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Assessing the impact of frequent floodings on the soil quality of paddy fields: multidimensional scaling approach

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Abstract The increase in flood frequency due to climate change may cause a decrease in the soil quality of paddy fields. The results of the study showed that the multidimensional scaling approach can be used to calculate the soil quality index and assess the impact of frequent flooding on soil quality of paddy fields. Several physical, chemical and biological characteristics of the soil were not significantly different in the paddy fields that were often flooded if compared to those that were not flooded, except for exchangeable kalium content. Frequent flooding on the paddy fields tends to decrease the Soil Quality Index. The Soil Quality Index of paddy fields have a tendency to decrease if the paddy fields were often flooded, either by standing water from rivers or sea water. The Soil Quality Index category of paddy fields that were not flooded was good (86.1). While the Soil Quality Index category of paddy fields that were flooded by rivers was average (62.0) and paddy fields that were flooded by sea water was slightly good (75.8). The leverage attributes of the soil characteristics are exchangeable natrium and kalium, and total phosphorus.

Keywords: Rice, Soil properties, Soil quality index

Introduction

Soil quality is an important aspect in defining the health and productivity of agricultural lands since it directly influences the land's ability to support crop growth and development while also providing crucial ecosystem services to ensure plant productivity and profitable yields (Doran and Parkin, 1996; Karlen, 2004). The health and quality of soils, including paddy field soils greatly influence the profitability of farmers who depend on the soils. At the moment, climate change may degrade the paddy fields through frequent flooding on the paddy fields since most (93%) of the paddy fields in Indonesia are located in the river plains or lowlands near the sea (MoA, 2024). The degradation of soils of

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the paddy field will definitely decrease the soil productivity and yields. Makarim and Ikhwani (2011) stated that the impacts of global climate change that have been detected and have an impact on rice production in Indonesia, among others areincreasing air temperature on the earth's surface, extreme rainfall, rising sea levels that cause flooding directly or indirectly due to blocked river flows. and frequent natural disasters.

In the agricultural sector, more frequent flooding that submerges paddy fields results in decreases rice production or even crop failure. According to Prayoga *et al*. (2017), the increase in the events of flooding as an effect of global climate change can be a serious threat to the sustainability of rice production. The flood phenomenon that occurs causes a decrease in rice production, both due to pest and disease attacks and due to submergent which causes rice not grow properly or even paddy fields ready for harvest submerged in floodwater. Farmers are susceptible with crop failure because in addition to being submerged, many rice plants also collapsed due to being hit by quite strong water currents. The impact of frequent flooding on paddy fields, such as in Bengkulu Province has intensified from year to year that caused significant losses for farmers. Data of BPS (2019) and BPS (2024) show that there has been a decrease in rice production in 2022 by 4% when compared to rice production in 2018. The increase in rainfall and flooding events in recent years is one of the impacts of global climate change and environmental damage.

Assessment of disaster-induced changes in soil quality is important for sustaining high crop yield. Soil quality assessment is an appropriate way to maintain soil function according to the limitations of a particular ecosystem, maintain biological productivity, maintain environmental quality and improve soil health. Soil quality is measured by observing indicators of inherent soil properties and dynamic soil properties (Jannah *et al*., 2021). Soil quality integrates the physical, chemical and biological components of the soil and their interactions. Soil quality refers to the soil's ability to operate as a crucial living system within the constraints of ecosystems and land to support animal and plant productivity (Doran and Zeiss, 2000). Proper land management based on soil quality is necessary to secure sustainability of the productive soils. One way to evaluate soil quality is to use the soil quality index (Zhang *et al*., 2022; Vasu *et al*., 2016). The level of soil quality on a land can be measured based on the soil quality index since inappropriate land management will be reflected in the soil quality index and can affect plant growth and productivity (Obade, 2017). The purpose of the assessment of the soil quality index itself is to manage targets that do not only focus on crop productivity but also the possibility of soil degradation. Soil quality index provides a comprehensive and quantitative measure of the overall condition of the soil, allowing for the identification of areas that may be degraded or in need of intervention. This information can then be used to inform targeted management strategies to improve soil health and enhance agricultural productivity. Indexing soil quality can help to track changes in soil conditions over time, enabling the assessment of the long-term impacts of different land use and management practices (Mukherjee and Lal, 2014).

Determination of the soil quality index has various benefits, including to monitor soil quality periodically so that land management efforts can be carried out that can maintain optimal soil productivity in the long term. Determination of the soil quality index will reveal the soil function and environmental conditions. Soil quality reflects multiple factors including physical, chemical and biological properties of the soils (Karlen *et al*., 2001). These multiple factors basically are multidimensional, hence multidimensional scaling (MDS) can be proposed for indexing the soil quality. The multidimensional scaling facilitates to simplify complex-multivariate data into simple interpretable form while preserving relationships between different soil quality indicators. MDS allows multiple soil quality factors to be considered simultaneously in indexing effeorts that reflect the complex interplay of physical, chemical and biological properties. MDS combines these dimensions into a comprehensive soil quality index, rather than oversimplifying by looking at just one or two factors in isolation. Therefore, the aim of this study was to assess the impact of frequent floodings on the soil quality of paddy fields using multidimensional scaling approach for determining the soil quality index.

Materials and methods

This research was conducted from April to October 2023 in not-flooded and flood-affected paddy fields in Rawa Makmur District, Bengkulu, Indonesia. Physical and biological properties of soils was analysed at the Soil Science Laboratory, Faculty of Agriculture, the University of Bengkulu, Bengkulu. Analysis of chemical properties of soils was conducted at the Soil and Land Resources Laboratory, IPB University, Bogor, Indonesia.

Data acquisition

The data acquisition was accomplished through field soil sampling and laboratory analysis. Soil sampling was carried out using a reference based on a land unit map. Determination of the soil sample location points based on the free grid method on the land unit map. There are 3 paddy field unit maps, namely paddy field flooded by sea water, paddy field flooded by river water and not flooded paddy field. Soil samples was taken at 3 locations on each paddy field unit map.

Sampling of undisturbed soil using a sample ring and sampling of disturbed soil from 5 points around the undisturbed soil sampling point with a distance of approximately 1-2 meters using a soil drill then composited and taken as much as 1-2 kg. Soil samples were then analysed in the laboratory. The analysis of soil characteristics consisted of 3 dimensions, namely chemical properties, physical properties and biological properties. The analysis of soil chemical and biological properties included soil acidity (pH), total soil nitrogen, soil phosphorus, soil potassium, cation exchange capacity (CEC), soil exchangeable calcium, magnesium, kalium and natrium, soil electric conductivity (EC), carbon respiration, and soil carbon content. While analysis of soil physical properties comprised of soil texture, bulk density, specific gravity, aggregate stability, permeability and total porosity.

Data analysis

The soil analysis results were tested to compare means one way analysis of variance using Duncan's Multiple Range Test with 0.05 significance level (Gomez and Gomez, 1984). The laboratory result data was then transformed into a certain status using criteria for assessing soil analysis results as a support or as a limiting factor for plant growth and yields, as presented in Table 1 (BPT, 2005; Lal, 1994). The score ranges from 1 to 5 for the availability supportive condition of each attribute which is interpreted as starting from very low (score 1) to very high (score 5). For certain soil properties, such as specific gravity, the score value of 1 is interpreted as extreme limiting factor to the score value of 5 for none limiting factor.

The scored data were then employed to analyse and determine the soil quality index using the multidimensional scaling (MDS) approach adapted from Rapfish - a rapid appraisal technique to evaluate the sustainabilty status of fisheries (Pitcher and Preikshot, 2001). The calculated soil quality index then is used to study the effect of frequent flooding on the soil quality.

Determination of soil quality index

Determination of the soil quality index utilised the multidimensional scaling (MDS) approach. Through the MDS method, the position of the soil quality index point can be visualized through the horizontal axis and the vertical axis. With the rotation process, the position of the point can be visualized on the horizontal axis with the soil quality index value given a score of 0 (bad) and 100 (good). Afterward the soil quality index is classified into a category as seen in Table 2.

Table 1. The score for soil properties status

Soil Properties	Assesment Score for Availability or Limitation				
	1	2	3	4	5
	Very low	Low	Medium	High	Very high
	Extreme	Severe	Moderate	Slight	None
Chemical properties					
pH H_2O (1:1 ratio)	< 5 and > 8.2	5.0-5.4 and 7.8-8.2	5.4-5.8 and 7.4-7.8	5.8-6.0 and 7.0-7.4	6.0-7.0
Electric Conductivity (dS.m^{-1})	> 10	7-10	5-7	3-5	< 3
N-total (%)	< 0.1	0.1-0.2	0.21-0.5	0.51-0.75	> 0.75
P-total (mg.kg^{-1})	< 4	5-7	8-10	11-15	> 15
K (me.100 g^{-1})	< 0.1	0.1-0.3	0.4-0.5	0.6-1.0	> 1.0
Na (me.100 g^{-1})	< 0.1	0.1-0.3	0.4-0.7	0.8-1.0	> 1.0
CEC (me.100 g^{-1})	< 5	5-16	17-24	25-40	> 40
Ca (m1.100 g^{-1})	< 2	2-5	6-10	11-20	> 20
Mg (me.100 g^{-1})	< 0.3	0.4-1.0	1.1-2.0	2.1-8.0	> 8.0
Physical properties					
Texture	Sand	Loamy sand	Sandy loam	Sandy clay, Loam, Silt, Silty loam, Sandy clay loam	Clay, Silty clay, Silty clay loam, Silty clay, Clay loam
Bulk density (g.cm^{-3})	> 1.5	1.4-1.5	1.3-1.4	1.2-1.3	< 1.2
Spesific gravity (g.cm^{-3})	> 2.5	2.3-2.5	2.1-2.3	1.9-2.1	< 1.9
Penetration resistance (kgF.cm^{-2})	< 1.0	1.0-1.5	1.5-2.0	2.0-2.5	> 2.5
Permeability (cm.hr^{-1})	> 12.5	6.0-12.5	4.0-6.0	2.0-4.0	< 2.0
Porosity (%)	> 25	20-25	18-20	15-18	< 15
Biological properties					
C-organic (%)	< 0.5	0.5-1.0	1.0-3.0	3.0-5.0	5.0-10.0
C-respiration (tonnes.CO_2.ha^{-1}year^{-1})	< 2.0	2.0-3.0	3.0-4.0	4.0-5.0	> 5.0

Table 2. Soil Quality Index assesment category

No	Soil Quality Index [1/]	Soil Quality Category
1	$0 < X \leq 40$	Very bad
2	$40 < X \leq 50$	Bad
3	$50 < X \leq 60$	Slightly bad
4	$60 < X \leq 70$	Average
5	$70 < X \leq 80$	Slightly good
6	$80 < X \leq 90$	Good
7	$90 < X \leq 100$	Very good

[1/] adapted from Rachman *et al.* (2020)

The soil quality indeks is developed through ordination of chemical, physical and biological dimension indexes. While chemical, physical and biological dimension indexes are resulted from the ordination of attributes or properties of each dimension. The value of the attributes used for ordination is the status value of the laboratory analysis results. Similar to soil quality index, the position of the point are visualized on the horizontal axis with the soil quality index value given a score of 0 (bad) and 100 (good).

A sensitivity analysis was conducted to examine the most dominant dimension or attributes that contribute to the soil quality index by looking at the shape of the root mean square (RMS) ordination change on the X-axis. The greater the change in the RMS value, the more dominant the attribute is in the development of the soil quality index (Pitcher and Preikshot, 2001).

The level of confidence of the sustainability index testing on each dimension is analyzed by Monte Carlo at a 95 percent confidence interval expressed in the form of a Monte Carlo index value which is then differentiated by the MDS result index value. If the difference between the two index values for each attribute is small, it indicates that: errors in scoring each attribute are small, variations in scoring due to differences in opinion are relatively small, the analysis process that is carried out repeatedly is stable, data entry errors and missing data can be avoided, high S-Stress values can be avoided, the system being studied has a high level of confidence.

Determining the goodness of fit of MDS ordination analysis uses the stress value and coefficient of determination (R^2) generated from the calculation. The stress value and coefficient of determination (R^2) function to determine whether or not additional attributes are needed to reflect the dimensions studied accurately. A good MDS ordination is indicated by a stress value of < 0.25. If the stress value is > 0.25, then the MDS ordination analysis results have low accuracy (Kavanagh and Pitcher, 2004). Clarke (1993) stated that stress value < 0.2 still indicated to a good usable ordination result without a risk of concluding false inference.

Results

The soil properties of paddy fields

Frequent flooding on the paddy fields did not significantly affect on the soil properties, except for exchangeable kalium. The results of comparing soil properties means using Duncan's Multiple Range Test show that only exchangeable kalium in not flooded paddy field is significantly different at 0.05 level with paddy field flooded by river water, as shown in Table 3.

The conversion outcomes of laboratory results into score ranges from 1 to 5 of each attribute are presented in Table 4. The scores reflect the soil properties status as a supportive condition or as a limiting factor for plant growth. These scored data were used to analyse and determine the soil quality index using the multidimensional scaling (MDS) approach.

Soil quality index

The determination of the soil quality index prodused the index as presented in Figure 1 to 3. The assesment of the soil quality index of paddy fields that carried out using MDS shows that frequent flooding of paddy field tends to decrease the soil quality index. However, the quality index of land affected by flooding from river water shows a decline that tends to be greater than flooding from sea water. The soil quality index category of paddy fields that were not flooded was good (86.1). Whereas the soil quality index category of paddy fields that were flooded by river water was average (62.0) and paddy fields that were flooded by sea water was slightly good (75.8).

Table 3. The results of soil properties analysis

Soil Properties	Paddy Field Flooded by Sea Water	Paddy Field Flooded by River Water	Not Flooded Paddy Field
	Average values $^{1/}$		
Chemical properties			
pH H_2O (1:1 ratio)	$5.79^{a} \pm 0.74$	$5.38^{a} \pm 0.61$	$5.47^{a} \pm 0.23$
Electric Conductivity (dS.m^{-1})	$0.14^{a} \pm 0.89$	$0.05^{a} \pm 0.01$	$0.15^{a} \pm 0.10$
N-total (%)	$0.33^{a} \pm 0.09$	$0.23^{a} \pm 0.03$	$0.21^{a} \pm 0.14$
P-total (mg.kg^{-1})	$4.31^{a} \pm 0.58$	$3.65^{a} \pm 0.58$	$3.63^{a} \pm 0.46$
K (me.100 g^{-1})	$0.29^{ab} \pm 0.07$	$0.16^{b} \pm 0.02$	$0.38^{a} \pm 0.10$
Na (me.100 g^{-1})	$2.58^{a} \pm 1.52$	$0.85^{a} \pm 0.14$	$2.57^{a} \pm 1.76$
CEC (me.100 g^{-1})	$32.54^{a} \pm 2.04$	$35.49^{a} \pm 1.39$	$32.26^{a} \pm 6.56$
Ca (m1.100 g^{-1})	$1.20^{a} \pm 0.36$	$1.56^{a} \pm 0.45$	$1.21^{a} \pm 0.22$
Mg (me.100 g^{-1})	$3.21^{a} \pm 0.53$	$1.94^{a} \pm 0.73$	$3.18^{a} \pm 0.64$
Physical properties			
Texture	Sandy clay	Sandy clay	Sandy clay
Bulk density (g.cm^{-3})	$1.13^{a} \pm 0.07$	$1.21^{a} \pm 0.06$	$1.09^{a} \pm 0.11$
Spesific gravity (g.cm^{-3})	$1.98^{a} \pm 0.09$	$2.00^{a} \pm 0.11$	$1.89^{a} \pm 0.18$
Penetration resistance (kgF.cm^{-2})	$0.72^{a} \pm 0.13$	$0.32^{a} \pm 0.24$	$0.42^{a} \pm 0.24$
Permeability (cm.hr^{-1})	$4.91^{a} \pm 3.11$	$9.40^{a} \pm 3.94$	$3.78^{a} \pm 2.74$
Porosity (%)	$0.77^{a} \pm 0.01$	$0.76^{a} \pm 0.01$	$0.77^{a} \pm 0.02$
Biological properties			
C-organic	$4.36^{a} \pm 1.43$	$3.35^{a} \pm 0.77$	$3.67^{a} \pm 1.99$
C-respiration (tonnes.CO_2.ha^{-1}year^{-1})	$3.39^{a} \pm 3.15$	$2.28^{a} \pm 1.11$	$4.08^{a} \pm 1.78$

$^{1/}$ Average value data are expressed as mean ± SD. Means in the same row followed by same letter are not significantly difference at 0.05 level.

Table 4. The status scores of the soil properties

Soil Properties	Paddy Field Flooded by Sea Water	Paddy Field Flooded by River Water	Not Flooded Paddy Field
	Average scores of soil property status [1/]		
Chemical properties			
pH H_2O	3	3	3
Electric Conductivity	5	5	5
Nitrogen-total	3	3	2
Phosporus total	1	1	1
Kalium	2	1	3
Natrium	5	4	5
Cation Exchange Capacity	4	4	4
Calsium	1	1	1
Magnesium	4	4	4
Physical properties			
Texture	2	2	2
Bulk density	5	4	5
Spesific gravity	4	4	5
Penetration resistance	1	1	1
Permeability	3	2	4
Porosity	1	1	1
Biological properties			
Carbon organic	4	4	4
Carbon respiration	3	2	4

[1/] Average score: 1=very low, 2=low, 3=medium, 4=high, 5=very high or 1=extreme, 2=severe, 3=moderate, 4=slight, 5=none

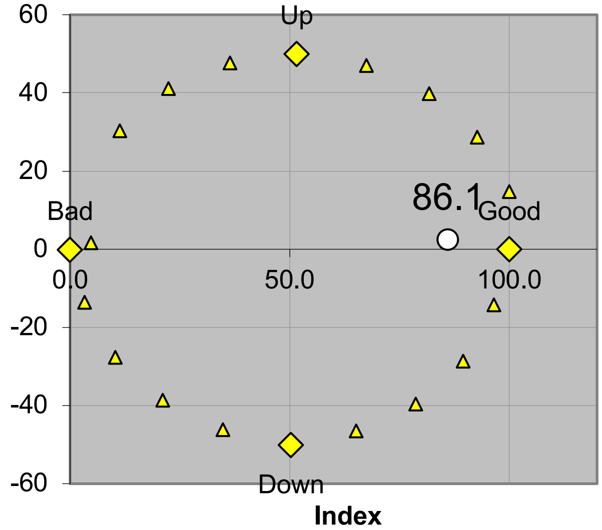

Figure 1. Soil quality index of not flooded paddy field

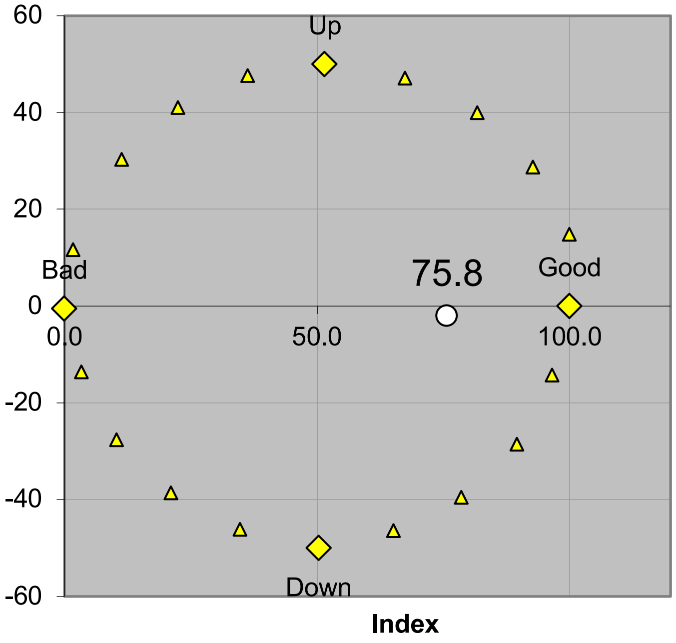

Figure 2. Soil quality index of paddy field flooded by sea water

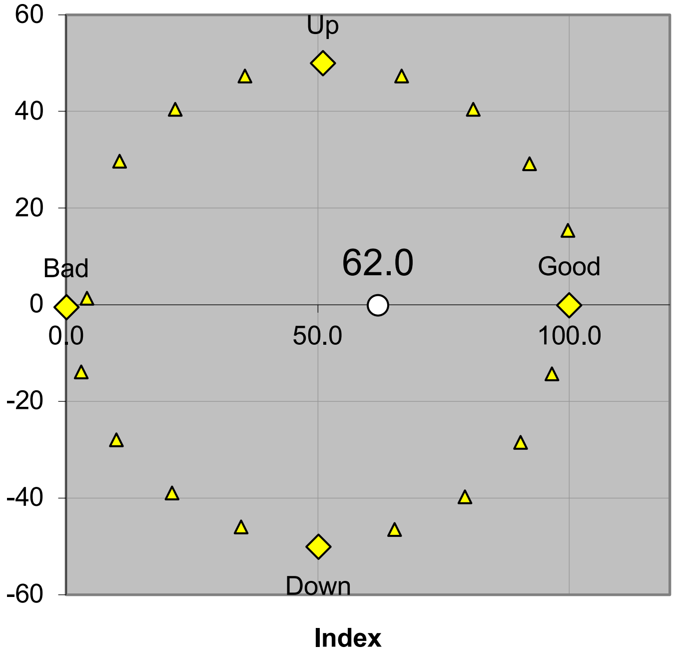

Figure 3. Soil quality index of paddy field flooded by river water

The goodness of fit of MDS ordination analysis reveals all the stress values are less than 20% and all of the coefficient of determination (R^2) are more than 0.87 (Table 5). The dominant dimension of not flooded paddy field is chemical dimension. While the dominant dimensions of paddy field flooded by river and sea water are biological dimension. Overall, the leverage attributes of the soil characteristics are penetration resistance, exchangeable natrium and kalium, and total phosphorus.

Table 5. The goodness of fit of multidimensional scaling ordination

Dimension	**Index**	**Stress (%)**	**R^2-determination**
Paddy field flooded by sea water			
Physical dimension	64.6	16.7	0.89
Chemical dimension	62.4	13.4	0.95
Biological dimension	66.1	9.8	0.98
Paddy field flooded by river water			
Physical dimension	54.3	17.1	0.88
Chemical dimension	55.8	13.5	0.95
Biological dimension	78.7	8.6	0.98
Paddy field not flooded			
Physical dimension	79.1	16.6	0.88
Chemical dimension	63.0	13.4	0.95
Biological dimension	79.2	9.4	0.98

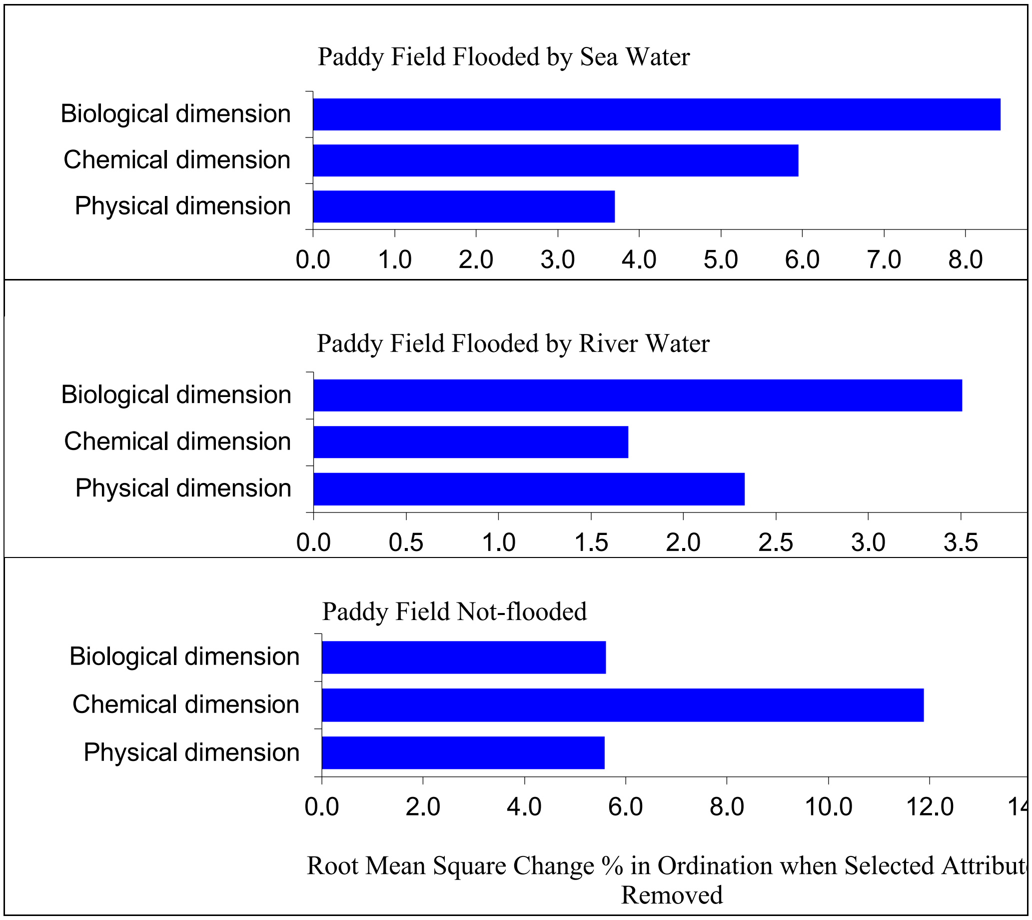

Figure 4. Leverage dimensions of the paddy fields

Discussion

The effect of increasing flood frequency on paddy fields is only seen in the significant decrease in exchangeable potassium content. Flood water originating from seawater runoff does not affect to decrease the exchangeable potassium content significantly. Exchangeable potassium content in paddy fields affected by river flooding is lower than in paddy fields not affected by flooding. During flooding, river water saturation on paddy field may lead to leaching of potassium from the soil. When water drains away after flooding, it can carry away nutrients, including exchangeable potassium, reducing its availability in the soil. In soils with a well-balanced ratio of cations, the impact of seawater flooding may be less pronounced. Since the paddy field contains high magnesium, natrium and cation exchange capacity, the buffer mechanism balances nutrient concentration in soil solution that is against sodium's impact by competing for exchange sites minimizes pottasium displacement (Grimme, 1985). The status of exchangeable pottasium in the paddy fields of this study originally was moderate. Other studies showed the status of exchangeable pottasium in the paddy fields in several locations in Java mostly were high (Kasno *et al*., 2021; Rachman *et al*., 2020; Agustina *et al*., 2020). Therefore, to maintain the availability of potassium for the growth of paddy fields, potassium must be added to paddy fields affected by river flooding.

Using MDS for indexing soil quality offers a robust and flexible approach to manage complex and multidimensional soil properties. The results of the MDS ordination analysis show that there is a shift in the dominance of chemical dimensions in paddy fields that are not flooded to biological dominance in paddy fields that are flooded. In not flooded paddy fields, the efforts to maintain and increase land productivity can be focused on the chemical dimension. This is because the soil chemical quality index is average. The condition of the soil chemical quality index at an average level was also found in the results of research conducted by Rachman *et al*. (2020) on paddy fields in West Java and Banten. Meanwhile, in paddy fields affected by flooding, the focus of efforts to maintain and increase land productivity is mainly in the biological dimension. Efforts to increase the productivity of flooded paddy fields can be done, among others by applying organic fertilizer. Applying organic fertilizer together with NPK fertilizer can increase the availability of potassium in paddy field soils, absorption of potassium, increase rice crop yields, such as the number of grains and filled per panicle, and dry milled grain (Kaya, 2014).

The ordination analysis results showed that the leverage attributes of the soil characteristics are exchangeable natrium and kalium, and total phosphorus. Total phosphorus needs to be increased because its current status is very low in all paddy fields. Exchangeable potassium also needs to be increased, especially in paddy fields affected by river floods and sea floods because its status is very low to low. While exchangeable sodium needs to be maintained so that it is not excessive.

Based on the results of this study, it can be concluded that rice fields can be negatively impacted by increased flooding, especially flooding from river water overflows. Soil quality studies can be carried out using the MDS approach to determine the soil quality index. However, the experiments on the impact of increasing flooding events on paddy fields may provide a clearer picture if carried out using an experimental multi-year design.

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