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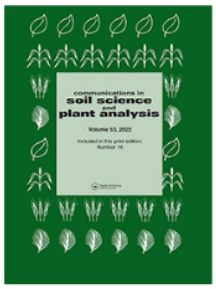

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Assessing Soil Quality Index Under Different Sugarcane Monoculture Periods and Soil Orders

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ABSTRACT

Intensive sugarcane cultivation has been carried out for more than 30 years in Indonesia and analysis of the Soil Quality Index (SQI) has not been widely carried out, especially on Entisols, Inceptisols, and Vertisols. This study aimed to assess SQI due to long-term monoculture periods in different soil orders. This study was conducted in multilocation design with two factors. The first factor was soil orders (Entisols, Inceptisols, and Vertisols), and the second one was monoculture periods (1–10, 11–20, and 21–30 years). The physical-chemical-biological properties of soil were analyzed. SQI score was calculated using Non-linear-Additive, Non-linear-Weighted Additive, Linear-Additive, and Linear-Weighted Additive scoring methods. The result show that SQI Linear-Additive method has the highest sensitivity level to observe the impact of the long-term sugarcane monoculture (2.210). SQI increased 28.2% in Inceptisols, decreased 25.8% in Vertisols and no clear pattern SQI in Entisols until monoculture 30 years monoculture periods. SQI has a greater effect on sugarcane productivity ($R^2 = 0.4472$), than the effect with sucrose content ($R^2 = 0.1056$). The long-term impact of sugarcane monoculture on SQI is highly dependent on soil order, so land management in a site-specific location is highly recommended based on the soil order so that sugarcane cultivation can be sustainable, resulting in optimal yields.

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KEYWORDS
Monoculture; productivity; soil quality index; sugarcane; yield

Introduction

The sugar cane industry in Indonesia has existed since Dutch colonialism. Sugarcane is widely chosen as a raw material because of its high sucrose content with low fiber (Solanki et al. 2017) which is still the main crop as raw material for commercial sugar production (Singh et al. 2008). During the 18th century, Indonesia became the world's largest supplier of sugar. It is reported that there were about 201 sugar factories operating in Java on 1925 (Krisprantono 2018). This condition changed when in 2017–2018, Indonesia became the largest sugar importer in the world due to the lack of increase in sugarcane yield or productivity (Sulaiman et al. 2019). In Indonesia, sugarcane crops mostly planted at Java island (Misran 2005) on Entisols, Inceptisols, and Vertisols soils orders (Pusdatin 2017). The difference in soil orders will affect the quality of the sugarcane produced (Zhou and Gwata 2015).

Soil is a natural formation that affects plant productivity by maintaining water and nutrient conditions in accordance with the five factors that make up the soil and its use (Karlen et al. 1997). Soil Quality Index (SQI) is an indicator of soil's capacity to function. Soil quality indicators can be classified as an inherent quality, which is determined by soil-forming factors such as climate, parent material, timing, topography and biota, and dynamic quality, which describes the condition of the soil due to the land use or management (Wienhold, Andrews, Karlen 2004). The SQI calculation aimed to observe the changes in soil properties caused by human use and land management (Friedman et al.

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2001). It can even assess changes in soil conditions that can lead to changes in plant productivity (Andrews, Karlen, and Cambardella 2004) based on the interaction of soil physical, chemical, and biological properties (Mausbach 1996). Analysis of changes in SQI due to land management is important to maintain high and sustainable yields (Mukherjee, Lal, and Sainju 2014). The results of this SQI can be used as input for improving soil quality with improved management (Cherubin et al. 2016). SQI analysis has been carried out to see the effect of conservation farming practices on improving soil quality on cereal intensive farms in India and the results show that an increase in SQI was positively correlated with an increase in yield (Roy et al. 2021). SQI analysis has also been carried out on wheat planted grown in India and the results show that conventional and conservation wheat farming systems have different SQI values (Datta et al. 2022). SQI documentation to evaluate land use and soil management has not been carried out well especially for sugarcane (Tesfahunegn 2014).

Sugarcane has long been planted in Indonesia, even now it is one of the strategic crops requested by the government for intensification. Discussions on the long-term impact of monoculture sugarcane cultivation have been carried out by other researchers using the Driver-Pressure-State-Impact-Response (DPSIR) framework, and the result is that this system causes a decrease in soil quality. These conditions are associated with decreased yields and productivity of sugarcane, increased pests and diseases, decreased farmer income, higher dependence on chemicals, and higher cultivation costs (Putra et al. 2020).

Information related to the impact of sugarcane monoculture on changes in soil quality in several soil orders is quite rare. Therefore, this study aimed to assess changes in the soil quality index (SQI) of the Entisols, Inceptisols, and Vertisols soils used for sugarcane monoculture for up to 30 years, as well as to determine whether the intrinsic soil quality (soil order) is more dominant than the dynamic quality of the soil (sugarcane monoculture).

Materials and method

This study was designed in a multi location (oversite design) with two factors. The first factor was the soil order (Entisols, Inceptisols, and Vertisols), and the second factor was the sugarcane monoculture period (1–10, 11–20, and 21–30 years). This monoculture period means the length of time the land is planted with sugar cane without changing the crop commodity being planted. The sugarcane crop used in this study was a second ratoon sugarcane crop, meaning that the sugar cane plant is not pruned until two-time harvests, or that crops were planted in 2015 with the Bululawangan variety. Research locations representing Entisols and Inceptisols are in Purworejo and Magelang, Central Java, while those representing Vertisols are in Kulonprogo, Yogyakarta (Figure 1). The area of the land block observed was 10 m-long and 10 m-wide (±100 m^2 wide). The research location has a type of Am climate (tropical monsoon) based on the Koppen-Geiger classification, with an average monthly temperature above 18°C and does not have a cold climate with high annual rainfall (Climate-Data.org 2019).

The sugarcane field used in the research belongs to local farmers under the standard operating procedure management of Madukismo sugar factory. Standard operating procedures for the maintenance of sugarcane include fertilizing, cleaning weeds, controlling pests and diseases, and activity of removing yellowed sugarcane leaves. Fertilization was carried out twice for ratoon plants with a total fertilizer dose of 500 kg/ha Zwavelzure Ammoniak fertilizer (ZA) and 400 kg/ha Phonska fertilizer. ZA fertilizer or ammonium sulfate has a nitrogen content of 20.8% and a minimum sulfur content of 23.8%. Phonska is a compound fertilizer with 15% N, 15% P_2O_5, and 15% K_2O. Fertilization was done manually, spread evenly into the land then covered by the soil. The application of fertilizer was made on 1–2 and 6–8 after harvest (*ratoon* plant). The activity of removing yellowed sugarcane leaves was carried out three times in one growing season with the aim that air circulation can run smoothly and sunlight can enter the garden and can illuminate the sugarcane stalks so that sugarcane does not collapse easily and suppress pests and diseases.

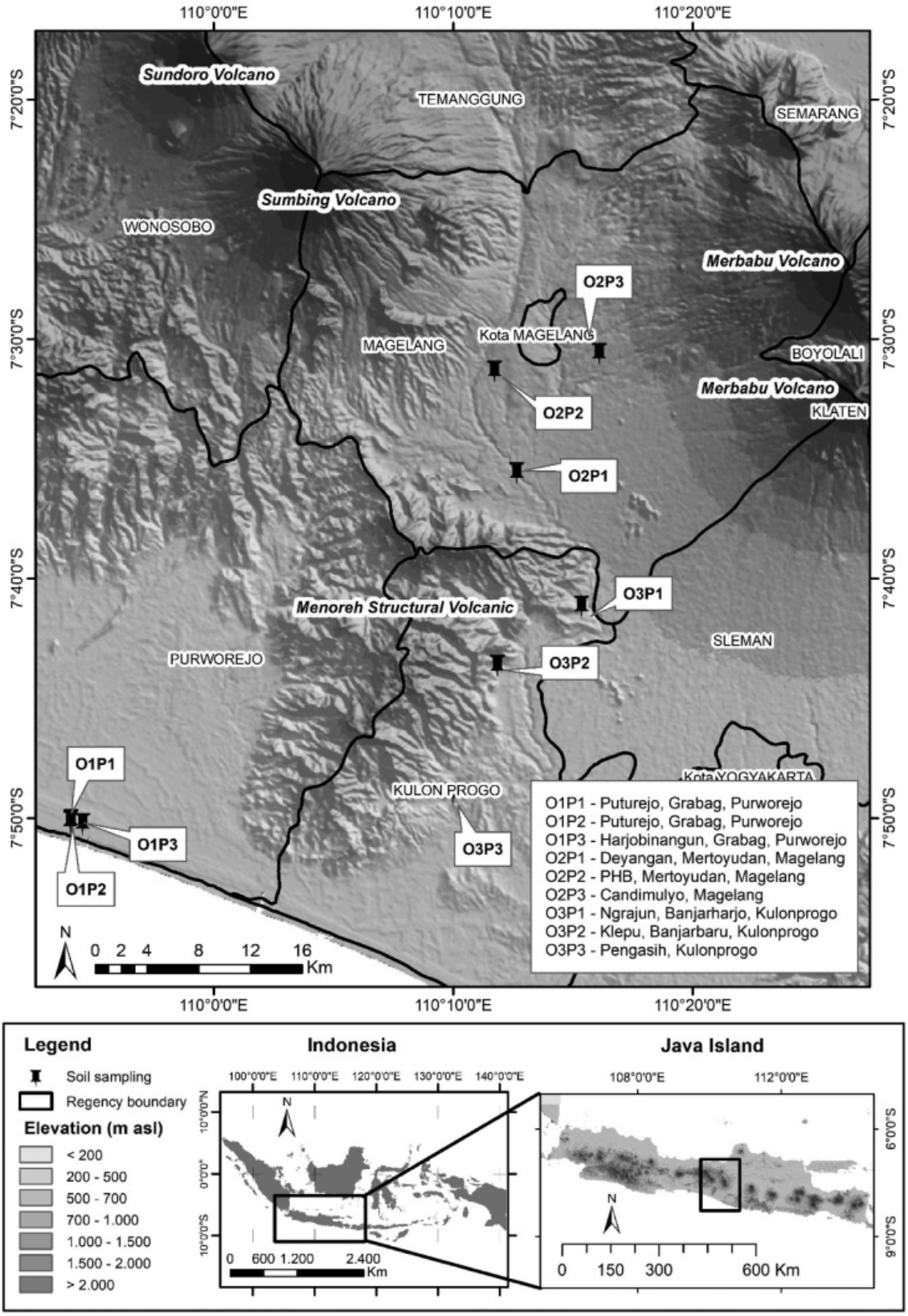

Figure 1. Research locations.

Analysis of soil and plant samples

Soil samples were taken from layer 1 and layer 2 of the soil profile found at each location. Three samples of each soil layer were taken randomly. Soil samples were dried and sieved through a diameter of 0.5 mm and 2 mm for the physical and chemical properties analysis. The stability of the aggregate was analyzed using the wet-dry sieve method (De-Boodt method), bulk density (BD) with ring sample, particle density (PD) with a pycnometer, percentage of sand, silt, and clay (Hamarashid, Othman, and Hussain 2010), and the soil porosity with the equation of n= (1- $\frac{BD}{PD}$) x 100%. The soil chemical properties determined include pH-H_2O with a ratio of 1: 2.5 for soil: water, nitrate (NO_3-) using the Cottenie method (Cottenie et al. 1982), organic C using the Walkley and Black method (Blakemore, Searle, and Daly 1981), the cation exchange capacity (CEC) using ammonium acetate at pH 7 (Hajek, Adams, and Cope 1972), available P using Olsen (if pH-H_2O >5.5) or Bray extractors if pH-H_2O <5.5 (Dengia and Lantinga 2016), and Zinc (Zn) using extracts of DTPA (diethylenetriaminepentaacetic acid) (Bigott, Hoy, and Fultz 2019). Boron (B) was analyzed using the hot water method and given Azomethin-H reagent (Xu et al. 2001). Sodium (Na), Potassium (K), Calcium (Ca), and Magnesium (Mg) were extracted using NH_4Cl, followed by reading with a Flame photometer (for Na and K) and Atomic Absorption Spectrophotometry (for Ca and Mg) (Qongqo and Antwerpen 2000).

Fresh soil samples were used for biological properties analysis. Soil samples were taken from layer 1 and layer 2 of the soil profile found at each location. After taken from the sites, the samples were put into a cooler box filled with ice in a closed container. The samples then stored in a refrigerator before being used for analysis on laboratory. Analysis of soil biological properties that have been carried out include: soil carbon mineralization (C Min) using the laboratory incubation technique method (Biederbeck et al. 1994), soil microbial biomass C (C Mic) using the chloroform fumigation-extraction method (Brookes et al. 1985), carbon particulate organic matter (C-POM) using the fractionation method (Marriott and Wander 2006), N mineralization (N Min) using the incubating re-wetted soils method, and N microbial biomass (N Mic) using the chloroform fumigation-extraction method (Biederbeck et al. 1994).

Plant analysis was carried out to determine yield and productivity. Plant samples were taken from each location, and 30 plants were used for yield analysis. The yield was calculated by multiplying sap value with sucrose content factor. Meanwhile, the sap value (%) was obtained from = pol − 0.4 (brix-pol). Brix (%) is the percentage of sugar and non-sugar (%), Pol (%) is the percentage of sugar (%), 0.58 is sucrose content factor and 0.4 is the stipulated number.

Analysis of soil quality index (SQI)

The Soil Quality Index (SQI) score was calculated using four methods schematically presented in Figure 2. The stages are as follows:

1. The Minimum Data Set (MDS) was determined by using Principal Component Analysis (PCA). The principal component with an eigenvalue of ≥ 1 was used for the identification of MDS. The indicator with the loading value included in the ten percent of the highest weighted loading value was chosen as an important indicator of each component.

2. Two ways of assessment (scoring) were applied on each indicator based on an appropriate curve to assess each indicator parameter. The appropriate curves and logical algorithms for the values of the assessment indicators were selected and interpreted based on the purpose of soil productivity. The scoring curves of “more is better” and “less is better” in the combination of linear and non-linear equations were applied to transfer MDS values into scores. The sigmoidal type equation was used for the non-linear variable assessment with a scale between 0 and 1, as seen in equation 1. Meanwhile, equations 2 and 3 were used to make an assessment using a linear scoring system, in which the “more is better” curve uses equation 2, and the “less is better” curve uses equation 3.

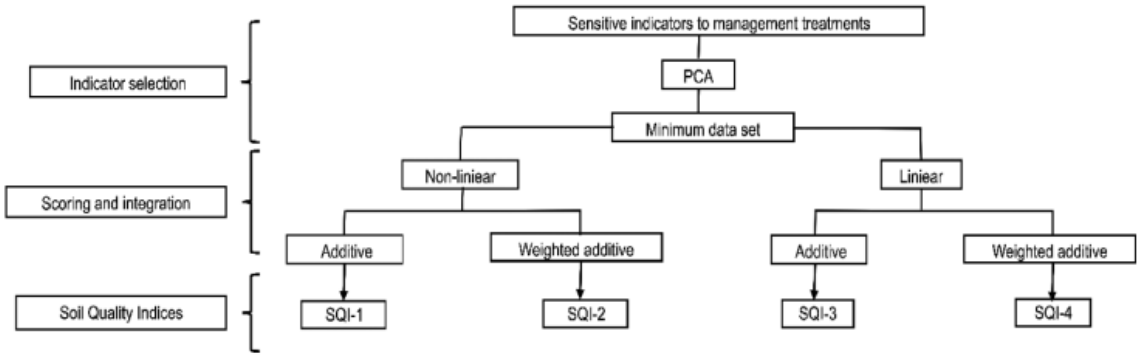

Figure 2. Diagram of the soil quality index analysis (Askari and Holden 2015). SQI-1 (Non-linear-Additive), SQI-2 (Non-linear-Weighted Additive), SQI-3 (Linear-additive), SQI-4 (Linear-Weighted Additive).

$$S_{NL} = \frac{a}{1 + \left(\frac{x}{xo}\right)^b} \tag{1}$$

S_{NL} is a score for non-linear soil variables, ranging between 0 and 1. Meanwhile, a is the maximum score (1 for this study), x is the value for soil variables/parameters, xo is the mean value of a soil parameter, and b is from the equation (-2.5 for the "more is better" curve and 2.5 for the "less is better" curve).

$$S_L = \left(\frac{x - l}{h - l}\right) \tag{2}$$

$$S_L = 1 - \left(\frac{x - l}{h - l}\right) \tag{3}$$

S_L is a linear score for soil parameters, ranging between 0 and 1. Meanwhile, x is the value of the soil parameter, in which l is the lowest and h is the highest value of the parameter (Askari and Holden 2015).

3. The SQI score was calculated using two approaches, namely SQI "additive" (SQI_A) and SQI "weighted additive" (SQI_w). The calculation for the "additive" approach uses equation 4, while that for the "weighted additive" uses equation 5.

$$SQI_A = \sum_{i=1}^{n} \frac{S_i}{n} \tag{4}$$

$$SQI_W = \sum_{i=1}^{n} W_i \times S_i \tag{5}$$

S_i is the score for both non-linear and linear, n is the number of parameters used to calculate SQI, and Wi is the weight value for each parameter obtained from PCA (Andrews, Karlen, and Mitchell 2002). After the SQI scores were obtained, the sensitivity level of each method was analyzed (Masto et al. 2008) using equation 6. SQI maximum is the higher score of SQI and SQI minimum is the lowest score of SQI.

$$Sensitivity(S) = \frac{SQI_{maximum}}{SQI_{minimum}} \tag{6}$$

Statistical analysis

The data obtained were analyzed using analysis of variance (ANOVA), followed by Duncan's multiple range test (DMRT) at 5% to compare the effects of the treatments. Principal component analysis (PCA) was performed using Minitab. The scoring, SQI, and correlation calculations were carried out using Microsoft Excel for Microsoft 365.

Results

Impacts of sugarcane monoculture on soil quality properties

Long-term sugarcane monoculture may have different effects on the physical, chemical, and biological properties of soil. This study analyzed 25 soil parameters to determine the impacts of sugarcane monoculture in different periods and soil orders (Table 1). The bulk density of Entisols soil in the 11–20-year monoculture period was 0.25 g cm^{-3} higher than in the 1–10-year period. However, in Inceptisols and Vertisols, the bulk density decreased with the longer monoculture period. The porosity

Table 1. Soil quality indicators in the three soil orders with different monoculture periods.

	Treatments								
Soil Parameter	O1P1	O1P2	O1P3	O2P1	O2P2	O2P3	O3P1	O3P2	O3P3
Physical Properties									
BD (g cm^{-3})	1.11	1.36	1.30	1.33	1.27	1.29	1.37	1.37	1.36
n (%)	58	51	52	44	45	47	34	34	35
Silt (%)	15	12	8	28	23	19	26	23	29
Clay (%)	12	8	8	20	34	20	43	57	40
Sand (%)	74	80	84	52	43	61	31	20	32
AS	59.3	62.7	66.7	60.3	73.9	74.6	60.9	59.3	60.0
Chemical Properties									
pH H_20	5.8	5.4	5.5	6.5	6.1	5.6	6.0	5.4	6.8
Organic C (%)	1.2	1.0	0.8	0.5	0.6	0.7	1.0	0.9	0.9
CEC (cmol(-)kg^{-1})	16.0	12.4	11.7	18.1	13.3	13.5	21.9	38.8	38.7
Total N (%)	0.13	0.10	0.10	0.10	0.10	0.09	0.10	0.08	0.10
C/N	10	10	8	6	7	7	9	10	9
N-NO_3- (mg kg^{-1})	51.16	60.50	48.80	57.18	62.39	66.32	71.21	64.49	54.30
Available P (mg kg^{-1})	9	13	14	17	25	17	29	27	25
Av-Ca (cmol$^{(+)}$ kg^{-1})	3.96	4.18	4.27	7.24	7.06	6.37	7.92	7.45	7.69
Av-Mg (cmol$^{(+)}$ kg^{-1})	1.55	1.44	1.38	1.90	2.00	1.83	2.16	2.06	2.10
Av-Na (cmol$^{(+)}$ kg^{-1})	1.01	1.44	1.56	0.54	0.62	0.55	0.77	0.80	0.72
Av-K (cmol$^{(+)}$$kg^{-1}$)	0.643	0.691	0.607	0.808	0.911	0.876	0.996	0.762	0.724
Base saturation (%)	43.6	60.6	64.8	56.1	77.9	68.9	52.3	27.7	28.5
Boron (mg kg^{-1})	0.394	0.442	0.401	0.507	0.276	0.175	0.141	0.207	0.311
Zinc (mg kg^{-1})	0.039	0.039	0.029	0.061	0.119	0.074	0.052	0.043	0.045
Biological Properties									
C Min (mg g^{-1})	0.103	0.064	0.018	0.058	0.040	0.055	0.077	0.024	0.019
C Mic (mg g^{-1})	0.040	0.031	0.060	0.040	0.026	0.064	0.081	0.041	0.035
C-POM (mg kg^{-1})	0.049	0.040	0.046	0.014	0.016	0.024	0.017	0.010	0.014
N Min (mg kg^{-1})	12.50	13.38	18.25	10.04	39.27	17.62	17.62	15.51	19.63
N Mic (mg kg^{-1})	33.90	30.16	21.83	28.83	30.23	29.80	34.08	39.74	24.71

Remarks: BD= bulk density, n= porosity, AS= aggregate stability, C/N= carbon/nitrogen ratio, Av-Ca= available Ca, Av-Mg= Available Mg, Av-Na= Available Na, Av-K= Available K, C Min=C mineralization, C Mic= C microbial biomass, C-POM=C-particulate organic matter, N Min= N mineralization, N-Mic= N microbial biomass. O1= Entisols, O2= Inceptisols, O3= Vertisols, P1= monoculture period of 1–10 years, P2= monoculture period of 11–20 years, P3= monoculture period of 21–30 years.

value (n) in Entisols decreased with the length of the monoculture period, while in Inceptisols and Vertisols, the 21–30-year monoculture period had a higher *n* value compared to the 11–20-year and 1–10-years monoculture period.

The percentage of silt in Entisols and Inceptisols in the 21–30-year monoculture period was lower than in the 1–10-year period. Meanwhile, the percentage of silt in Vertisols in the 11–20-year monoculture period was lower than in the 1–10 and 21–30-year periods. The percentage of sand in Entisols in the 1–10-year monoculture period was lower than in the 11–20 and 21–30-year periods. On average, the clay percentage in Vertisols was higher than that in Inceptisols and Entisols. The stability of the Vertisols aggregate increased with the longer monoculture period. However, it was different in Entisols and Inceptisols. In general, the aggregate stability of the three soil orders is categorized as low to moderate. The aggregate stability was not changed due to the sugarcane monoculture period of up to 30 years.

The longer monoculture period decreased the pH-H_2O values in Entisols and Inceptisols. Meanwhile, the monoculture period of 1–10 years showed lower pH-H_2O in Vertisols compared to the monoculture period of 21–30 years but higher than that of 11–20 years. The value of organic C varied in each soil order due to the monoculture periods. Table 1 shows that in Entisols, the longer the sugarcane monoculture period, the lower the soil organic C content. In Inceptisols and Vertisols, the longer the sugarcane monoculture period, the soil organic C value tended to be stable. The total N in all locations is categorized as very low to low. The average total N in Vertisols in the monoculture period of 21–30 years was greater than that in the monoculture period of 1–10 years. This condition is different from that in Entisols, which has a sandy texture. The C/N ratio of Entisols in the monoculture period of 21–30 years was lower than in that of 11–20 and 1–10 years. However, the C/N ratio in Inceptisols was higher in the monoculture period of 21–30 years. The conditions were different for the C/N ratio in Vertisols, and the average C/N ratio in Entisols was higher than in Vertisols and Inceptisols.

The average available P in Vertisols was greater than in Inceptisols and Entisols. The available P in Entisols was greater in the monoculture period of 21–30 years than in the period of 11–20 years and 1–10 years. Meanwhile, the available P in Inceptisols and Vertisols was same in the monoculture period of 1–10 years than in the period of 21–30 years. Table 1 shows that the available soil cations varied greatly in different sugarcane monoculture periods for each soil order. In Entisols, it can be seen that available Ca increase with increase in the sugarcane monoculture period. A different pattern was observed in Inceptisols and Vertisols, showing a decrease in the available Ca with the longer monoculture period. There was not much difference in the available Mg between all treatments. The average available Na in Entisols was greater than in Vertisols and Inceptisols, and the value decreased with the longer monoculture period. The available K in Vertisols decreased with the longer monoculture period. Soil CEC also varied as affected by different sugarcane monoculture periods and soil orders. The CEC in Entisols and Inceptisols decreased with the longer monoculture period but increased in Vertisols. The same pattern was also observed in base saturation, which increased in Entisols and Inceptisols with the increasing monoculture period and decreased in Vertisols. Based on the values, the base saturation in Entisols and Inceptisols is considered medium to high, while the base saturation in Vertisols is considered low except for 1–10 years period. The longer monoculture period decreased the B levels in Inceptisols. Conversely, the longer the monoculture period increased the available B in Vertisols. Variable Zn values were also seen as a result of the different monoculture periods and soil orders.

C Min in the three soil orders decreased with the increasing period of sugarcane monoculture. The longer monoculture period also decreased C Mic in Vertisols. However, the C Mic values in Entisols and Inceptisols increased with the increasing of monoculture period. C-POM in all treatments showed varying values. N Min in Entisols increased with the increasing of monoculture period. Meanwhile, the increasing of monoculture period will decreased the value of N Mic on Entisols and Vertisols.

Soil quality index estimation using four methods

The calculation of the Soil Quality Index (SQI) resulted in seven components of PCA with an eigenvalue of > 1 (Table 2). Principle Component 1 (PC1) shows Available-Ca (Av-Ca) was selected for assessment because it has the high loading factor value. Available-Mg (Av-Mg), percentage of sand, Available-P (Av-P), and n were also selected because they have a loading factor of ±10% of the highest loading factor. Organic C was selected from PC2, while Available-K (Av-K) and base saturation were selected from PC3. Meanwhile, C Min, C Mic, N Min, and aggregate stability (AS) were selected from PC4, PC5, PC6, and PC7, respectively. Several parameters selected from the PCA were then weighted for the calculation of SQI Non-Linear-Weighted Additive and SQI Linear-Weighted Additive were calculated. The type of score curve, mean value, highest and lowest values, and weight for each parameter are summarized and presented in Table 3.

Figure 3 provides information that long-term sugarcane monoculture has an impact on soil quality index (SQI), and the impact is different for the three soil orders. According to the SQI-1 (Non-Linear-Additive) method, there were no changes in the SQI of Entisols and Inceptisols, remaining in the moderate category, from the monoculture period of 1–10, 11–20, and 21–30 years. A different result was seen in Vertisols, experiencing a change in SQI from moderate (in the monoculture period of 1–10

Table 2. Principle component analysis (PCA) results.

Eigenvalue	8.451	3.427	2.789	1.883	1.518	1.231	1.047
Proportion	0.338	0.137	0.112	0.075	0.061	0.049	0.042
Cumulative	0.338	0.475	0.587	0.662	0.723	0.772	0.814
Eigenvectors							
Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
BD	0.149	0.158	-0.045	-0.420	0.165	-0.282	0.246
N	**-0.313**	-0.101	-0.085	0.152	0.016	0.112	-0.103
Silt	0.250	-0.135	0.061	0.144	0.149	0.239	0.149
Clay	0.292	0.096	0.046	0.071	-0.163	-0.033	-0.229
Sand	**-0.317**	-0.023	-0.058	-0.108	0.070	-0.064	0.121
AS	-0.004	-0.034	-0.334	-0.075	0.010	-0.300	**-0.374**
pH H_20	0.120	-0.327	0.257	0.098	0.195	0.004	0.048
Organic C	-0.033	**0.479**	-0.113	0.137	0.120	0.062	0.040
CEC	0.234	0.190	0.334	0.004	0.074	-0.030	-0.114
Total N	-0.036	0.184	-0.265	0.129	0.375	-0.186	0.215
C/N	-0.015	0.427	0.082	0.098	-0.116	0.188	-0.133
N-NO_3-	0.073	-0.029	-0.094	0.232	-0.395	-0.494	-0.117
Av-P	**0.304**	0.093	-0.098	-0.202	0.010	-0.007	-0.042
Av-Ca	**0.326**	-0.033	-0.061	-0.063	0.075	-0.031	0.140
Av-Mg	**0.326**	0.031	-0.100	0.051	0.071	0.024	0.075
Av-Na	-0.240	0.255	0.070	-0.251	-0.035	-0.019	-0.119
Av-K	0.173	0.114	**-0.409**	-0.049	0.181	0.107	0.214
Base saturation	-0.108	-0.207	**-0.440**	-0.182	-0.072	0.065	0.019
B	-0.169	-0.126	0.221	0.020	0.380	-0.146	0.000
Zn	0.115	-0.312	-0.291	0.097	-0.044	-0.023	-0.142
C Min	-0.091	-0.048	-0.105	**0.550**	0.040	0.074	0.290
C Mic	-0.011	0.037	0.011	-0.094	**-0.592**	0.118	0.551
C-POM	**-0.299**	0.175	-0.075	-0.007	0.049	0.012	0.037
N Min	0.042	-0.032	-0.184	-0.149	0.012	**0.614**	-0.299
N Mic	0.098	0.256	-0.147	0.401	-0.011	-0.027	-0.140

Remarks: bold signifies the highest loading factor value. BD= bulk density, *n*= porosity, AS= aggregate stability, C/N= carbon/nitrogen ratio, Av-Ca = available Ca, Av-Mg= available Mg, Av-Na= available Na, Av-K= available K, C Min= C mineralization, C Mic= C microbial biomass, C-POM= C-particulate organic matter, N Min= N mineralization, N Mic= N-microbial biomass.

Table 3. Types of scoring curves, parameters of non-linear and linear equations, and the weighted results of the selected parameters (MDS).

		Non-linear		Linear		
Parameter	Scoring curve	Mean (xo)	Slope (b)	*h*	*l*	Weight
Org-C	more is better	1.09082	-2.5	1.494	0.591	0.168
Av-P	more is better	21.7643	-2.5	30.045	10.286	0.067
Av-Ca	more is better	6.59253	-2.5	8.089	4.386	0.072
Av-Mg	more is better	1.9117	-2.5	2.349	1.502	0.072
Av-K	more is better	0.91253	-2.5	1.081	0.734	0.066
AS	more is better	65.6123	-2.5	80.559	59.070	0.052
C Min	more is better	0.04709	-2.5	0.090	0.012	0.092
C Mic	more is better	0.04279	-2.5	0.068	0.021	0.075
C-POM	more is better	0.02934	-2.5	0.055	0.013	0.066
N Min	more is better	18.8432	-2.5	28.871	13.668	0.060
N	optimum	43.203	-2.5 or 2.5	54.385	32.796	0.069
BS	more is better	56.5113	-2.5	77.968	29.858	0.071
Sand	optimum	52.9606	-2.5 or 2.5	84.707	12.387	0.070

Remarks: Org-C= organic Carbon, Av-*P*= available P, Av-Ca = available Ca, Av-Mg= available Mg, Av-K= available K, AS= aggregate stability, C Min= C mineralization, C Mic= C microbial biomass, C-POM= C-particulate organic matter, N Min= N mineralization, n= porosity, BS=Base saturation, *l*= the lowest value, *h*= the highest value. Org-C= organic Carbon, Av-*P*= available P, Av-Ca= available Ca, Av-Mg= available Mg, Av-K= available K, AS= aggregate stability, C Min= C mineralization, C Mic= C microbial biomass, C-POM= C-particulate organic matter, N Min= N mineralization, n= porosity, BS=Base saturation, l= the lowest value, h= the highest value.

and 11–20 years) to low (in the monoculture period of 21–30 years) category. Meanwhile, according to the SQI-2 (Non-Linear-Weighted Additive) method, all of the soil orders tested (Entisols, Inceptisols, and Vertisols) did not experience changes in the SQI, remaining in the moderate category from monoculture period of 1–10, 11–20, and 21–30 years. This result is because the SQI-2 method has the lowest sensitivity value compared to the other methods (Figure 4).

Based on the SQI-3 (Linear-Additive) method with the highest sensitivity level (Figure 3), there was no change in the SQI of Entisols and Inceptisols, remaining low and moderate, respectively, in all monoculture periods. A different result was observed in Vertisols, experiencing a change in the SQI from high to moderate. According to SQI-4 (Linear-Weighted Additive), Entisols and Vertisols showed a change in the SQI, respectively, from moderate to low and from high to moderate. Whereas, Inceptisols did not show any changes in SQI, which was moderate in all monoculture periods.

Sugarcane yield and productivity

There was an interaction effect of soil order and monoculture period on the sucrose content and productivity of sugarcane (Figure 5). The sucrose content of sugarcane grown in Entisols with a monoculture period of 1–10 years (6%) was lower than that with the monoculture period of 11–20 (7.4%) and 21–30 years (7.8%). Meanwhile, the sucrose content of sugarcane grown in Inceptisol with a monoculture period of 1–10 years was higher than that with a monoculture period of 11–20 years (6.8%). The similar to sugarcane in Vertisols, showing higher yield in a monoculture period of 1–10 years (8%).

The highest productivity of sugarcane was found in sugarcane planted in Vertisols for the period of 21–30 years, amounting to 76.18 t ha^{-1}, which was not significantly different from that grown in Inceptisol for the period of 21–30 years. The lowest productivity was found in the sugarcane grown in Entisols for 1–10 years (30.21 t ha^{-1}), which was not significantly different from that in Entisols for the period of 11–20 years. The sugarcane yield in Inceptisol and Vertisols showed a lower value, while that

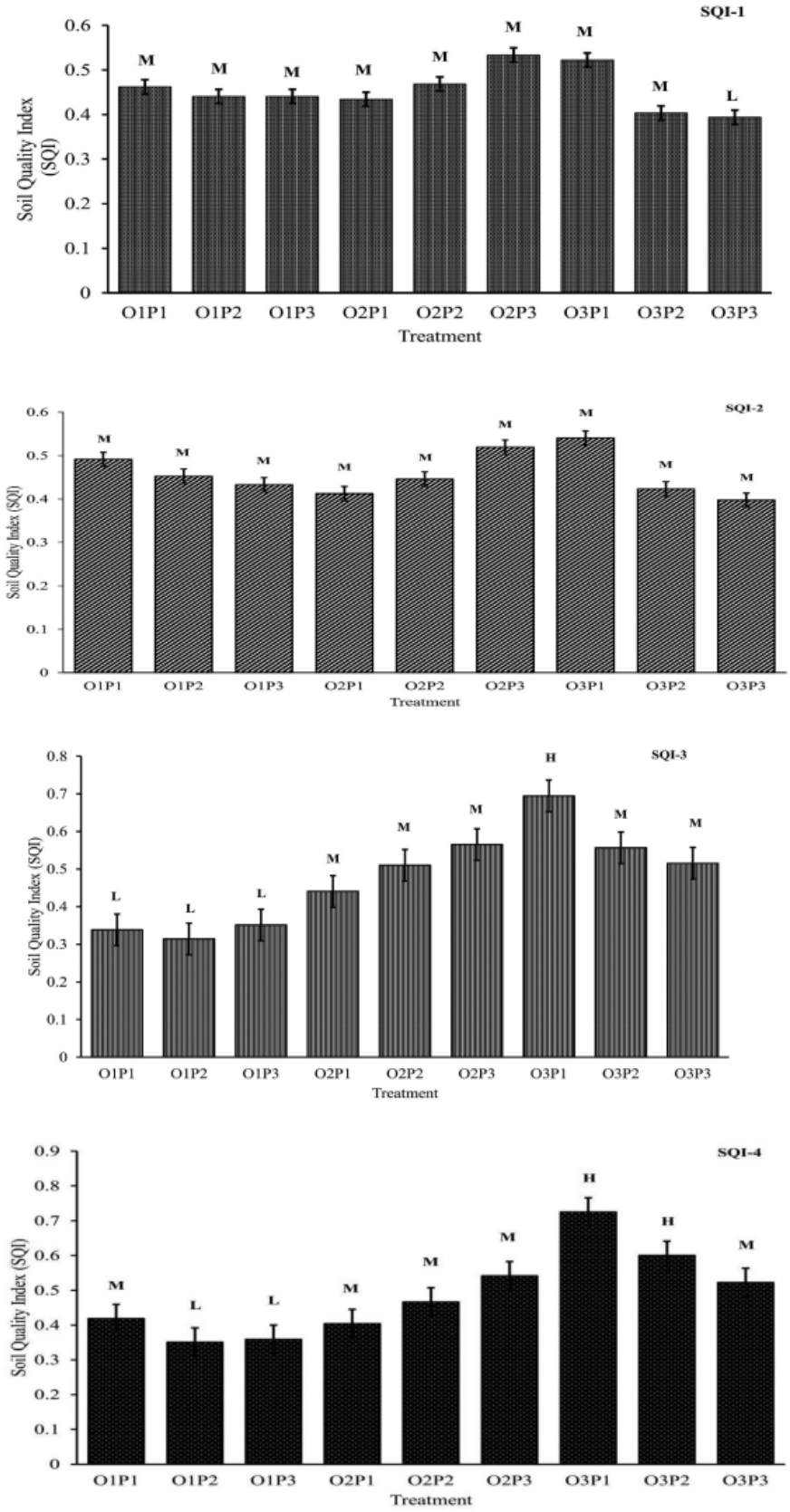

Figure 3. Comparison of the results of the SQI methods based on the sugarcane monoculture periods in three soil orders. O1= Entisols, O2= Inceptisols, O3= Vertisols, P1= monoculture period of 1–10 years, P2= monoculture period of 11–20 years, P3= monoculture period of 21–30 years, L= low, *M*= medium, H= high, SQI-1 (Non-linear-additive), SQI-2 (Non-Linear-Weighted Additive), SQI-2 *(Linear-additive)*, SQI-4 (Linear-Weighted Additive).

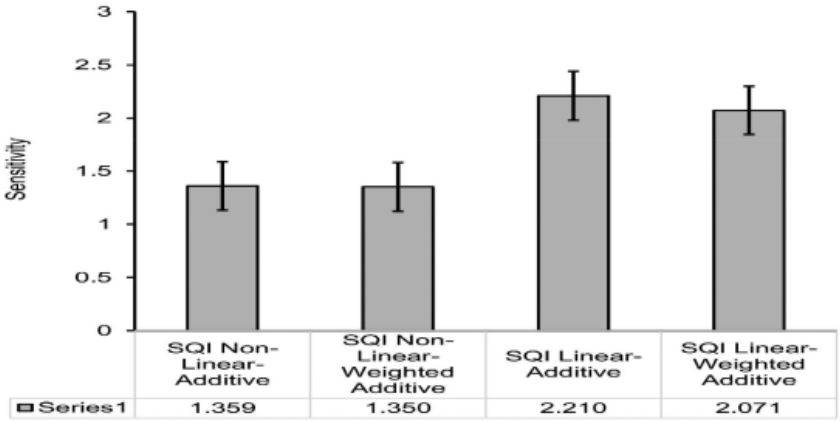

Figure 4. Sensitivity values of each SQI method.

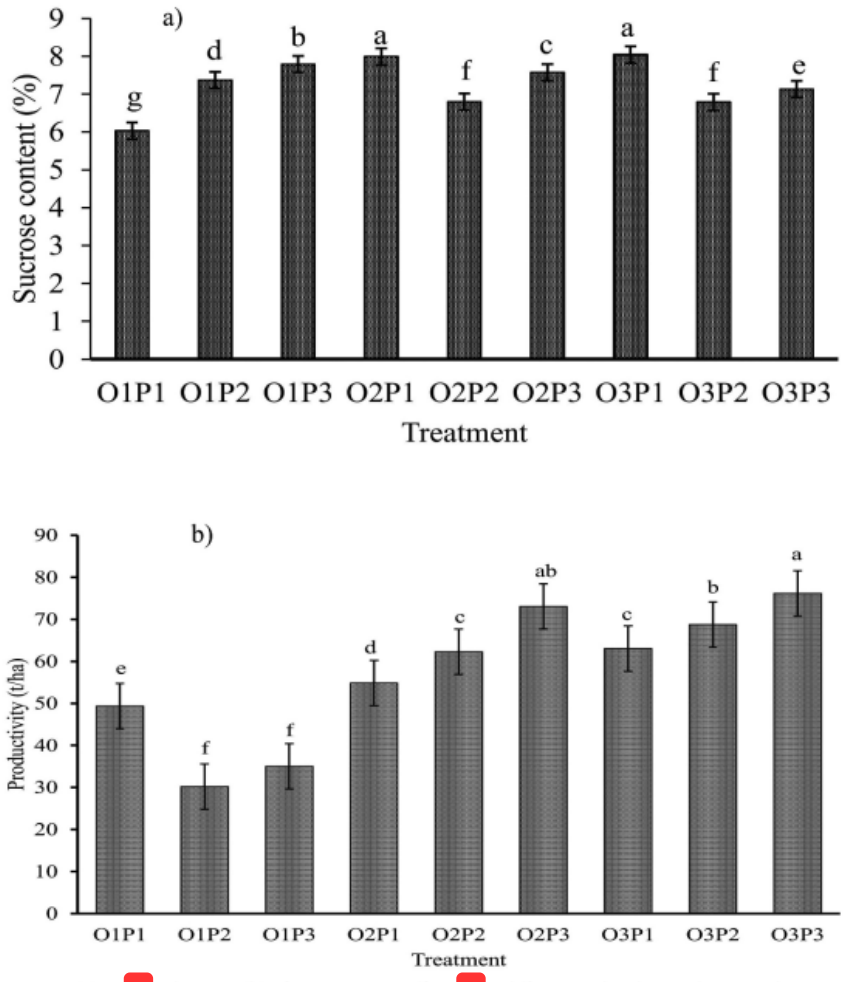

Figure 5. Sucrose content (a) and productivity (b) of sugarcane as affected by different soil orders and monoculture periods. O1=Entisols, O2=Inceptisol, O3=Vertisols, P1=Monoculture period of 1–10 years, P2= Monoculture period of 11–20 years, P3= Monoculture period of 21–30 years. Values followed by the same lowercase letters were not significantly different according to DMRT 5%.

in Entisols increased with the longer monoculture period. Conversely, the sugarcane productivity in Inceptisols and Vertisols increased, while that in Entisols decreased with the longer monoculture period. The growth and yield of sugarcane are influenced by the soil order as the planting medium (Kawuyo and Wada 2004).

Discussion

Soil quality attributes as affected by sugarcane monoculture

Soil texture has a significant role in determining the availability of water and nutrients for plants (Hamarashid, Othman, and Hussain 2010). Entisols is a soil type that has not undergone a developed horizon, which is dominated by a sand fraction, and its properties are still the same as its parent material (Ozsoy and Aksoy 2011). Inceptisols is a soil type that has undergone modification of the parent material with a higher percentage of clay and silt fractions than Entisols (Khresat 2005). Vertisols is heavy soil that has high clay content and clay minerals that expand like smectite. The pedoturbation process in Vertisols causes Vertisols not to experience horizonization (Pal, Wani, and Sahrawat 2012).

Table 1 shows that the change in aggregate stability caused by the sugarcane monoculture has a different tendency in each type of soil. Aggregate stability affects a variety of soil properties, including soil carbon stability, soil porosity, bulk density, water retention, and resistance to erosion, which in turn will affect plant growth and yield, so this parameter is important for assessing soil quality (Aksakal, Angin, and Sari 2020). Aggregate stability is influenced by the percentage of soil fraction (texture) and binder materials such as organic matters (Mikha and Rice 2004).

Long-term monoculture will cause changes in soil chemical properties (Fu et al. 2017). The value of pH H_2O in Entisols decreased to 0.3-units and in Inceptisols decreased to 0.9-units during 30 years of sugarcane monoculture. This result shows that there is soil acidification in the land cultivated with sugarcane in a long-term monoculture. The use of ammonium sulfate for the long term is thought to be the cause of the decrease in soil pH. Another cause could be the washing of NO_3-, which is always accompanied by positively charged base cations, such as Ca^{2+}, Mg^{2+}, and K+ (to maintain charge). These cations will be replaced by H+ ions, which accelerate the soil acidification process (Fageria, Dos Santos, and Moraes 2010). Decrease in soil pH can also be mediated by decomposition of sugarcane crop residues (Xu, Tang, and Chen 2006). This pH reduction condition occurs more in sandy soils than in clay, thereby becoming a constraint on sandy soils with intensive processing (Fujii et al. 2017).

Long-term sugarcane monoculture causes the accumulation of organic matter in soils with high clay content. Since the decomposition rate is inhibited due to acidic soil pH and high clay content, organic matter is firmly bound to clay minerals (Eleftheriadis, Lafuente, and Turrión 2018). In soils with a sandy texture such as Entisols, a decrease in the organic matter content of the soil occurs as a form of soil degradation (Fujii et al. 2009). The N content in the soil is influenced by many things, one of which is the soil texture. The C/N showed low values in all treatments. This result indicates that the availability of N is high because the mineralization process is going well. The decomposition of organic matter, which affects the value of C, is influenced by environmental conditions such as aeration, temperature, and humidity, and these environmental conditions are influenced by the texture and land processing process (Sugirahayu and Rusdiana 2011).

The content of available P in Vertisols was higher than in Inceptisols and Entisols (Vertisols>Inceptisols>Entisols). P availability is influenced by soil pH, clay mineralogy, organic matter, free iron and aluminum, calcium carbonate, soil temperature, and availability of other nutrients. In Entisols, which has a low pH, the available P content is low due to the binding of P by soil Al and Fe. Besides, the organic matter in Entisols is low, making the available P content low (Muindi 2019). Soil physical and chemical properties influence soil P availability (Goundar, Morrison, and Togamana 2014).

The CEC in Entisols and Inceptisols decreased with the longer monoculture period, but it increased in Vertisols. The CEC in Entisols and Inceptisols was lower than in Vertisols because it is more influenced by the constituent minerals of the parent material, the content of organic matter, and the soil texture (Iturri and Buschiazzo 2014). The values of Na, K, Ca, and Mg of the soil also varied. The availability of B is influenced by soil texture and organic matter. Soils that have a loamy texture and high organic matter will have a high content of available B (Marzadori et al. 1991). Soil properties such as soil pH and organic matter are also reported to affect the availability of Zn in the soil. At high pH, the availability of Zn^{2+} decreases because Zn is in an insoluble form. The Zn^{2+} ion can also form stable complexes with high molecular weight organic compounds such as humic and fulvic acids, so they are not available to plants (Jin, Martens, and Zelazny 1987).

Long-term sugarcane monoculture affects C Mic, C Min, C-POM, N Mic, and N Min of the soils because these parameters are sensitive to tillage (Mrabet et al. 2001). However, the impact is different on each soil order depending on the content of organic matter and soil texture (Nciizah and Wakindiki 2012).

The SQI value as affected by different sugarcane monoculture periods and soil orders

Long-term sugarcane monoculture significantly affected SQI. There were no changes in the SQI of Inceptisols, as affected by different sugarcane monoculture periods of up to 30 years, for the four SQI methods, with the moderate category for SQI Non-Linear-Additive and Non-Linear-Weighted Additive. Meanwhile, in Vertisols, the SQI changed from medium to low (SQI Non-Linear-Additive) and high to medium (SQI Linear-Additive and Linear-Weighted Additive) due to sugarcane monoculture periods of 1–10, 11–20, and 21–30 years. The SQI of Entisols and Inceptisols in the sugarcane monoculture period of 1–10 years was already in the low and moderate category, so the possibility of a decrease in the SQI value was low. A different result was seen in Vertisols. The lowest SQI value of Vertisols due to sugarcane monoculture for up to 30 years was at a low category, with a high SQI value at the initial cultivation. This condition illustrates that SQI is influenced not only by land use (long-term sugarcane monoculture) but also by the soil order because the intrinsic nature of the soil has a bigger role in determining changes in SQI (Mukherjee, Lal, and Sainju 2014). Sugarcane planting has an impact on soil conditions, namely a decrease in the value of SQI (Cherubin et al. 2016). This decrease is due to changes in soil physical, chemical, and biological soil properties (Mubarak, Elshami, and Azhari 2005).

Each soil order has a different buffering capacity, and this condition is determined by the properties of each soil. Based on the SQI calculation results, Vertisols has the highest buffering capacity against land use in the form of long-term sugarcane monocultures. Soil buffering capacity has a positive relationship with organic matter content, soil clay content, and soil mineralogical content (Jansen van Rensburg, Claassens, and Beukes 2009). Vertisols has a high clay content, so it has a high soil buffering capacity. Vertisols also did not experience a decrease in organic matter content with the longer monoculture period. The high organic matter in the soil with heavy texture is caused by the accumulation of organic matter. This accumulation occurs because the decomposition rate is inhibited due to the high clay content so that the organic matter is firmly bound to clay minerals (Eleftheriadis, Lafuente, and Turrión 2018). On the contrary, Entisols, which has a low clay content, experienced loss of organic matter from the soil with the longer sugarcane monoculture period due to low CEC, making the organic matter binding low (Nelson and Su 2010). In addition to changes in organic matter content, in soils with low clay content, such as Entisols, the availability of water and nutrients is also a problem that might occur (Minhal et al. 2020). This buffering capacity is thought to be the cause of the difference in the impact of the long-term sugarcane monoculture on the SQI value.

All methods for assessing SQI in different soil orders as affected by long-term sugarcane monoculture can be used. However, the sensitivity level of each method is slightly different. Figure 4 shows that the SQI assessment using the SQI-3 (Linear-Additive) method has the highest sensitivity level to observe the impact of the long-term sugarcane monoculture on SQI values in Entisols, Inceptisol, and

Vertisols. The SQI value with a linear scoring system is more effective to measure the impact of management on land. The SQI calculation methods, either using weighted or non-weighted, do not provide change in the category (Cherubin et al. 2016). Reducing indicators, which is the first step to obtain a Minimum Data Set using Principal Component Analysis (PCA), is the best and indispensable way to provide accurate information, making it easier to select representative parameters for calculating SQI (Andrews, Karlen, and Mitchell 2002).

Relationship between SQI value and sugarcane yield and productivity

The decrease in sucrose content and productivity of sugarcane is probably closely related to soil degradation as a result of long-term sugarcane monoculture (Bramley et al. 1996). The relationship of SQI with sucrose content and productivity is shown in Figures 6 and 7. All SQI methods have a positive relationship, both with sugarcane yield and sugarcane productivity, but each has a different coefficient of determination. The relationship between the two parameters gets stronger if the coefficient of determination approaches 1. SQI-4 (Linear-Weighted Additive) showed a very low coefficient of determination on sugarcane yield ($R^2 = 0.0076$), while SQI-1 (Non-Linear-Additive) showed a higher coefficient of determination ($R^2 = 0.1056$).

A different result was observed in productivity. SQI-3 (Linear-Additive) and sugarcane productivity showed a strong coefficient of determination ($R^2 = 0.4472$), while SQI-2 (Non-Linear-Weighted

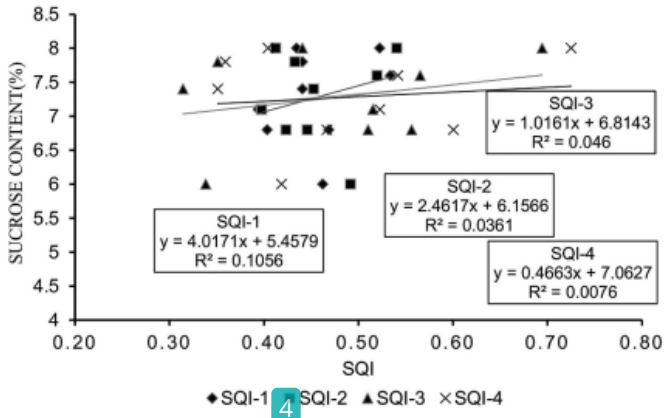

Figure 6. Relationship between SQI and sucrose content. SQI-1 (Non-linear-additive), SQI-2 (Non-Linear-Weighted Additive), SQI-2 *(Linear-Additive)*, SQI-4 (Linear-Weighted Additive).

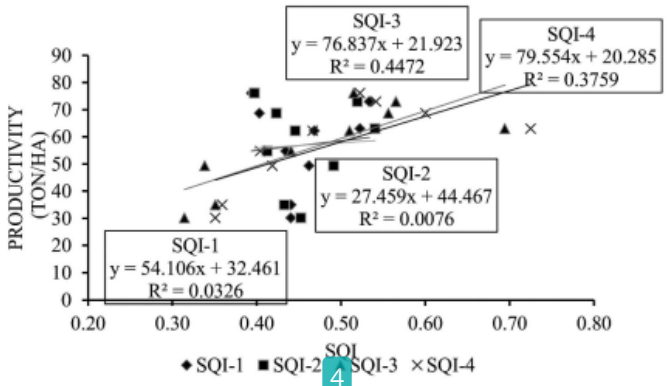

Figure 7. Relationship between SQI and sugarcane productivity. SQI-1 (Non-Linear-Additive), SQI-2 (Non-Linear-Weighted Additive), SQI-2 *(Linear-Additive)*, SQI-4 (Linear-Weighted Additive).

Additive) and sugarcane productivity showed the lowest coefficient of determination ($R^2 = 0.0076$). The SQI and sugarcane yield showed a low coefficient of determination ($R^2 = 0.1056$), while the coefficient of determination between SQI and sugarcane productivity was moderate ($R^2 = 0.4472$). This result shows that SQI affects sugarcane productivity by 44.7%, greater than its effect on sugarcane yield, which is only 10.6%. SQI analysis is still a sensitive tool for observing soil conditions as a result of land use (Cherubin et al. 2016). Soil conditions that reflect soil physical, chemical, and biological attributes have an effect on sugarcane yields (Diana, Supriyadi, and Djumali 2016), and SQI affects sugarcane yields (Vasu et al. 2016).

Conclusion

Long-term sugarcane monoculture significantly affected the soil quality index (SQI). Inceptisols did not show changes in SQI, as calculated with four methods, in all the sugarcane monoculture periods of up to 30 years. Meanwhile, there was a change in SQI of Vertisols from medium to low (SQI Non-Linear-Additive) and high to medium (SQI Linear-Additive and SQI Linear-Weighted Additive) as affected by the monoculture periods, and by SQI Linear-Weighted Additive there was a change in SQI of Entisols from medium to low. This result suggests that the soil order is responsible for determining the impact of sugarcane monoculture on SQI. SQI-3 (Linear-Additive) has the highest sensitivity level to observe the impact of the long-term sugarcane monoculture on soil SQI in Entisols, Inceptisol, and Vertisols. The relationship between SQI and sugarcane yield showed a low coefficient of determination ($R^2 = 0.1056$), while the coefficient of determination between SQI and sugarcane productivity was moderate ($R^2 = 0.4472$). Since the impact of the long-term sugarcane monoculture on SQI is highly dependent on the soil order, site-specific location is highly recommended as a basis for land management to support sustainable long-term sugarcane cultivation.

Disclosure statement

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