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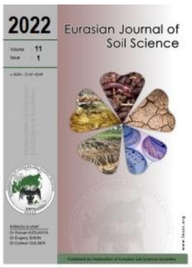

Contrasting rice management systems – Site-specific effects on soil parameters

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Abstract

Conventional rice production systems (CRPS) with continuous flooding demand much water. While population growth increases the demand for rice and, consequently, water consumption, agricultural production needs to reduce its water demand. The System of Rice Intensification (SRI) is promoted as an alternative cropland management strategy to sustainably maintain rice yields while optimizing water use. Here, we aimed at investigating whether different management translates into differences in soil parameters. To this end, the two contrasting rice production systems were compared on the same soil types, at four different study sites of D.I. Yogyakarta Province, Indonesia. Crop yields were estimated, and soils were analysed for soil total soil organic carbon (TOC), total nitrogen (TN), dissolved organic carbon (DOC), macro-aggregate stability, and a fungal biomarker (ergosterol) indicative of oxidative soil conditions. Rice yields in the study area were between 6.7 and 9 t ha^{-1}. For TOC, the combined effect of management and site was significant; in particular, in Kulonprogo and Bantul, SRI significantly exceeded CRPS' TOC values. However, a significant management effect was observed for ergosterol and DOC concentrations. Significantly higher ergosterol concentrations in SRI vs CRPS were found in Sleman and Bantul. DOC was significantly higher under SRI compared to CRPS only in Sleman. DOC and ergosterol were most responsive to management and were improved in SRI systems. The observed site-specific effects suggest the importance to consider the prevailing site conditions for adapting management strategies.

Keywords: System of rice intensification (SRI), water use efficiency, soil parameters, on-site farm studies, Indonesia.

Introduction

Worldwide 50-60% of the population uses rice as their primary staple crop (FAO, 2013), in Indonesia even 90% (Kurniadiningsih and Legowo, 2012). Increased demand for rice contributes to increasing worldwide water demand. Competition among alternative uses for surface and groundwater is starting to affect the agricultural sector. As the largest agricultural consumer of irrigation water worldwide with 24-30 % of the total freshwater withdrawals (Gathorne-Hardy et al., 2016), the rice sector was under increasing pressure to economize water use (Uphoff, 2011). As an anthropogenic source of methane (CH_4) emissions, rice paddies also contribute to global warming (Suryavanshi et al., 2013). Hence, the system of rice intensification (SRI)

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has being promoted as an alternative resource management strategy in wide areas of eastern Asia, and particularly in Indonesia (Dobermann, 2004). SRI focuses on water and nutrient use efficiency to increase rice yields while reducing external inputs (Stoop et al., 2002; Uphoff, 2003; Krupnik et al., 2012). Additionally, efficient irrigation water management such as intermittent drainage can reduce CH_4 emissions from paddy soil (Suryavanshi et al., 2013). SRI was reported to have a positive impact on grain yield (Maftukhah et al., 2015), directly benefitting both, subsistence and semi-commercial farming households. Conventional flooded rice production and SRI have several distinct features: SRI favours younger seedlings, uses wider spacing of plants, emphasizes compost or other organic fertilizers, and improves water use efficiency as compared to conventional methods (Uphoff, 1999; Uphoff et al., 2011; Gathorne-Hardy et al., 2016). Reducing demand for water and seeds, as well as, greenhouse gas emissions make SRI a promising alternative production system that is affordable to poor and marginalized communities and farmers facing water scarcity.

A more controversial claim is that the productivity of the system increases through positive synergetic interactions among the SRI practices (Stoop et al., 2002; Uphoff, 2011). Application of organic fertilizers could maintain rice yields under SRI (Dawe et al., 2003; Tsujimoto et al., 2009); intermittent drainage and intensive irrigation during SRI cultivation lead to mineralization of the accumulated soil organic matter, providing more nutrients for rice. This practice also improved the development of the root system and enhanced plant growth (Tsujimoto et al., 2009). The management of the rice fields could also affect soil properties. Tang et al. (2011) reported that adding organic fertilizer in rice fields can promote macro-aggregate formation and improve soil stability. Intact soil aggregates improve physical and chemical processes in soil. These processes are influenced by different factors including environmental conditions, soil management, agronomic practices, and soil properties (Zhang et al., 2016). Understanding how management practices in rice farming influence soil properties is important for sustainable production.

This study aimed at investigating soil parameters as potential indicators for changes in management systems. We hypothesized that different management systems (CRPS vs. SRI) are reflected in changes in soil parameters. Four test sites in D.I. Yogyakarta, where SRI and CRPS are practiced in proximity by smallholder farmers, were established as demonstration farms to educate SRI practices to farmers under a program of the Irrigation section, Indonesian Ministry of Public Work. These test sites were selected to study the influence of different management practices on comparable fields on the same soil types.

Material and Methods

Experimental site

The four study sites are located in the districts of Gunungkidul, Kulonprogo, Bantul, and Sleman in D.I. Yogyakarta, Java Island, Indonesia (Figure 1). Most of the farmers in these areas are smallholders owning 0.5–1 ha of agricultural land. The sites differ in soil types with Leptosol in Gunungkidul and Kulonprogo, Ferralsol in Bantul, and Vertisol in Sleman (Table 1, FAO, 2015). The soil physical characteristics of each site and production system are described in Table 2. These sites were selected because SRI and CRPS are being used next to each other on the same soil types. Crop yields were estimated by the farmers for each field (Table 3).

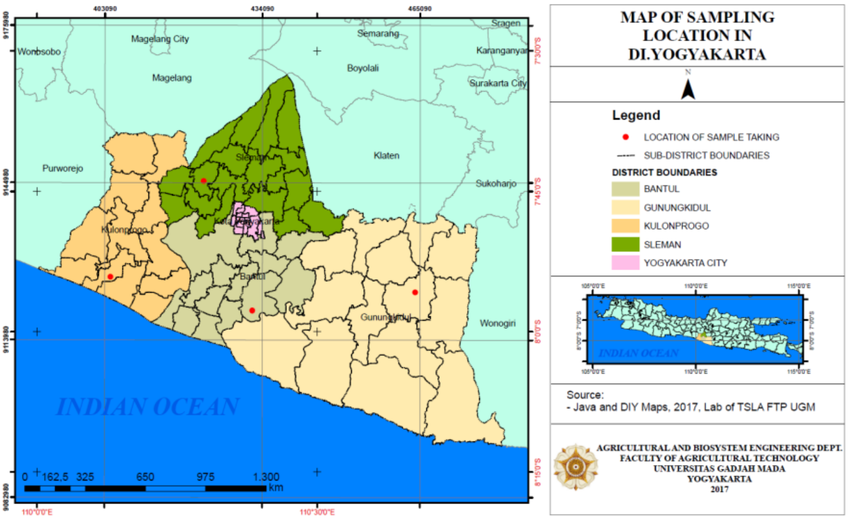

Figure 1. Location of study sites in D.I. Yogyakarta, Java Island, Indonesia. The four sites Gunungkidul, Kulonprogo, Bantul, Sleman are indicated by red points.

Table 1. Description of study sites summarizing locations, GPS data, soil type, and available irrigation schemes.

Site	Gunungkidul (G)	Kulonprogo (K)	Bantul (B)	Sleman (S)
GPS coordinates	7°55’49.42” S 110°40’30.56” E	7°54’8.93” S 110°07’53.01” E	7°43’55.01” S 110°17’51.28” E	7°57’45.82” S 110°23’04.30” E
Soil type	Leptosol	Leptosol	Ferralsol	Vertisol
Water availability	all year	No irrigation from June - Oct	Less water from Jun - Oct	all year

Table 2. Particle density (ρ_s), bulk density (ρ_b), and texture for soils under System of Rice Intensification (SRI) and Conventional Rice Production Systems (CRPS) at the study sites.

Site		Physical soil characteristics					Texture
		ρ_s	ρ_b	Particle size distribution			
		[g cm^{-3}]	[g cm^{-3}]	% Sand	% Clay	% Silt	
Gunungkidul	SRI	2.31	1.63	23	25	51	Silt Loam
	CRPS	2.03	1.59	23	26	52	Silt Loam
Kulonprogo	SRI	1.99	1.62	36	40	21	Clay
	CRPS	2.01	1.52	31	53	16	Clay
Bantul	SRI	2.17	1.36	14	45	41	Silty clay
	CRPS	2.35	1.57	17	41	43	Silty clay loam
Sleman	SRI	1.90	1.50	26	39	35	Clay loam
	CRPS	2.29	1.72	18	45	37	Clay

Table 3. Overview of soil management practices at the study sites. The cultivation type is given: System of Rice Intensification (SRI), or Conventional Rice Production Systems (CRPS). Fertilizer application rates for all schemes are given for compost, urea, and NPK (nitrogen, phosphate, and potassium fertilizer). ZA is ammonium sulphate (nitrogen 21 w/w%, sulphur 24 w/w%). ΣC is the sum of (organic) carbon from the fertilizers added (in t ha^{-1}) and ΣN sum of nitrogen from the fertilizers added (in t ha^{-1}). Yields (in t ha^{-1}) refer to the cropping season.

Site	Cultivation	SRI	Fertilizer application rates [t ha^{-1}]				ΣC	ΣN	Rice yield
		Start	Compost	Urea	NPK	remarks	[t ha^{-1}]	[t ha^{-1}]	[t ha^{-1}]
Gunungkidul	SRI	2000	15	0.10	0.15		3.42	0.32	7.50
	CRPS	---		0.20	0.20	0.10 ZA	0.04	0.14	6.10
Kulonprogo	SRI	2003	10	0.15	0.10		2.30	0.25	9.00
	CRPS	---		0.30	0.20		0.06	0.17	8.60
Bantul	SRI	2006	20	0.15	0.05		4.56	0.41	8.00
	CRPS	---		0.20	0.10	0.10 ZA	0.04	0.13	6.80
Sleman	SRI	2007	10		0.10		2.27	0.18	8.00
	CRPS	---		0.20	0.20		0.04	0.12	6.70

Management systems

Some farmers in this area have been using SRI since 2000, while others are still producing rice in a conventional way. Land management is fully comparable among the sites, the cropping patterns were the same (rice-rice-secondary crop (*palawija*)). For both systems (SRI and CRPS), land was prepared under wet condition using a hand tractor. Plowing and harrowing were carried out during land preparation to attain puddled soils as described by De Datta (1983). In this study, a local rice variety (*Oryza sativa* var. Javanica (Rojolele)) was cultivated by the farmers for its high economic value. SRI uses young seedlings (7–10 days) and single seedlings with wider spacing (30 x 30 cm), while CRPS uses older seedlings (20–25 days) and three to four seedlings with smaller spacing (25 x 25 cm).

While SRI systems are irrigated intermittently, CRPS fields are continuously flooded. In both systems, the fields are flooded to a water depth of 3-5 cm for the first ten days after transplanting to optimize seedling development and control weeds. In CRPS, fields remained flooded with water 5-10 cm deep during the entire period of rice growth. Contrarily, in SRI fields, water levels were reduced to 1 cm above soil surface ten days after transplanting and kept at this level for sufficient oxygen supply until the generative stage. At the generative stage, water was increased to 5 cm to support grain formation, then continued with 1 cm after grains had appeared. For nutrient management, CRPS farmers followed the recommendations of the Indonesian government for synthetic fertilizers (Kementerian Pertanian, 2007). SRI farmers applied both compost and a reduced amount of synthetic fertilizer compared to CRPS farmers (Table 3).

Soil sampling and analyses

Soil samples were collected in 2016 during the vegetative phase at a depth of 0-15 cm (topsoil) in three replicates per field. Field sizes were approximately 50 m^2. Total soil organic carbon (TOC) and total nitrogen (TN) were analysed by dry combustion elementary analysis (the soils did not contain carbonates) according to ISO 10694 (2009), using a Carlo Erba CNA 1500 chromatographic separation system equipped with a thermo-conductivity detector.

The particle size distribution in mineral soil material was determined by sieving and sedimentation following ISO 11277 (2009). Particle density (ρ_s) was determined using a pycnometer. The bulk density (ρ_b) was determined using the wax method which is used in Indonesia (Agus et al., 2006) based on Russell and Balcerek (1944). Dissolved organic carbon (DOC) was determined in a 1:10 w/v extract of soil in water and analysed using a UV-VIS spectrophotometer (Agilent 8453 Diode Array UV-VIS), at a wavelength of 254 nm (Brandstetter et al., 1996).

Ergosterol, a biomarker for fungal biomass, was extracted according to (Gong et al., 2001), with minor modifications as described recently in (Ferretti et al., 2018).

Ultrasonic aggregate stability (USAS) of macro-aggregates (2000 – 250 µm) was determined at 17.4 J mL^{-1} ultrasound energy applied with an ultrasonic device (Bandelin Sonopuls HD 2200). Sonification was performed with 10 g soil in 200 ml water (Mentler and Mayer, 2004; Schomakers et al., 2011). The suspension was subsequently sieved through 250 µm mesh for further calculation of macro-aggregate stability. The sand fraction was collected after sonification with 630 J mL^{-1}.

Data evaluation and statistical analyses

Data were analysed using SigmaPlot 11.0 and summarized as means ± standard deviation (SD), except for TOC (median). The statistical significance of differences in soil parameters among different management systems and sites was analysed by ANOVA, using the Tukey post hoc test ($p < 0.05$). Differences between SRI and CRPS in the same village were tested using the t-test ($p < 0.05$). In the case of TOC levels, statistical significance was determined using the Mann-Whitney-U-test. In addition, all CRPS sites were compared to all SRI sites using t-test ($p < 0.05$), except for USAS, where only Gunungkidul and Kulonprogo were compared according to different management systems.

Results and Discussion

Our results show that, some of the investigated soil parameters can be used to distinguish between the two production systems; however, for others, site-specific effects seem to dominate. For example, TOC showed site-specific management effects, and was significantly higher under SRI than under CRPS in Kulonprogo and Bantul ($p < 0.05$, Figure 2a), while in Sleman and Gunungkidul there was no significant difference between the production systems. The higher amounts of TOC under SRI in Kulonprogo and Bantul are likely due to the application of compost, the duration since when SRI management was implemented and the respective application rate of compost (Table 3). Yang et al (2005) previously reported that TOC was significantly higher when a combination of organic and inorganic fertilizers was applied in rice fields under intermittent irrigation. Even though more aerobic conditions under SRI favor C losses from the soil via mineralization due to the higher redox potential (Dobermann, 2004), the regular compost amendment that is part of the SRI management resulted in higher TOC concentrations.

Since crop yields in both systems were comparable, we can conclude that SRI can be implemented in the studied sites. The higher N inputs (Table 3) for SRI may compensate for lower plant availability (Uphoff, 2003). In our study, this has resulted in significantly elevated soil TN concentrations for Bantul and Sleman (Figure 2c, d). The turnover (mineralization) and potential losses of N were probably exceptionally high in the SRI of Gunungkidul and Kulonprogo. Hence, our results demonstrate that SRI-managed fields show many benefits over CRPS, with major drawbacks in fertilizer requirements, as also shown in another study by Thakur et al. (2022). Divergent findings in other studies might be due to differences in compared soil types rather than reflecting management differences. Bertora et al. (2018) reported that the influence of management in rice cultivation on C and N content could be strongly dependent on soil properties (soil mineralogy, soil organic carbon content) and pore-water sampling depth. The mean C/N ratios for SRI and CRPS-soils were comparable (16.9 and 16.7) and showed no statistically significant differences between the production systems (Figure 2e).

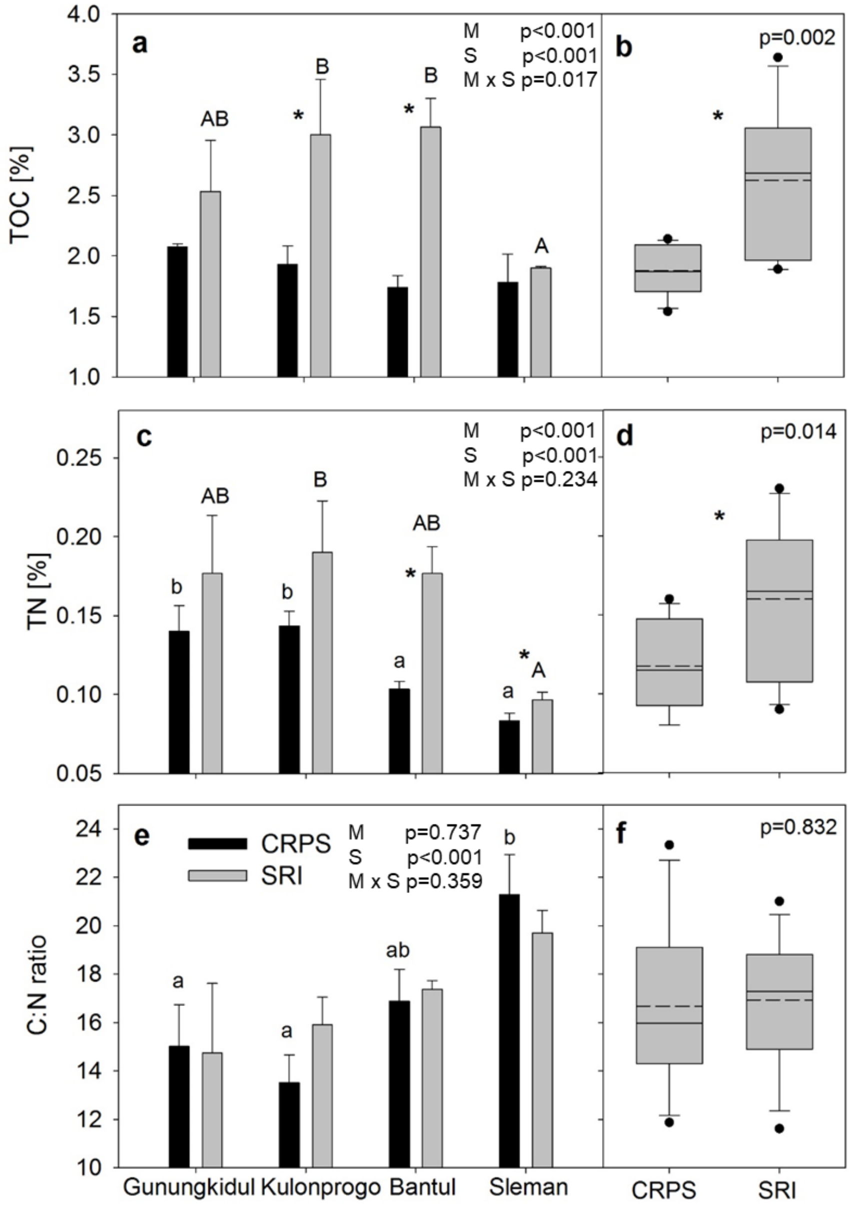

Figure 2 (a, b). Total soil organic carbon (TOC), (c, d) Total soil nitrogen (TN), (e, f) soil carbon to nitrogen (C/N) ratio in different crop management systems. Black bars indicate conventional management (CRPS), and grey bars depict system of rice intensification (SRI) at the four different locations in D.I. Yogyakarta, Java Island, Indonesia. In (a), (c) and (e), mean values of the different locations are shown, ANOVA analysis using the Tukey post-hoc test was performed for all sites. If a power of 0.8 could be reached, statistical significance ($p < 0.05$) is indicated using uppercase letters (SRI sites) or lowercase letters (CRPS sites); p-values are given in the upper right corner, for management (M), site (S), and their combined effects (MxS). Asterisks (*) indicate statistically significant differences between individual sites of different management in the same village as tested using the Mann-Whitney-U-test (a), or the t-test (c, e). In (b, d, f), box-plots of all sites of the same management system are compared (b: TOC, d: TN, f: C:N ratio). The dashed and solid lines indicate mean and median, while dot depict outliers. Statistical significance of differences was tested using the t-test; p-values are given in the upper right corner.

DOC is a bulk parameter that quantifies C solubility in water and indicates an easily available C fraction. In soils used for rice cultivation, this fraction has been suggested to result from rhizodeposition (Shen et al., 2015). Jones et al. (2014) described that the quantity of DOC depends on vegetation and soil type. We found a significant management effect on DOC concentration, which was generally higher in SRI, however, only significantly different in Sleman ($p < 0.05$, Figure 3a,b). In the other sites, the differences were not significant most likely due to weathering and soil formation (Lilienfein et al., 2004) and also high data variability. A higher DOC concentration may reflect increased rice growth and indicate more root deposits and plant residues under SRI compared to CRPS. Bertora et al. (2018) demonstrated that root exudates, plant residues, and soil organic carbon (SOC) are important sources of DOC in soil. Several studies have shown that the degradation of crop residues significantly contributes to DOC (Said-Pullicino et al., 2016), and is considered as a soil quality indicator (Wang et al., 2015).

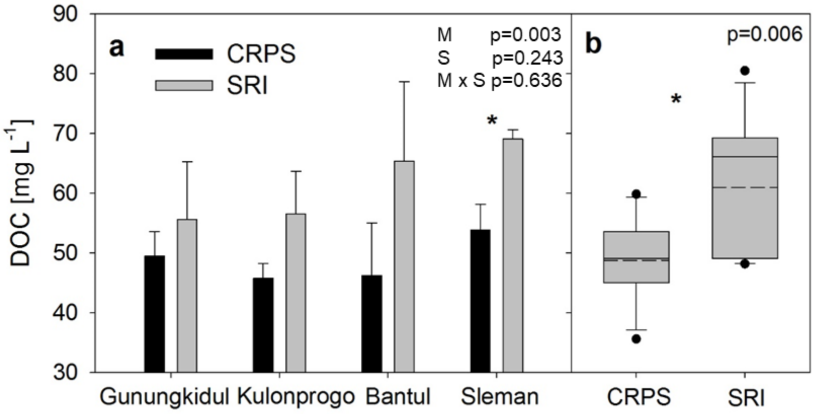

Figure 3. Dissolved organic carbon (DOC) in soils under different crop management systems. Black bars indicate conventional management (CRPS), and grey bars depict system of rice intensification (SRI) at the four different locations in D.I. Yogyakarta, Java Island, Indonesia. In (a), mean values of the different locations are shown, ANOVA-analysis was performed for all sites; p-values are given in the upper right corner, for management (M), site (S), and their combined effects (MxS). Asterisks (*) indicate statistically significant differences between individual sites of different management in the same village as tested using the t-test. In (b), box-plots of all sites of the same management system are compared. The dashed and solid lines indicate mean and median, while dot depict outliers. Statistical significance of differences was tested using the t-test; p-value is given in the upper right corner.

Ergosterol, the predominant sterol found in most fungi, is considered an indicator of fungal biomass (Srzednicki et al., 2004). The presence of fungi, in turn, signals aerobic conditions, and the fungi contribute to soil aggregation and stabilization (Ritz and Young, 2004). Again, management effects on ergosterol concentrations were detected, however, significantly higher concentrations in SRI only for Bantul and Sleman (1.81±0.28 and 1.83±0.05 mg kg^{-1}, respectively) (Figure 4a, b). The higher ergosterol was likely due to the addition of organic fertilizer and more oxidative conditions under SRI management. Interestingly, DOC and ergosterol are the only two parameters where the factorial ANOVA resulted in significant management effects, supporting higher DOC and ergosterol with SRI management. In addition, there is a significant positive correlation (r=0.532, p = 0.0074), between DOC and ergosterol. The latter has also been reported for a soil tillage experiment, where a direct positive effect of DOC for viable fungi was found (Sae-Tun et al. in revision). The authors further note a direct positive effect of viable fungi on soil aggregate stability.

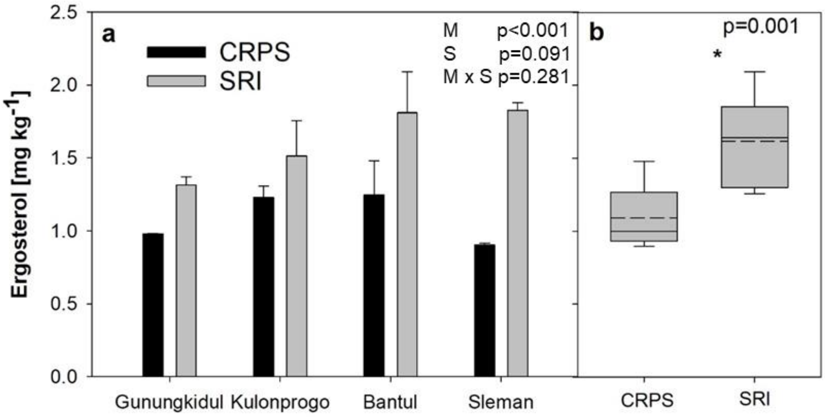

Figure 4 (a, b). Soil ergosterol concentration in different crop management systems, black bars indicate conventional management (CRPS), and grey bars depict system of rice intensification (SRI) at the four different locations in D.I. Yogyakarta, Java Island, Indonesia. In (a), mean values of the different locations are shown, ANOVA-analysis was performed for all sites; p-values are given in the upper right corner, for management (M), site (S), and their combined effects (MxS). In (b), box-plots of all sites of the same management system are compared. The dashed and solid lines indicate mean and median. Statistical significance of differences was tested using the t-test; p-values are given in the upper right corner.

Soil macro-aggregate stability is an integrative indicator of soil management changes (Mustafa et al., 2020). A higher USAS indicates better conditions for root system development, and fungal development, especially important for crop rotations in rice production systems (Menete et al., 2008). Hyphae build an extensive network extending beyond the rhizosphere and penetrate soil pores more intensively than fine roots or root hairs because of their smaller hyphal diameter (Bodner et al., 2021).

The Leptosols in Kulonprogo and Gunungkidul exhibited significantly more stable macro-aggregates under SRI conditions compared to CRPS ($p< 0.05$, Figure 5). The USAS results of Bantul and Sleman are not shown. The Vertisol (Sleman) in paddy culture is fully dispersed during the vegetation period (when the sampling was conducted), hence, no significant macro-aggregate fraction can be determined. The Ferralsol (Bantul) is dominated by micro-aggregates due to cementation by iron oxides, and ultrasound energy is too weak to disperse this cementation (also in the macro-aggregate fraction). Similarly, Yang et al (2005) found aggregates to be more water-stable under intermittent irrigation than under conditions of waterlogging (like in CRPS). This may protect organic carbon by a physicochemical mechanism in paddy soil, and protection might be further enhanced by the application of organic fertilizers. Intermittent irrigation is believed to improve oxygen supply to rice roots, decreasing aerenchym development and causing a stronger, healthier root system with potential advantages for nutrient uptake (Stoop et al., 2002). Under CRPS schemes, crop rotation is challenging and requires assiduous tillage; in contrast, soils under SRI management lend themselves much more to crop rotation because of their improved physical soil structure (macro-aggregate stability), as found for the two Leptosols in our study (Figure 5). Further, the application of organic manure and crop straw improves macro-aggregation and significantly promotes soil fertility (Bandyopadhyay et al., 2010; Huang et al., 2010).

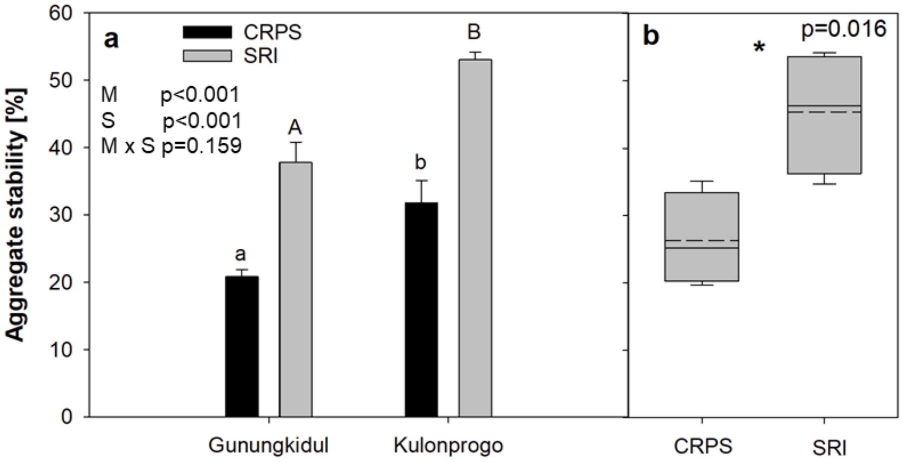

Figure 5 (a, b). Macro-aggregate stability in different crop management systems, black bars indicate conventional management (CRPS), and grey bars depict system of rice intensification (SRI) at Gunungkidul and Kulonprogo (D.I. Yogyakarta), Java Island, Indonesia. In (a), mean values of different locations are shown, ANOVA analysis using the Tukey post-hoc test was performed for all sites. If a power of 0.8 could be reached, statistical significance ($p <0.05$) is indicated using uppercase letters (SRI sites) or lowercase letters (CRPS sites); p-values are given in the upper left corner, management (M), site (S), and their combined effects (MxS). In (b), box-plots of all sites of the same management system are compared. The dashed and solid lines indicate mean and median. Statistical significance of differences was tested using the t-test; p-values are given in the upper right corner.

The International Rice Research Institute (IRRI) showed that continuous rice cropping systems, like CRPS, lead to a significant reduction in productivity, due to a loss of organic carbon and microbial biomass (Reichardt et al., 1997). Considering that Indonesia is expected to be highly vulnerable to climate change, the present study shows that SRI could be a viable alternative rice production system to address this issue. Rendering soil conditions more aerobic could improve soil aggregation and stabilization, and thus facilitate C sequestration and contribute to climate change mitigation. Previous studies on SRI reported a deeper rooting system, which further supports SRI as more resilient than conventional systems (Uphoff and Thakur, 2019; Thakur et al., 2022).

Conclusion

As water becomes increasingly scarce, the necessity for less water-intensive production systems like SRI grows. This system is a viable option to ensure sustainable rice production under a changing climate and increased pressure to produce for a growing population, as in the present study SRI could increase DOC and ergosterol concentrations as well as sustain rice yield. The site-specific effects observed in our study suggest the importance to consider the prevailing site conditions for adapting management strategies.

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