553 (*p* = *0.003*)
Grain yield vs. NUE	0.423 (*p* = *0.001*)	0.518 (*p* = *0.007*)	0.429 (*p* = *0.032*)	0.500 (*p* = *0.000*)	0.600 (*p* = *0.003*)	0.743 (*p* = *0.000*)
Grain yield vs. MOP application	0.102 (*p* = *0.457*)	0.241 (*p* = *0.236*)	0.325 (*p* = *0.113*)	0.015 (*p* = *0.911*)	0.372 (*p* = *0.088*)	0.440 (*p* = *0.022*)
Grain yield vs. PUE	0.275 (*p* = *0.042*)	0.305 (*p* = *0.130*)	0.512 (*p* = *0.009*)	0.422 (*p* = *0.001*)	0.518 (*p* = *0.014*)	0.620 (*p* = *0.001*)
Grain yield vs. irrigation depth	0.007 (*p* = *0.961*)	0.086 (*p* = *0.678*)	−0.151 (*p* = *0.472*)	0.253 (*p* = *0.062*)	0.099 (*p* = *0.660*)	−0.355 (*p* = *0.069*)
Grain yield vs. water productivity	0.492 (*p* = *0.000*)	0.553 (*p* = *0.003*)	0.669 (*p* = *0.000*)	0.405 (*p* = *0.002*)	0.635 (*p* = *0.001*)	0.871 (*p* = *0.000*)

p = *P*-value at 0.05; cells are shaded when the *P* value is below 0.05.

4.1.1. Economic sustainability

All the sites showed a potential of achieving economic, environmental, and social sustainability, to varying degrees. Notably, high exploitable gaps in profitability values across upstream, midstream, and downstream sites indicate a high potential for enhancing the economic sustainability of all sites. Overall, the profitability was higher in dry season possibly with less water logging, high sun light, and less pest and diseases. The downstream site exhibited higher profitability, which could be attributed to three factors; having larger plot areas, leading to higher profits as evidenced in China also (Lu et al., 2018), favorable demographic features of downstream farmers such as higher education and younger age. The downstream area belongs to different agro-climatic zone with a distinct soil type compared to upstream and midstream areas (DOA, 2023), potentially making the soil another factor in yield differences. Additionally, the downstream area is periodically inundated by flood water of *Kolamunu Oya*, which may have resulted in highly fertile soil sedimentation. Considering there were no flood and drought events during the study period, the climate risk factors of inter-topo sequence yield variations can be ruled out. The overall study area shows high profitably compared to Polonnaruwa in Sri Lanka (Devkota et al., 2019) as well as to Thailand (Mungkung et al., 2022), but exhibiting lesser profitability compared to other Asian and African

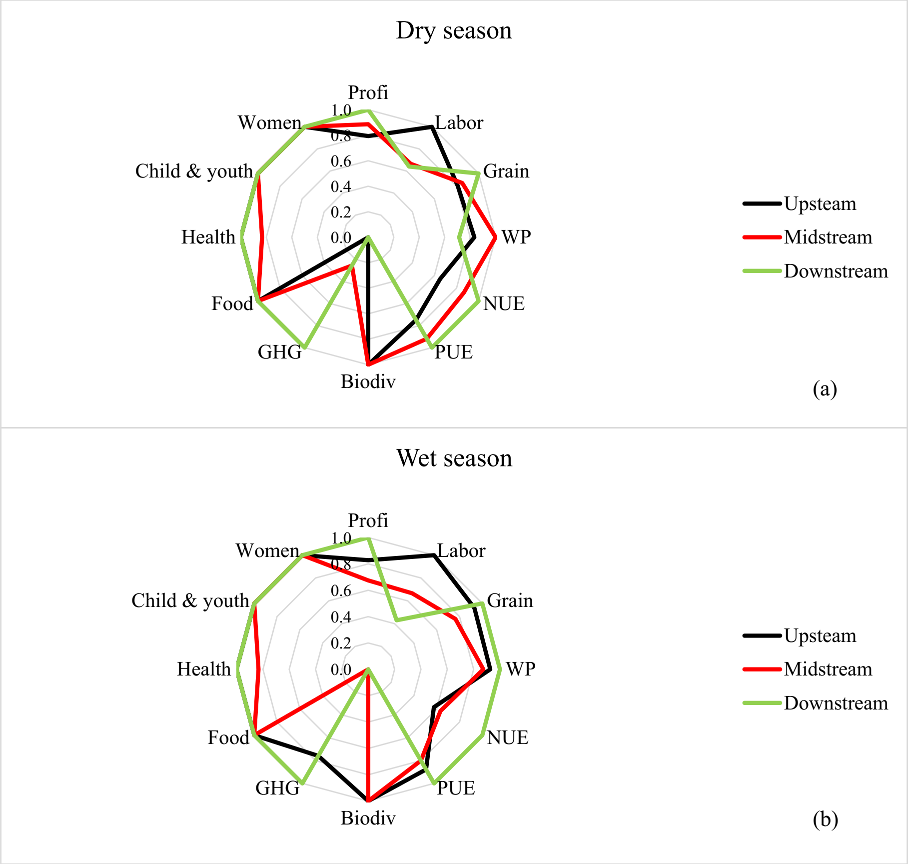


Fig. 7. Comparison of sustainability dynamics across three sites in (a) Dry season and, (b) Wet season. (Profi = Profitability; Labor = Labor productivity, Grain = Grain yield, WP = Water productivity, NUE = Nitrogen use efficiency, PUE = Phosphorous use efficiency, Biodiv = Biodiversity, GHG = Greenhouse gas emission, Food = Food safety, Health = Health and safety, Child & Youth = Child labor and youth engagement, Women = Women Empowerment).

regions (Devkota et al., 2019; Arouna et al., 2021). In some parcels, negative profitability was reported. The Department of Agriculture also reported comparable findings of negative profitability of rice, observed in various parts of Sri Lanka (DOA, 2020a; DOA, 2020b).

The cost of paddy production was mainly attributed to land preparation, pesticide inputs, harvesting and hired labor costs in the study sites (Fig. S2). Specifically, the harvesting cost in upstream and labor cost in midstream sites were higher than in the other two sites, likely due to site-specific reasons such as; poorly leveled land in the upstream sites and water-logged smaller plots in the midstream sites. At all three sites, labor productivity showed very high exploitable gaps, possibly due to the lack of interest of the younger generation in agriculture. The majority of surveyed paddy cultivators were around 55 years old. Additionally, the practice of fixed daily wages, as opposed to task-based wages, may negatively impacts labor productivity. The lesser labor productivity in the study area is consistent with the research conducted in Sri Lanka by Devkota et al. (2019) and Suresh et al. (2021). According to the DOA (2019), labor costs account for about half of the cost of producing rice; therefore, enhancing labor productivity is crucial for reducing the economic disparities in rice systems.

When it comes to grain yield, the average yield of this study area is lower than that of the Asian countries except Myanmar and the African regions (Arouna et al., 2021). The downstream site surpassed the national average of land productivity (SRP-PI: grain yield, t/ha), while the other two sites fell below it, which can be attributed to several factors, including larger plot areas, favorable demographic characteristics of the farmer community, and better nutrient management. To enhance grain yield, appropriate methods should be practiced, including increasing soil organic carbon and improving water use efficiency (Arunrat et al., 2020; Mallareddy et al., 2023).

4.1.2. Environmental sustainability

The water productivity was highly variable across the study sites, perhaps due to the varying practices of irrigation. Higher variation of WP has also been observed in Mahaweli 'system H' in Sri Lanka; one of the most highly intensive rice cultivating areas within the country (Cai and Bastiaanssen, 2018). Compared to other Asian and African rice-growing countries, WP and nutrient management in Sri Lanka remain subpar, possibly due to the fertilizer subsidy, freely available irrigation water, and perception of the farmers about the water requirement of paddy.

Devkota et al. (2022) defined a target range of 40–80 as sustainable NUE and 150–400 as sustainable PUE, and overall, all three study sites of this study are still on the lower end or below this range. The optimal NUE for paddy in Sri Lanka was reported to be 50 (Marambe and Nissanka, 2019), and more than half of the parcels in all sites are below that value. However, the optimal NUE depends on soil fertility. Notably, some tropical countries like Brazil obtained higher PUEs, reaching 465 (Fageria et al., 2013). Therefore, all sites need improved nutrient management for better environmental and economic sustainability.

Higher pesticide application observed in the downstream site may be attributed to high pest attacks resulting from inundation of water. The high frequency of pesticide application in the downstream site also poses a higher risk to biodiversity (Bourguet and Guillemaud, 2016), thereby threatening environmental sustainability. Qin and Lü (2020) observed that larger farms apply pesticides frequently compared to smaller ones, which is consistent with our findings.

The GHG emission was highly varying and high in the wet season, probably due to water and other management practices. Similar ranges of GHG emissions have been reported in paddy fields in Polonnaruwa, Sri Lanka, an intensive rice-growing area (Devkota et al., 2019), and

Thailand (Toolkiattiwong et al., 2023), which have similar agro-climatic conditions. Given the critical importance of reducing GHG emissions to mitigate climate change, it is imperative to address these issues.

4.1.3. Social sustainability

The study area exhibits poor conditions in terms of health and safety, a finding that aligns with Sumudumali et al. (2021). Development of health and safety programs for farm workers, health facilities in villages or farms, and investment in awareness programs, are critical to reducing sustainability gaps.

The farmers in Sri Lanka are getting older. Suresh et al. (2021) reported an average age of 51 ± 10 years of Sri Lankan paddy farmers. Damayanthi et al. (2013) surveyed youth aged 15–30 in major agricultural areas in Sri Lanka and found a declining engagement with agriculture. The youth engagement has been overlooked by the SRP indicator framework as it currently considers child labor and youth engagement together. In Sri Lanka, the free education policy has been in place for the past 70 years, guaranteeing education up to bachelor's degree, therefore, child labor in agriculture is not a significant issue.

The results highlight considerable variation in perceptions of women's empowerment, with a large number of women in agriculture likely not empowered due to a lack of awareness, attitudes, and cultural boundaries. Rice farming is generally male-dominated both in terms of labor and cultural rituals. Many rituals associated with Sri Lankan paddy cultivation are traditionally performed exclusively by men, which psychologically distances women from engaging with rice systems. Additionally, the labor and machinery work in agriculture is socially seen as men's responsibility, along with land ownership. All of these factors contribute to the under-representation and lack of empowerment of women in the agricultural sector.

Comparing social indicators with other countries, food safety and work safety in the Deduru Oya basin have no major differences with Thailand. However, Thailand has made comparatively remarkable improvements in the other two social indicators: child labor and youth engagement and women empowerment (Mungkung et al., 2022). Overall, each of the social indicators showed scores of similar ranges for all three sites. However, we suggest that more detailed information is required to understand the variation within that narrow range, and the farm typology approach may be much more suitable to understand such variations.

4.2. Understanding of spatio-temporal variability

Regardless of the location, the parcels with high nitrogen (and phosphate) application were scattered, indicating the dominance of individual agricultural practices over topographic variation. The observed low levels of NUE across the paddy fields could be linked to insufficient land leveling, poor water management and timing of fertilizer application which are critical factors in nitrogen uptake, in addition to the application rate (Sun et al., 2012). Throughout both seasons, parcels with high-nutrient input did not necessarily match with the parcels with high-use efficiencies, indicating a risk of water pollution. Notably, parcels fertilized with the recommended phosphorus dose did not exhibit optimal PUE, highlighting gaps in accessing soil fertility status, fertilizer quality, and timing of fertilizer application.

Based on the aforementioned results, it was observed that parcels with high fertilizer and irrigation water inputs did not necessarily exhibit high input use efficiencies. The grain yield only showed a statistically significant correlation with input use efficiency, however not with the input application, as shown in Table 1 (The complete correlation matrix is presented in Fig. S6).

The nutrient management is linked with water management. Farmers' perception and their assessment of the risk of dry spells may influence irrigation management and flooding depth in different seasons. The water management gaps can be field-specific. Field characteristics, such as the absence of a canal system and plot-to-plot irrigation water delivery in downstream or inadequate infrastructure maintenance and site-specific canal morphology in the midstream, could also impact water management. The midstream irrigation canal traverses the head end of the paddy field at a higher elevation and the tail end at a lower elevation compared to paddy plots, resulting in flooding of the tail end parcels in the wet season, rendering them uncultivated. The large variation in water management at the midstream site may have contributed to its high mean greenhouse gas emissions and high variation.

The consistency of overapplication of fertilizers and inputs in all sites and seasons might be due to various reasons, one of which could be farmers' misunderstanding of the size of their paddy land area. A considerable mismatch was observed in the paddy parcel area reported through the questionnaire survey and the area computed through drone images and as indicated by the R-squared values; 0.67, 0.81, and 0.69 for upstream, midstream, and downstream, respectively (Fig. 8).

4.3. Potential pathways for reaching sustainable rice systems

The findings of this study highlight the significant spatial heterogeneity in management practices across the paddy parcels in all three sites, indicating the potential for improvement in the rice system practices. Therefore, it is critical to factor-in spatial heterogeneity of perception and practices for designing and updating the existing extension approaches for sustainable agriculture. Sri Lanka currently faces several gaps in its extension services, including outdated extension approaches, a shortage of extension experts, limited stakeholder interaction, and insufficient policy support (Sivayoganathan, 2020). In addition to tailoring extension approaches to address spatial heterogeneity, the country must focus on upskilling stakeholders (including growers) to address some of the critical sustainability gaps.

The study also reveals wide gaps in nutrient management, including nutrient type, source, and application practices. These gaps have also been reported in previous studies (Marambe and Nissanka, 2019; Sirisena and Suriyagoda, 2018); yet there is a lack of well-designed policy interventions and implementation strategies (Kishore et al., 2021). The use of decision-enabling tools such as rice crop manager, which is based on the principle of site-specific nutrient management (Sharma et al., 2019) and cropping techniques that support high NUE such as deep placement of nitrogen fertilizer (Li et al., 2021), coating granulated urea (Dimkpa et al., 2020), adopting PUE-enhancing approaches like the use of phosphate-solubilizing bacteria (Rawat et al., 2022) can generate tailored recommendations for individual parcels, might be able to address some of these gaps.

Efficient nutrient management is closely linked to effective irrigation management (Liang et al., 2021; Usman, 2013). The field water management in all the study sites needs considerable improvements. Various approaches to improve field water use, such as alternative wetting and drying techniques (Carrijo et al., 2017), shifting planting dates (Dharmarathna et al., 2014), and laser leveling (Nguyen-Van-Hung et al., 2022), have been suggested and tested globally. Additionally, the institutional support for infrastructure development, particularly irrigation canal rehabilitation and maintenance (Sirimewan et al., 2021), effective field-scale water governance system (Jayasiri et al., 2023), and national level governance arrangements (Jayasiri et al., 2022b) play a significant role in productive irrigation water use. Therefore, the improvements in WP should be considered at all scales, not just confined to the field level gains.

The study indicated the probable link between water management practices and GHG emissions which aligned with other reports worldwide (Gupta et al., 2016; Scheer et al., 2012; Zou et al., 2015). Effective water management can contribute to several sustainability indicators, including profitability, NUE, PUE, WP, and GHG emissions. However, insufficient scientific attention is being paid to the GHG emissions from Sri Lankan paddies, and indicating a need for further research. Strategies to reduce GHG emissions in paddy fields, such as modified irrigation scheduling (mid-season drainage, alternative wetting and drying),

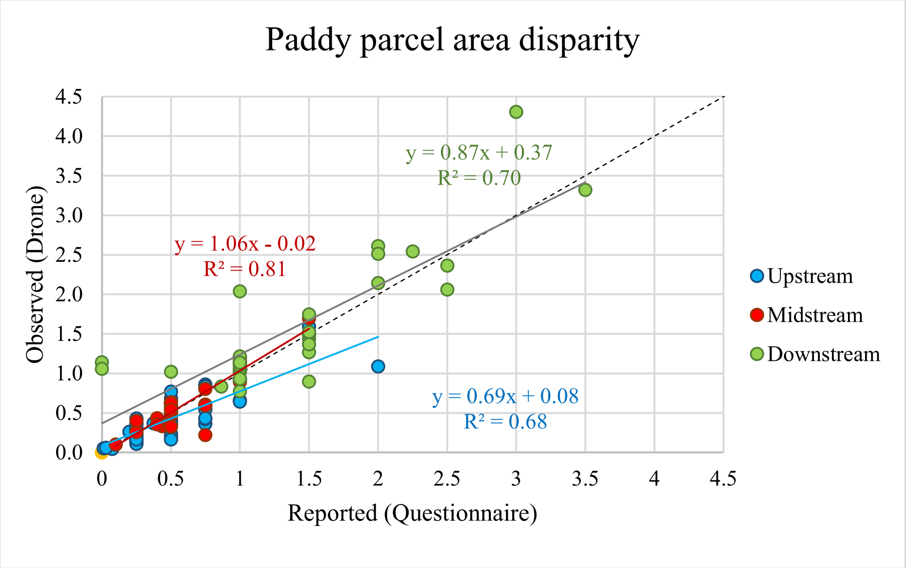


Fig. 8. Paddy parcel area differences among observed area by drone survey and reported area by the questionnaire survey; Black dotted lines indicate 1:1 line, and other lines indicate respective trend lines.

optimal nutrient management, suitable cropping systems, and straw management, have been widely discussed (Hussain et al., 2015; Xia et al., 2016).

In terms of social sustainability, farm worker "Health and Safety" indicator was not at a satisfactory level, highlighting the need to ensure the safety of pesticide applicators through knowledge dissemination and regulation of pesticide application practices. As described in section 3.2.9, the social dimension of "Child Labor and Youth Engagement in Agriculture" fails to address the issue of youth inclusiveness, which poses a significant social sustainability gap in rice systems. Understanding and promoting youth engagement and inclusion in Sri Lankan rice production systems should be a priority. To make this happen, the government must focus on upgrading the agricultural sector with smart agricultural technologies, promoting social recognition, providing training and knowledge sharing, offering attractive credit facilities and ensuring market facilities. Although women's empowerment in the rice systems has been emphasized in different regions of the world (Akter et al., 2017; Rasheed et al., 2020), gender studies in the context of Sri Lankan rice systems still lack sufficient scholarly and policy attention. It is crucial to address this gap by promoting gender equality, enabling women's participation in decision-making processes, and improving their access to resources and benefits within the paddy farming sector.

All the SRP-PIs involve trade-offs in rice production, particularly in economic and environmental aspects. SRP-PIs generally enhance production, with the exception of greenhouse gas emissions and biodiversity. In addition to economic and environmental factors, social SRP-PIs also support the long-term sustainability of rice systems. While the performance indicators aim to assess improvements in sustainability due to changes in farming practices, the tool also facilitates benchmarking across various rice farming systems within a landscape.

4.4. *Areas of improvement in sustainability indicators*

Overall, the SRP performance indicators performed quite well in assessing sustainability gaps in rice systems. There are, however, significant opportunities to further strengthen and improve these indicators.

4.4.1. *Sustainability assessment at scale*

The findings of this study show that several management practices and decision-making occur on different scales. While farmers have control over certain inputs such as seeds and fertilizer at the plot scale, water management in canal-based irrigation systems operates at the paddy track level. Plot-to-plot water flow impedes effective plot-level water management, leading to issues of getting contaminated with high levels of pesticide residue in the paddy fields (Jayasiri et al., 2022a). The incoming water quality checklist in the current version of SRP indicators for intermediate and advanced measurement is limited to salinity and groundwater depletion, however, many countries face challenges related to pesticide, mineral, and heavy metal toxicity. To address this, we recommend revising the water quality checklist and food safety assessment scorecard, particularly for advanced measurements, to encompass a broader range of contaminants.

Similarly, social indicators often reflect the farming environment as a whole rather than specific plot-level practices. Several of these indicators are more relevant to measurements at the household level or at the community level. The scale for each indicator must be explicitly defined to avoid any misinterpretation.

4.4.2. *Assessment of biodiversity*

While SRP the framework includes several metrics for evaluating biodiversity in rice production systems, an important aspect missing is the assessment of pesticide toxicity levels. Jayasiri et al. (2021) have reported on ecotoxicity of different pesticides and their impact on various species. To enhance the biodiversity performance indicators within the SRP framework, we suggest the following options to restructure the indices; 1) appropriate hazard class classification of applied pesticides; 2) toxicity levels based on active ingredient strength and application dosage; 3) pesticide residue testing with a comparison of environmental standards, or 4) environmental impacts of applied active ingredient quantities through indices; 5) pesticide over-application compared to national or regional recommendations for pesticide application.

5. Conclusion

The findings of this study carry significant implications for the advancement of sustainable rice production systems in Sri Lanka. The results indicate that Sustainable Rice Platform Performance Indicators are a valuable and effective tool for identifying sustainability gaps in rice-based agro-food systems. Moreover, the study has also highlighted the diverse range of sustainability gaps in the rice systems across various scales. These gaps are largely linked to individual farmer practices rather than any attributing to a particular location.

One of the key sustainability gaps of rice production systems is high labor productivity gaps which is consistently prominent across all locations and seasons when compared to other SRP-PIs. Furthermore, water productivity and nutrient use efficiency gaps represent critical challenges, with the highest pressure observed in midstream, followed by the other two sites. Narrowing these gaps could substantially improve the economic sustainability of paddy production. Overall sustainability gaps were mainly driven by the heterogeneity of farm practices across paddy fields, followed by inadequate extension services, input mismanagement infrastructure, and governance issues. These factors, along with their interactions, contribute to various sustainability gaps. In addition, the study has identified several opportunities for improving the environmental sustainability of rice production systems through effective input management, such as water, nutrients, and pesticides. It is particularly important to consider the interplay between inputs such as water and nutrients, in conjunction with location-specific factors like geography, canal morphology, and water sharing practices. Though respondents were positive about food safety in this study, there are still noteworthy social sustainability gaps in all study sites for women's empowerment and health and safety. Addressing these social sustainability gaps requires attention at a national or regional level, as they are influenced by broader socio-political factors compared to the other two sustainability domains.

The study underscores the importance of implementing multi-stakeholder interventions to target the diverse sustainability gaps across different domains, as well as the necessity for agricultural managers to comprehend the interconnectedness among sustainability indicators to make well-informed decisions. Further, the SRP framework allows practitioners to understand the plot level variations, identify pressure points and make decisions at regional level accordingly.

CRediT authorship contribution statement

M.M.J.G.C.N. Jayasiri: Investigation, Formal analysis, Visualization, Writing – original draft. **N.D.K. Dayawansa:** Supervision, Writing – review & editing. **Karin Ingold:** Supervision, Writing – review & editing. **Sudhir Yadav:** Conceptualization, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

This study was financed with grants received from the Swiss Agency for Development and Cooperation (SDC) through the CORIGAP project entitled “Closing Rice Yield Gaps in Asia with Reduced Environmental Footprint” (grant no. 81016734). The support of the Department of Agrarian Development of Sri Lanka and farmer organizations in the study area in reaching out to farmers is greatly appreciated. We are also thankful to Prof Grant Singleton for funding acquisition and guidance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107503.

References

Akite, I., Okello, D.M., Kasharu, A., Mugonola, B., 2022. Estimation of profit efficiency of smallholder rice farmers in Uganda: a stochastic frontier approach. J. Agricult. Food Res. 8, 100315 https://doi.org/10.1016/j.jafr.2022.100315.

Akter, S., Rutsaert, P., Luis, J., Htwe, N.M., San, S.S., Raharjo, B., Pustika, A., 2017. Women’s empowerment and gender equity in agriculture: a different perspective from Southeast Asia. Food Policy 69, 270–279. https://doi.org/10.1016/j.foodpol.2017.05.003.

Amarasingha, R.P.R.K., Suriyagoda, L.D.B., Marambe, B., Gaydon, D.S., Galagedara, L. W., Punyawardena, R., Silva, G.L.L.P., Nidumolu, U., Howden, M., 2015. Simulation of crop and water productivity for rice (*Oryza sativa* L.) using APSIM under diverse agro-climatic conditions and water management techniques in Sri Lanka. Agric. Water Manag. 160, 132–143. https://doi.org/10.1016/j.agwat.2015.07.001.

Arouna, A., Devkota, K.P., Yergo, W.G., Saito, K., Frimpong, B.N., Adegbola, P.Y., Depieu, M.E., Kenyi, D.M., Ibro, G., Fall, A.A., Usman, S., 2021. Assessing rice production sustainability performance indicators and their gaps in twelve sub-Saharan African countries. Field Crop Res. 271, 108263 https://doi.org/10.1016/j.fcr.2021.108263.

Arunrat, N., Kongsurakan, P., Sereenonchai, S., Hatano, R., 2020. Soil organic carbon in Sandy Paddy fields of Northeast Thailand: a review. Agronomy 10 (8), 1061. https://doi.org/10.3390/agronomy10081061.

Arunrat, N., Sereenonchai, S., Chaowiwat, W., Wang, C., Hatano, R., 2022. Carbon, nitrogen and water footprints of organic rice and conventional rice production over 4 years of cultivation: a case study in the lower north of Thailand. Agronomy 12 (2). https://doi.org/10.3390/agronomy12020380.

Bandara, K.M.P.S., 2003. Monitoring irrigation performance in Sri Lanka with high-frequency satellite measurements during the dry season. Agric. Water Manag. 58, 159–170. https://doi.org/10.1016/S0378-3774(02)00132-4.

Bourguet, D., Guillemaud, T., 2016. The hidden and external costs of pesticide use. In: Lichtfouse, E. (Ed.), Sustainable agriculture reviews. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-26777-7_2.

Cai, X., Bastiaanssen, W., 2018. Water productivity assessment for improved irrigation performance and water security in the Asia-Pacific region: Sri Lanka. Asian Development Bank. https://www.adb.org/sites/default/files/project-documents/42384/42384-012-tacr-en_2.pdf (accessed 20 October 2022).

Cai, X., Rosegrant, M.W., 2003. World water productivity: Current situation and future options. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI International, Cambridge, pp. 163–178. https://doi.org/10.1079/9780851996691.0163.

Carrijo, Daniela R., Lundy, Mark E., Linquist, Bruce A., 2017. Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. Field Crop Res. 203, 173–180. https://doi.org/10.1016/j.fcr.2016.12.002.

Chavez, H., Nadolnyak, D., Saravia, M., 2013. Socioeconomic and environmental impact of development interventions: Rice production at the Gallito Ciego reservoir in Peru [WWW document]. URL. https://cgspace.cgiar.org/handle/10568/33464.

Chowdhury, N.T., 2016. The relative efficiency of hired and family labour in Bangladesh agriculture. J. Int. Dev. 28, 1075–1091. https://doi.org/10.1002/jid.2919.

Damayanthi, M.K.N., Samarasinhe, G.G.D.L.W., Bandara, M.A.C.S., Hitihamu, H.M.S.J. M., Perera, S., 2013. Youth in development: Sri Lanka. Colombo, Sri Lanka: Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI). http://www.harti.gov.lk/images/download/reasearch_report/new1/161.pdf. (accessed 13 May 2021).

Darpeix, A., Bignebat, C., Perrier-Cornet, P., 2014. Demand for seasonal wage labour in agriculture: what does family farming hide? J. Agric. Econ. 65, 257–272. https://doi.org/10.1111/1477-9552.12019.

DCS, 2021. Paddy Statistics. Department of Census and Statistics (DCS), Colombo, Sri Lanka http://www.statistics.gov.lk/Agriculture/StaticalInformation/PaddyStatistics (Accessed vol. 11.07 2022).

DCS, 2024. Paddy Statistics. Department of Census and Statistics (DCS), Colombo, Sri Lanka http://www.statistics.gov.lk/Agriculture/StaticalInformation/PaddyStatistics#gsc.tab=0 (Accessed 18.03.2024).

Devkota, K.P., Pasuquin, E., Elmido-Mabilangan, A., Dikitanan, R., Singleton, G.R., Stuart, A.M., Vithoonjit, D., Vidiyangkura, L., Pustika, A.B., Afriani, R., Listyowati, C.L., Keerthisena, R.S.K., Kieu, N.T., Malabayabas, A.J., Hu, R., Pan, J., Beebout, S.E.J., 2019. Economic and environmental indicators of sustainable rice cultivation: a comparison across intensive irrigated rice cropping systems in six Asian countries. Ecol. Indic. 105, 199–214. https://doi.org/10.1016/j.ecolind.2019.05.029.

Devkota, K.P., Yadav, S., Khanda, C.M., Beebout, S.J., Mohapatra, B.K., Singleton, G.R., Puskur, R., 2020. Assessing alternative crop establishment methods with a sustainability lens in rice production systems of eastern India. J. Clean. Prod. 244, 118835 https://doi.org/10.1016/j.jclepro.2019.118835.

Devkota, K.P., Beebout, S.E.J., Sudhir, Y., Bunquin, M.A., 2022. Setting sustainability targets for irrigated rice production and application of the sustainable rice platform performance indicators. Environ. Impact Assess. Rev. 92, 106697 https://doi.org/10.1016/j.eiar.2021.106697.

Dharmarathna, W.R.S.S., Herath, S., Weerakoon, S.B., 2014. Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district, Sri Lanka. Sustain. Sci. 9, 103–111. https://doi.org/10.1007/s11625-012-0192-2.

Dimkpa, C.O., Fugice, J., Singh, U., Lewis, T.D., 2020. Development of fertilizers for enhanced nitrogen use efficiency – trends and perspectives. Sci. Total Environ. 731, 139113 https://doi.org/10.1016/j.scitotenv.2020.139113.

Dissanayake, A.K.A., Udari, U.D.R., Perera, M.D.D., Wickramasinghe, W.A.R., 2019. Possibilities to Minimize Pesticide Usage in Sri Lankan Paddy Cultivation: An Emphasis on Risk Management. Hector Kobbekaduwa Agrarian Research and

Training Institute (HARTI), Colombo, Sri Lanka http://www.harti.gov.lk/images/download/reasearch_report/new1/report_no_226.pdf. (accessed 17 June 2022).

DOA, 2019. AgStat; Agricultural statistics. In: Peradeniya, Sri Lanka: Socio-Economic and Planning Center. Agriculture (DOA), Department of.

DOA, 2020a. Cost of Cultivation of Agricultural Crops; 2019 Yala. Socio economics and planning centre, Department of Agriculture (DOA), Peradeniya, Sri Lanka.

DOA, 2020b. Cost of Cultivation of Agricultural Crops; 2019/2020 Maha. Socio economics and planning centre, Department of Agriculture (DOA) Peradeniya, Sri Lanka.

DOA, 2023. Agro-Ecological Regions of Sri Lanka. Map Gallery. Department of Agriculture (DOA) Peradeniya, Sri Lanka. https://www.arcgis.com/apps/instant/minimalist/index.html?appid=d244641b5f3e4206a7c98f5cda1892e7 (Accessed 14 November 2023).

Fageria, N.K., Moreira, A., dos Santos, A.B., 2013. Phosphorus uptake and use efficiency in field crops. J. Plant Nutr. 36 (13), 2013–2022. https://doi.org/10.1080/01904167.2013.816728.

Gupta, D.K., Bhatia, A., Kumar, A., Das, T.K., Jain, N., Tomer, R., Malyan, Sandeep K., Fagodiya, R.K., Dubey, R., Pathak, H., 2016. Mitigation of greenhouse gas emission from rice–wheat system of the indo-Gangetic plains: through tillage, irrigation and fertilizer management. Agric. Ecosyst. Environ. 230, 1–9. https://doi.org/10.1016/j.agee.2016.05.023.

Hussain, S., Peng, S., Fahad, S., Khaliq, A., Huang, J., Cui, K., Nie, L., 2015. Rice management interventions to mitigate greenhouse gas emissions: a review. Environ. Sci. Pollut. Res. 22, 3342–3360. https://doi.org/10.1007/s11356-014-3760-4.

Jayasiri, M.M.J.C.N., Yadav, S., Propper, C.R., Kumar, V., Dayawansa, N.D.K., Singleton, G.R., 2021. Assessing potential environmental impacts of pesticide usage in Paddy ecosystems: a case study in the Deduru Oya River Basin, Sri Lanka. Environ. Toxicol. Chem. 41 (2), 343–355. https://doi.org/10.1002/etc.5261.

Jayasiri, M.M.J.C.N., Yadav, S., Dayawansa, N.D.K., Propper, C.R., Kumar, V., Singleton, G.R., 2022a. Spatio-temporal analysis of water quality for pesticides and other agricultural pollutants in Deduru Oya river basin of Sri Lanka. J. Clean. Prod. 330, 129897 https://doi.org/10.1016/j.jclepro.2021.129897.

Jayasiri, M.M.J.C.N., Yadav, S., Dayawansa, N.D.K., Ingold, K., 2022b. Managing agricultural water resources: addressing the complexity of innovation, social perspectives, and water governance in Sri Lanka. Irrig. Drain. 71 (S1), 71–85. https://doi.org/10.1002/ird.2693.

Jayasiri, M.M.J.G.C.N., Dayawansa, N.D.K., Yadav, S., 2023. Assessing the roles of farmer organizations for effective agricultural water management in Sri Lanka. Agric. Syst. 205 (103587), 1–12. https://doi.org/10.1016/j.agsy.2022.103587.

Kadupitiya, H.K., Madushan, R.N.D., Gunawardhane, D., Sirisena, D., Rathnayake, U., Dissanayaka, D.M.S.B., Ariyaratne, M., Marambe, B., Suriyagoda, L., 2022. Mapping productivity-related spatial characteristics in rice-based cropping systems in Sri Lanka. J. Geovis. Spat. Anal. 6, 26. https://doi.org/10.1007/s41651-022-00122-0.

Kishore, A., Alvia, M., Krupnik, T.J., 2021. Development of balanced nutrient management innovations in South Asia: perspectives from Bangladesh, India, Nepal, and Sri Lanka. Glob. Food Sec. 28, 100464 https://doi.org/10.1016/j.gfs.2020.100464.

Li, L., Tian, H., Zhang, M., Fan, P., Ashraf, U., Liu, H., Chen, X., Duan, M., Tang, X., Wang, Z., Zhang, Z., Pan, S., 2021. Deep placement of nitrogen fertilizer increases rice yield and nitrogen use efficiency with fewer greenhouse gas emissions in a mechanical direct-seeded cropping system. Crop J. 9 (6), 1386–1396. https://doi.org/10.1016/j.cj.2020.12.011.

Liang, H., Yang, S., Xu, J., Hu, K., 2021. Modeling water consumption, N fates, and rice yield for water-saving and conventional rice production systems. Soil Tillage Res. 209, 104944 https://doi.org/10.1016/j.still.2021.104944.

Liu, L., Han, J., Xu, X., Xu, Z., Abeysinghe, K.S., Atapattu, A.J., De Silva, P.M.C.S., Lu, Q., Qiu, G., 2020. Dietary exposure assessment of cadmium, arsenic, and lead in market rice from Sri Lanka. Environ. Sci. Pollut. Res. 27, 42704–42712. https://doi.org/10.1007/s11356-020-10209-0.

Lu, H., Xie, H., He, Y., Wu, Z., Zhang, X., 2018. Assessing the impacts of land fragmentation and plot size on yields and costs: a translog production model and cost function approach. Agric. Syst. 161, 81–88. https://doi.org/10.1016/j.agsy.2018.01.001.

Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., Eazhilkrishna, N., Choudhary, A.K., Deiveegan, M., Subramanian, E., Padmaja, B., Vijayakumar, S., 2023. Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies. Water 15 (10), 1802. https://doi.org/10.3390/w15101802.

Marambe, B., Nissanka, S., 2019. Sri Lanka Status Report on Sustainable Nitrogen Management. Ministry of Mahaweli Development and Environment, Sri Lanka. http://slees.org/wp-content/uploads/2020/01/Sri-Lanka-Status-Report-on-Sustainable-Nitrogen-Management.pdf (accessed 11 September 2022).

Mungkung, R., Sitthikitpanya, S., Chaichana, R., Bamrungwong, K., Santitaweeroek, Y., Jakrawatana, N., Silalertruksa, T., Gheewala, S.H., 2022. Measuring sustainability performance of rice cultivation in Thailand using sustainable rice platform indicators. Int. J. Agric. Sustain. 20 (7), 1278–1293. https://doi.org/10.1080/14735903.2022.2105008.

Navarathna, C., Pathiratne, S., de Silva, D.S.M., Rinklebe, J., Mohan, D., Mlsna, T., 2021. Intrusion of heavy metals/metalloids into rice (Oryza sativa L.) in relation to their status in two different agricultural management systems in Sri Lanka. Groundwater for. Sustain. Dev. 14, 100619 https://doi.org/10.1016/j.gsd.2021.100619.

Nguyen-Van-Hung, Balingbing, C., Sandro, J., Khandai, S., Chea, H., Songmethakrit, T., Meas, P., Hitzler, G., Zwick, W., Viriyangkura, L., Bautista, E., Gummert, M., 2022. Precision land leveling for sustainable rice production: case studies in Cambodia, Thailand, Philippines, Vietnam, and India. Precis. Agric. 23, 1633–1652. https://doi.org/10.1007/s11119-022-09900-8.

Qin, S., Lü, X., 2020. Do large-scale farmers use more pesticides? Empirical evidence from rice farmers in five Chinese provinces. J. Integr. Agric. 19 (2), 590–599. https://doi.org/10.1016/S2095-3119(19)62864-9.

Rasheed, A., Mwalupaso, G.E., Abbas, Q., Tian, X., Waseem, R., 2020. Women participation: a productivity strategy in rice production. Sustainability 12 (7), 2870. https://doi.org/10.3390/su12072870.

Ratnasiri, S., Walisinghe, R., Rohde, N., Guest, R., 2019. The effects of climatic variation on rice production in Sri Lanka. Appl. Econ. 51, 4700–4710. https://doi.org/10.1080/00036846.2019.1597253.

Rawat, P., Sharma, A., Shankhdhar, D., Shankhdhar, S.C., 2022. Improvement of phosphorus uptake, phosphorus use efficiency, and grain yield in upland rice (Oryza sativa L.) in response to phosphate-solubilizing bacteria blended with phosphorus fertilizer. Pedosphere 32 (5), 752–763. https://doi.org/10.1016/j.pedsph.2022.06.005.

Ricciardi, V., Wane, A., Sidhu, B.S., Godde, C., Solomon, D., McCullough, E., Diekmann, F., Porciello, J., Jain, M., Randall, N., Mehrabi, Z., 2020. A scoping review of research funding for small-scale farmers in water scarce regions. Nat. Sustain. 3, 836–844. https://doi.org/10.1038/s41893-020-00623-0.

Saito, K., Six, J., Komatsu, S., Snapp, S., Rosenstock, T., Arouna, A., Cole, S., Taulya, G., Vanlauwe, B., 2021. Agronomic gain: definition, approach, and application. Field Crop Res. 270, 14. https://doi.org/10.1016/j.fcr.2021.108193.

Scheer, C., Grace, P.R., Rowlings, D.W., Payero, J., 2012. Nitrous oxide emissions from irrigated wheat in Australia: impact of irrigation management. Plant Soil 359, 351–362. https://doi.org/10.1007/s11104-012-1197-4.

Sharma, S., Rout, K.K., Khanda, C.M., Tripathi, R., Shahid, M., Nayak, A., Satpathy, S., Banik, N.C., Iftikar, W., Parida, N., Kumar, V., Mishra, A., Castillo, R.L., Velasco, T., Buresh, R.J., 2019. Field-specific nutrient management using Rice Crop Manager decision support tool in Odisha, India. Field Crop Res. 241, 107578 https://doi.org/10.1016/j.fcr.2019.107578.

Sirimewan, D.C., Samaraweera, A., Manjula, N.H.C., Ekanayake, E.M.A.C., 2021. A guideline for sustainable irrigation water management: a case of a developing country. Intell. Build. Int. 13, 129–141. https://doi.org/10.1080/17508975.2020.1809982.

Sirisena, D., Suriyagoda, L.D.B., 2018. Toward sustainable phosphorus management in Sri Lankan rice and vegetable-based cropping systems: a review. Agricult. Nat. Res. 52, 9–15. https://doi.org/10.1016/j.anres.2018.03.004.

Sirisena, D.N., Wickramasinghe, D.B., Silva, L.S., 2001. Recovery of fertilizer nitrogen applied to paddy soils. In: Annals of the Sri Lanka Department of Agriculture, 3, pp. 231–236.

Sivayoganathan, C., 2020. Evolution of agricultural extension system in Sri Lanka. In: Marambe, B., Weerahewa, J., Dandeniya, W.S. (Eds.), Agricultural Research for Sustainable Food Systems in Sri Lanka. Springer Singapore, Singapore. https://doi.org/10.1007/978-981-15-2152-2_15.

SRP, 2020. The SRP Performance Indicators for Sustainable Rice Cultivation (Version 2.1). Sustainable Rice Platform, Bangkok. https://www.sustainablerice.org/wp-content/uploads/2021/10/203-SRP-Performance-Indicators-Version-2.1.pdf (accessed 28 January 2020).

Sumudumali, R.G.I., Jayawardana, J.M.C.K., Piyathilake, I.D.U.H., Randika, J.L.P.C., Udayakumara, E.P.N., Gunatilake, S.K., Malavipathirana, S., 2021. What drives the pesticide user practices among farmers in tropical regions? A case study in Sri Lanka. Environ. Monit. Assess. 193, 860. https://doi.org/10.1007/s10661-021-09611-z.

Sun, Y., Ma, J., Sun, Y., Xu, H., Yang, Z., Liu, S., Jia, X., Zheng, H., 2012. The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China. Field Crop Res. 127, 85–98. https://doi.org/10.1016/j.fcr.2011.11.015.

Suresh, K., Wilson, C., Khanal, U., Managi, S., Santhirakumar, S., 2021. How productive are rice farmers in Sri Lanka? The impact of resource accessibility, seed sources and varietal diversification. Heliyon 7, e07398. https://doi.org/10.1016/j.heliyon.2021.e07398.

Toolkiattiwong, P., Arunrat, N., Sereenonchai, S., 2023. Environmental, human and Ecotoxicological impacts of different Rice cultivation Systems in Northern Thailand. Int. J. Environ. Res. Public Health 20 (3), 2738. https://doi.org/10.3390/ijerph20032738.

Usman, K., 2013. Effect of Phosphorus and irrigation levels on yield, water productivity, phosphorus use efficiency and income of lowland rice in Northwest Pakistan. Rice Sci. 20, 61–72. https://doi.org/10.1016/S1672-6308(13)60109-2.

Wassmann, R., Pasco, R., Zerrudo, J., Ngo, D.M., Vo, T.B.T., Sander, B.O., 2019. Introducing a new tool for greenhouse gas calculation tailored for cropland: rationale, operational framework and potential application. Carbon Manag. 10, 79–92. https://doi.org/10.1080/17583004.2018.1553436.

Wickramasinghe, M.R.C.P., Dayawansa, N.D.K., Jayasiri, M.M.J.G.C.N., Silva, De, Premalal, Ranjith, 2023. A study on external pressures of an ancient irrigation cascade system in Sri Lanka. Agric. Syst. 205, 103593 https://doi.org/10.1016/j.agsy.2022.103593.

Xia, L., Xia, Y., Li, B., Wang, J., Wang, S., Zhou, W., Yan, X., 2016. Integrating agronomic practices to reduce greenhouse gas emissions while increasing the economic return in a rice-based cropping system. Agric. Ecosyst. Environ. 231, 24–33. https://doi.org/10.1016/j.agee.2016.06.020.

Zou, X., Li, Y., Li, K., Cremades, R., Gao, Q., Wan, Y., Qin, X., 2015. Greenhouse gas emissions from agricultural irrigation in China. Mitig. Adapt. Strateg. Glob. Chang. 20, 295–315. https://doi.org/10.1007/s11027-013-9492-9.