



# The genesis of rainfed agricultural soils in Indonesian lowlands with two different climate types

Asmita Ahmad<sup>1</sup> · Meutia Farida<sup>2</sup> · Christianto Lopulisa<sup>1</sup>

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## Abstract

This study analyzes the genesis of rainfed agricultural soil derived from carbonate rocks in two climates types of the South Sulawesi Indonesian lowlands. Soil analysis included the physical and chemical characteristics of soil, clay minerals, and oxide minerals. Rock samples were analyzed using petrography analysis. There are ten soil profiles, 51 soil samples, and ten rock samples. Correlation statistics were used to determine the correlation between climate and soil characteristics. The Bantimurung District has a C-2 climate type, and Bangkala District has a D-3 climate type. The Bantimurung District as a wet area has a positive correlation between rainfall and cation exchange capacity but negative correlation with soil pH and base saturation. The dry Bangkala District shows a positive correlation between c-organic with base saturation and a negative correlation between water content and soil bulk density. Finding shows that the process of mineral transformation is strongly influenced by hydropedology activity. Kaolinite minerals are more commonly found in Bantimurung District, while nontronite-montmorillonite minerals are more common in Bangkala District. The pan-oxide plow was only found in Bantimurung District with a thickness of up to 3–8cm, indicating intensive land cultivation. Soil derived from carbonate rocks with high hydropedological activity demonstrates a faster soil formation process. To maintain soil fertility, C-organic levels of the soil need to be increased by returning harvest waste to the soil. Increasing the soil water content can be done with water harvesting and the use of perennial rivers for irrigation.

**Keywords** Soil · Rainfed · Kaolinite · Montmorillonite · Oxide · Indonesia

## Introduction

Rainfed lowlands are characterized by a lack of water control, and their soil can only be flooded with water to a depth of 50 cm for no more than ten consecutive days during the cropping season (Dobermann and Fairhurst 2000). Rainfed agriculture includes a unique type of land use because the land undergoes an inundation process that affects the soil characteristics. According to some experts, water is essential for soil genesis in wetlands and drylands (Kipkemoi et al. 2021; de Vicente

2021). Inundated of the rainfed soil for paddy field increased in the reduction process, while at the end of the planting process, the oxidation process replaced the reduction process, and results in mineral weathering alterations and changes in soil physical, chemical, and biological properties for developing different soils in drylands (Hardjowigeno et al. 2005). Hydropedological characteristics influence the water in rainfed agricultural soils and present a complete view of a soil unit from the microscopic to the macroscopic levels, which is extremely useful for research on soil classification and genesis (Mello and Curi 2012). The soil genesis, parent rock characteristics, and different climates contribute to the hydropedological characteristics, which can differ with location and particularly morphology (such as lowland, hilly, and mountainous areas) (Van Tol et al. 2017).

The rainfed lowlands have high agricultural potential in South Sulawesi, Indonesia, with an area of up to 255,516 ha (Central Bureau of South Sulawesi 2015). However, rainfed lowlands in this area have been cultivated 70 years on average which has reduced their ability to support rice production. The capacity of rainfed lowland to support food production has decreased over

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✉ Asmita Ahmad  
asmita.ahmad@agri.unhas.ac.id

<sup>1</sup> Department of Soil Science, Faculty of Agriculture, Hasanuddin University, Makassar 90245, Indonesia

<sup>2</sup> Department of Geology, Faculty of Engineering, Hasanuddin University, Makassar 90245, Indonesia

the last decade, particularly with the onset of global climate change, because they are highly dependent on rainfall (Tanure et al. 2020). Soil plays an important role in increasing the value of ecosystems, especially in crop production (Abd El-hamid et al. 2020). However, soil nutrient loss is an increasing problem in the tropics due to global climate change (Kumar and Das 2014). Climate change factors, such as rainfall and temperature, considerably impact soil nutrients (Pareek 2017). Rainfall increases the downward movement of water in the soil, causing the loss of soil nutrients. Moreno et al. (2012) studied the relationship between rainfed lowland soil and the fertilization response in Castilla-La Mancha (Central Spain) and concluded that is more strongly influenced by climate than fertilization treatment. However, the impact of climate change has considerably increased the use of chemical fertilizers, decreased soil quality, and induced widespread poverty (Erbaş and Solakoglu 2017). Negative implications owing to changes in land use lead to land degradation through landslides, floods, and flash floods (Ahmad et al. 2018; Olsson et al. 2019). In Indonesia, the government is continuously pursuing efforts to expand productive paddy fields in South Sulawesi to contribute to food security (Rusono et al. 2010). Nevertheless, additional information is needed on the genesis of rainfed lowland soil to guide its successful management, particularly in areas with high and low rainfall. The present study analyzes the genesis of rainfed agricultural soil from carbonate rocks for two climates in the lowlands of South Sulawesi.

## Material and methods

### Study site

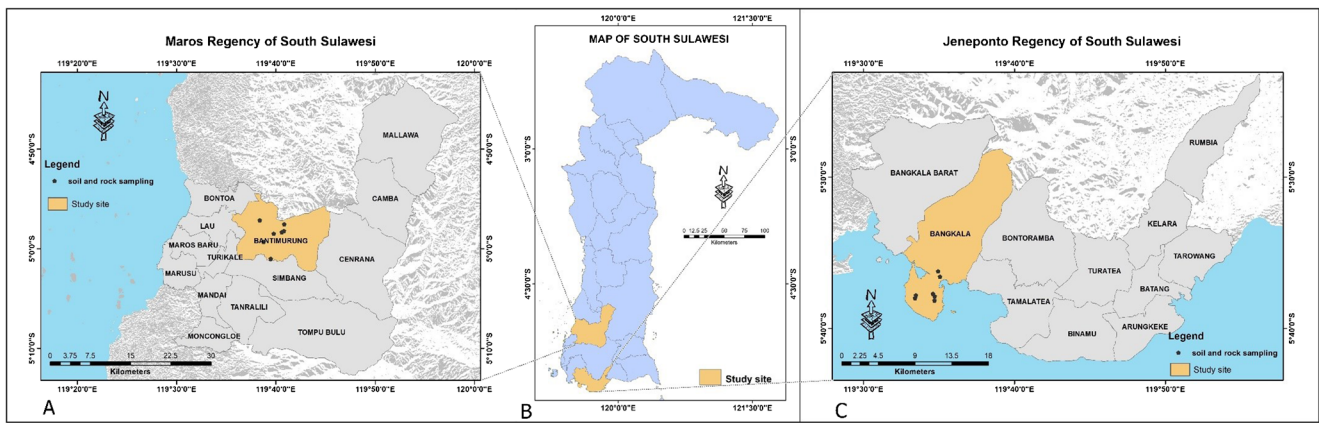
In the tropics, climatic factors and land use strongly influence soil formation originating from Tonasa Formation (Eocene to Miocene) (Sukamto 1982). South Sulawesi is a tropical region in Indonesia that shows a varied morphology (Desaunettes 1977), resulting in different rainfall distribution among districts, with a range of wet to dry climates (BMKG 2016). This study evaluated the genesis of soil development in the rainfed lowlands of South Sulawesi and the impact of different climatic factors on soil formation. Two study sites were considered (Fig. 1). The first study site was located in the Bangkala District of Jeneponto Regency. This site exhibits a dry climate and is located 119° 34' 0" E and 5° 38' 0" S with slope 2–8% (RePPProT 1988). The second study site was located in Bantimuring District of Maros Regency. This site has a slightly wet climate and is located at 119° 39' 0" E and 5° 0' 0" S, with slope of 2–8%.

### The geological site

During the Early Cretaceous period, plate tectonic attributed to the Australian, Indian, and Asian plates formed the Indonesian plate, which actively produced the Sulawesi Islands in the Early Paleocene epoch (Hall 2012). According to Sukamto (1982), the Eocene Malawa Formation (Tem) comprised sedimentary rock mainly characterized by land and coal deposits. This formation showed a thickness of at least 400 m. From the Lower Eocene to the Lower Middle Miocene, the Tonasa Formation (Temt) was above the Malawa Formation and comprised partially stretched solid coral limestones in white and light gray as well as bioclastic and calcarenite limestones in white, light brown, and light gray. Some of these deposits were well layered and alternated with marl. The Tonasa Formation is approximately 3000 m thick and forms a karst landscape called the Maros-Pangkep karst area. It subsequently formed sedimentary rocks interspersed with volcanic rocks from the Middle Miocene to Lower Pliocene (Tmc and Tmcv). The rock unit members included tuffaceous sandstones interspersed with tuffs, sandstones, siltstone, claystone, marl, limestone, conglomerates, and volcanic breccia. This formation contained limestones from the Tonasa Formation and rocks from the Malawa Formation. According to Sukamto and Supriatna (1982), volcanic activities continued during the Pliocene to produce Baturape-Cindako volcanic rocks (Tpbv and Tpbl). The igneous rocks occurring in this area were all linked to volcanic activities. These breakthroughs comprised stocks, sills, and dykes in basalt and diorite aged 8.3–19, 2 million years. No significant deposition or volcanic activity occurred in this area after the Upper Pliocene. The Maros-Pangkep karst area contains large Holocene deposits in the form of alluvium.

The Middle Miocene geological structure showed a major fault trending north-northwest that grew after the Pliocene (Sukamto and Supriatna, 1982; Maulana et al. 2010). In Tertiary and Quaternary (Pleistocene) rocks, the rock layers exhibited a slope characterized by a folding structure, implying that the fold occurred after the Pleistocene. The fault structure was linked to magmatic activities in the Upper Pleistocene, followed by tectonic movements that caused faults in this area. The fault runs in three directions: north-south, southwest-northeast, and northwest-southeast.

During the Holocene period, soil formation was affected by a combination of rock factors, climate, topography, organisms, and time (Weil and Brady 2016). The characteristics of the rock and the structures acting on the rock had a significant impact on the soil formation. Rock provides a substantial subsidy for soil fertility. In particular, soil formed from carbonate rock show neutral reaction and high nutrient contents, making them suitable for crop production (Ferreira et al. 2016).



**Fig. 1** Location of study site; the light brown color is the study site in Bantimurung District in Maros Regency (A) and Bangkala District in Jeneponto Regency (C). Map index of South Sulawesi (B) and the black points are the soil and rock sampling site

Carbonated rocks have immense agricultural potential in several regencies of South Sulawesi, with the largest found in the Tonasa Formation (Temt). Fig. 2 shows geological maps of Bantimurung District and Bangkala District.

**Soil and parent rock sampling**

Soil samples were collected from several locations used/not used for rainfed lowland agriculture as the control for both of the study sites (Fig. 1). We created 10 soil profiles, collected 51 soil samples for analyzing the physical and chemical characteristics, and collected 10 parent rock samples in R horizon for petrography analysis.

**Soil analysis**

Soil pH was measured with a pH meter (van Reeuwijk 2002). The C-organic level was determined using the Walkley and Black method. The particle size distribution was determined using the hydrometer method. The cation exchange capacity

(CEC) and exchangeable cations ( $Ca^{2+}$ ,  $Na^+$ ,  $K^+$ , and  $Mg^{2+}$ ) were measured using the  $NH_4OAc$  process (Ngewoh et al. 1989). The base saturation (BS) of exchangeable cations was estimated using the following equation:

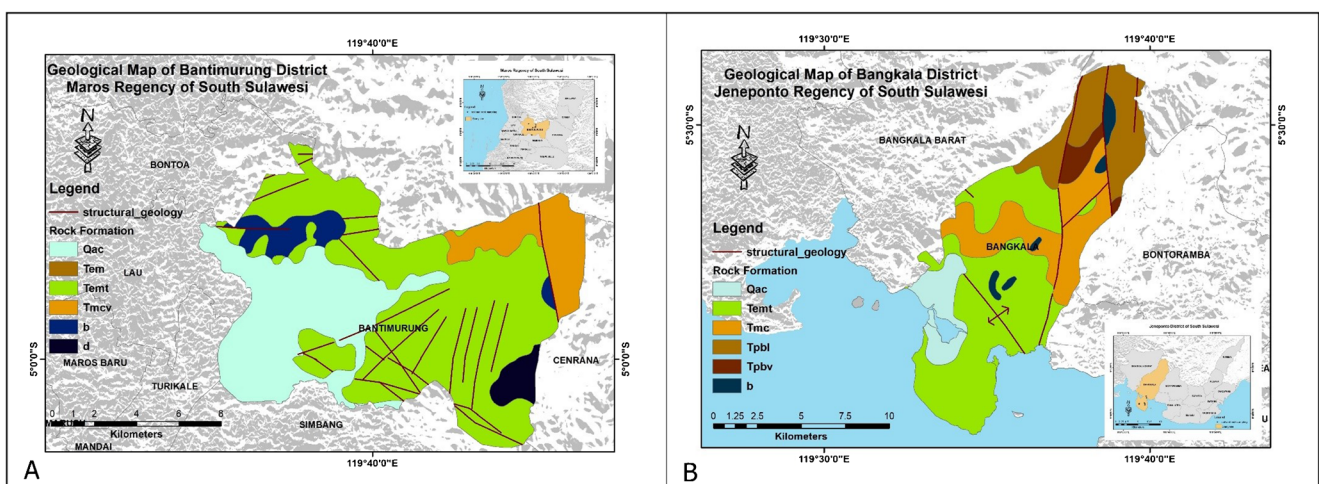
$$BS = \frac{Ca + Mg + K + Na}{CEC} \times 100\% \tag{1}$$

where CEC refers to the cation exchange capacity of the soil. The bulk density was obtained using the gravimetric method (BPT 2005):

$$BD = \frac{drysoilweight(g)}{soilvolume(cm^3)} \tag{2}$$

The soil water content was calculated using the following equation (BPT 2005):

$$\%soilwater = \frac{weightofwater(g) - weightofdrysoil(g)}{weightofdrysoil(g)} \times 100 \tag{3}$$



**Fig. 2** Geological map of the study site; A geological map of Bantimurung District and B geological map of Bangkala District

## Minerals analysis

Mineral oxides were analyzed using X-ray fluorescence based on the method provided by IAEA (IAEA 1997). Powdered samples of clay and nonclay minerals were analyzed using an X-ray diffractometer.

## Statistical analysis

The correlation between the climate and soil characteristics was statistically determined as follows:

$$r = \frac{\sum (xi - \bar{x})(yi - \bar{y})}{\sqrt{\sum (xi - \bar{x})^2} \sqrt{\sum (yi - \bar{y})^2}} \quad (4)$$

where  $r$  is correlation coefficient,  $xi$  is values of the x-variable in a sample,  $\bar{x}$  is mean of the values of the x-variable,  $yi$  is values of the y-variable in a sample, and  $\bar{y}$  is mean of the values of the y-variable.

## Petrography analysis

For analysis, the Buehler procedure (Buehler 2015) was used to convert rock samples into thin section using a polarizing microscope and mineral identification based on the Kerr guidelines (Kerr 1959).

## Precipitation

Precipitation data were collected from 2000 to 2019. Monthly rainfall data were obtained from the satellite image analysis of the data from Climate Hazard Group Infrared Precipitation with Station (<https://www.chc.ucsb.edu/data/chirps>) and the meteorological, climatological, and geophysical agency of Indonesia (<https://www.bmkg.go.id/?lang=EN>).

## Soil type

The US Department of Agriculture (USDA) method (Soil Survey Staff 2014) was used to classify soil type from orders/suborders and groups/subgroups.

## Result

### Precipitation

As shown in Fig. 3, Bantimurung District has an average rainfall (2000–2019) of 3374 mm/year (Fig. 3), with six wet months and three dry months, corresponding to the C-2 climate based on the Oldeman climate type (Munandar

and Sumiati 2017). Bangkala District has an average rainfall (2000–2019) of 1989 mm/year with four wet months and four dry months, corresponding to the D-3 climate (Munandar and Sumiati 2017). The effects of global climate change were observed in 2010, with changing rainfall patterns that occasionally flooded the study site at Bangkala District.

### Parent rock

The parent rock obtained from the two study site comprised sedimentary carbonate rock from the Tonasa Formation (Temt), which was Eocene to Miocene (Sukanto 1982). Because of high rainfall activities, the sedimentary carbonate rocks in Bantimurung District were characterized by calcite recrystallizing in rock cavities (Fig. 4), although they originated from the same rock formation. In contrast, the parent rock in Bangkala District exhibited a lack of climatic influence on mineral recrystallization. As shown in Fig. 5, the pores of the rock body were only partially filled by the recrystallization of calcite.

### Soil characteristic

The soil color in Bantimurung District showed a higher value and chroma (Table 1) than in the dry area of Bangkala District (Table 2). The depth of the soil solum at the two study sites was affected by climatic activities and lowland morphologies. At both study sites, the depth of the soil solum reached  $\pm 70$ cm. The alkaline and clastic nature of the parent rock made it prone to weathering and influenced the soil depth, which is also strongly influenced by the hydrogeological and topographic processes of the area (Schoeneberger and Wysocki 2005; Yu et al. 2017). Because of the accumulation of sedimentary materials in the lowland morphology, the study sites were amply supplied by weathering material from the surrounding areas, which were predominantly hilly and mountainous landform.

Because of the low hydrogeological activity in Bangkala District, the soil exhibited a neutral pH. The soil samples showed a high CEC, attributed to high content of  $Ca^{2+}$  and  $Mg^{2+}$  in the soil (Table 2). When clay minerals and organic content captured a cation, CEC can directly influence the soil pH (Aprile and Lorandi 2012). As an evidence of high nutrient content in the soil, BS was in the medium-high category. However, opposite trend was for Bantimurung District, which exhibited a relatively high hydrogeological activity. The study site also showed a low soil pH, and the CEC value was from 10.74 to 20.27cmol (+)/kg (Table 1), indicating a low-moderate alkaline cation content.

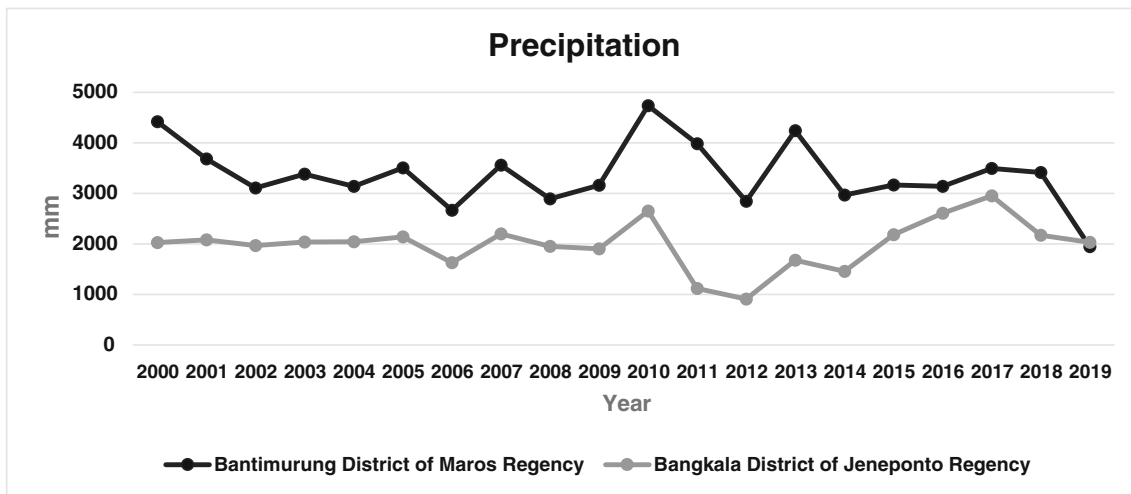


Fig. 3 Precipitation in Bantimurung District of Maros Regency and Bangkala District of Jeneponto Regency (2000–2019)

**Statistical correlation**

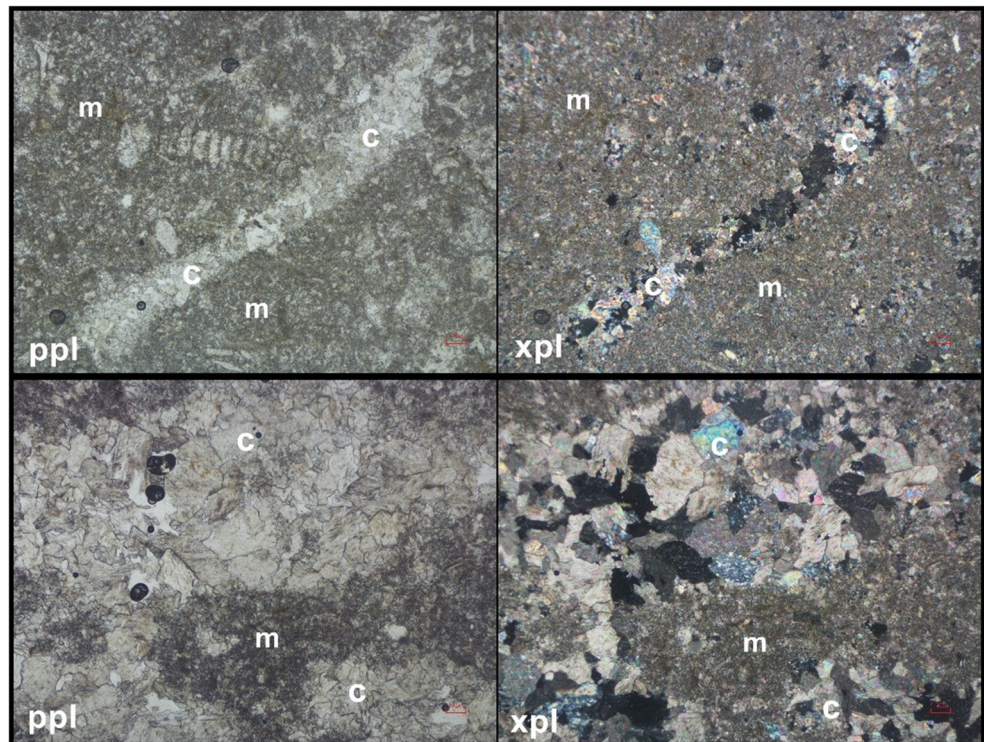
A statistical correlation test was performed to identify the relationship between soil parameters. In Bantimurung District, the rainfall has a positive correlation with soil water content and CEC but a negative correlation with soil pH and BS (Table 3). This shows that the parent rock in areas with sufficient rainfall contributes to soil fertility to small extent. In Bangkala District, the C-organic level exhibited positive correlations with BS, Ca<sup>2+</sup>, and Mg<sup>2+</sup>; however, the water content and soil bulk density showed a negative

correlation (Table 4). Bantimurung District has two cropping seasons a year, resulting in a greater soil bulk density than in Bangkala District, which has one cropping season a year.

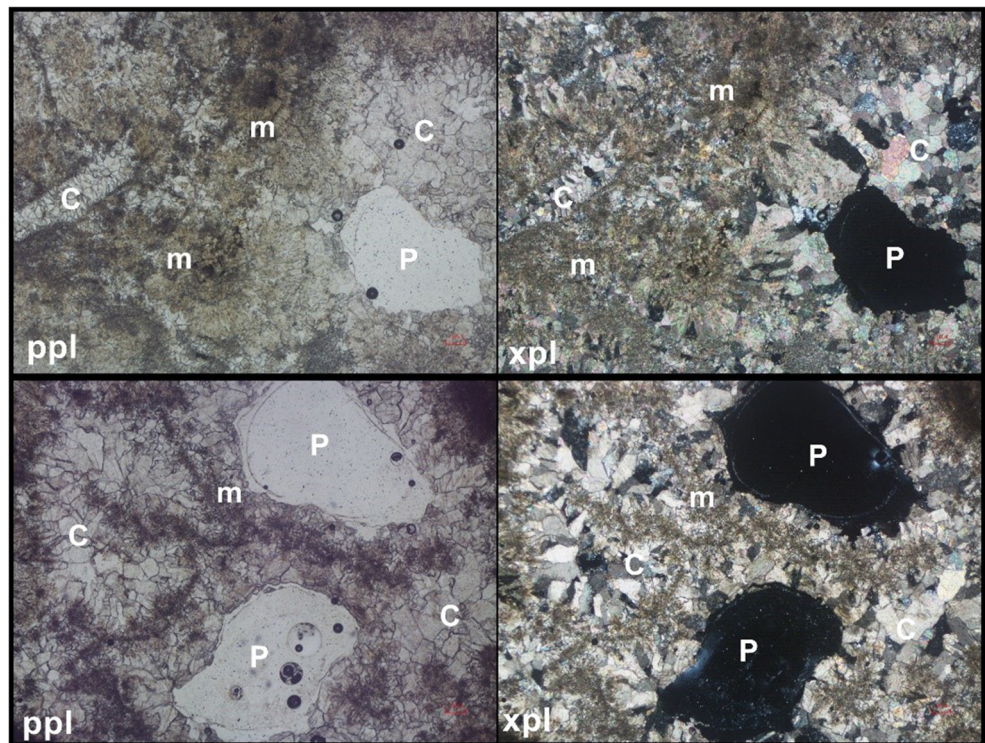
**Clay minerals**

Clay minerals formed from carbonate rock showed approximately the same composition at the two study sites. However, dry areas exhibited a 2:1 clay mineral content (55.33%) which is higher than in the slightly wet areas (38.67%).

Fig. 4 The appearance of parent rock in the Bantimurung District showed recrystallization of calcite minerals (C) in vein and cracked with a mass of calcite called micrite (m). Size 100µm



**Fig. 5** The appearance of parent rock in the Bangkala sub-district showed calcite minerals (C), a mass of calcite called micrite (m), and pore (p). Size 100 $\mu$ m



Montmorillonite, nontronite, and vermiculite are examples of the 2:1 clay mineral content, whereas kaolinite and halloysite are examples of the 1:1 clay mineral content (Figs. 6 and 7). Halloysite was found only in Bantimurung District because of its high rainfall activities (Fig. 6). Moreover, the presence of vermiculite and nontronite in the soil was strongly influenced by  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  contents in the carbonate parent rock (Hazen et al. 2013).

### Oxide minerals in soils

At the study sites, the rainfed lowland undergoes the inundation process twice a year, which increased the formation of oxide minerals in the soil. The oxides formed pan-oxides plows with thicknesses of 3–8 cm (Fig. 8). The mineral oxides with the highest contents were  $\text{Fe}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$  (Table 5) in the form of ferrihydrite, hematite, and goethite. Ferrihydrite and goethite are commonly found in paddy fields (Maisch et al. 2020). Goethite gives the soil a yellowish color (Mehmood et al. 2014) (Table 1). The rainfed land in Bangkala District was plowed only once a year; hence, no pan-oxide plow was observed. However, mineral oxides in the form of ferrihydrite and lepidocrocite were found in the soil because of the inundation process. These minerals were still easily transformed into mineral oxides (Maisch et al. 2020) and show the rainfed age of <50 years, which does not indicate intensive land cultivation (Ahmad et al. 2019).

### Soil type

In Bantimurung District (Fig. 8), the soil showed a cambic horizon: a fine silt texture, no aquatic conditions within 50 cm of the soil surface, high of hue, value, and chroma, and the evidence of carbonate compound displacement. The soil was categorized in the Inceptisol order and Udepts suborder with an udic soil moisture regime. Further, the soil exhibited a cemented pan-oxide horizon within 100 cm of the soil surface and was categorized in the Durudepts group. It was also categorized in the Aquic Durudepts subgroup because it showed redox activities owing to inundation process.

In Bangkala District (Fig. 9), all horizons exhibited a clay content >30%, slickensides, and cracks that opened and closed periodically. Thus, the soil was categorized in the Vertisols order. The cracks were >5cm wide and 50cm thick; hence, the soil was further categorized in the Usterts suborder. Moreover, the soil was categorized in the Haplusterts groups because it lacked salic, gypsic, calcic, or petrocalcic horizon. If the soil is not irrigated for at least 150 cumulative days/year, it generates cracks with a width of  $\geq 5$  mm and a thickness of  $\geq 25$  cm within 50 cm of the soil surface; hence, it was categorized in the Udic Haplusterts subgroups.

### Discussion

In Bantimurung District (Fig. 3), the wet climate encouraged the recrystallization of calcite, which increased the content of

**Table 1** Soils physical and chemical characteristic in Bantimurung District, Maros Regency

Profile	Depth	Sand	Silt	Clay	Texture	Water content	BD	Color	pH	C-organic	Ca	Mg	K	Na	CEC	BS
	cm	%				%	g/cm <sup>3</sup>		H <sub>2</sub> O	%	cmol (+)kg <sup>-1</sup>				%	
1M	0–10	8	69	23	Silt loam	20.55	1.32	10YR 5/8 (yellowish brown)	6.13	2.61	6.42	2.74	0.36	0.41	20.27	49
	10–33	16	61	23	Silt loam	17.43	1.36	10YR 5/4 (yellowish brown)	6.07	2.42	5.09	0.76	0.22	0.36	19.22	33
	33–70	9	61	30	Silty clay loam	15.59		10YR 5/6 (yellowish brown)	6.12	1.78	5.92	1.33	0.41	0.25	20.20	39
2M	0–5	4	86	10	Silt	13.39	1.29	2,5Y 7/4 (pale yellow)	6.18	3.02	4.01	2.80	0.19	0.41	15.53	48
	5–15	3	87	10	Silt	16.15	1.36	2,5Y 7/4 (pale yellow)	6.09	2.38	4.38	2.80	0.22	0.32	13.38	58
	20–50	8	70	22	Silt loam	17.98		2,5Y 6/4 (light yellow brown)	6.18	2.31	3.81	2.71	0.19	0.25	18.53	38
3M	0–10	12	77	11	Silt loam	15.41	1.29	2,5Y 7/3 (pale yellow)	6.19	1.78	3.52	2.90	0.22	0.19	17.97	38
	20–40	13	63	24	Silt loam	21.84	1.29	2,5Y 5/4 (light olive brown)	6.67	3.15	6.43	0.99	0.39	0.25	16.40	49
	40–60	19	57	24	Silt loam	15.41	1.39	2,5 5/6 (light olive brown)	6.65	1.89	5.76	1.36	0.24	0.34	18.11	43
4M	0–20	9	81	10	Silt	17.62		2,5 4/4 (olive brown)	6.62	1.56	4.92	2.12	0.19	0.19	17.16	43
	20–30	6	84	10	Silt	16.33	1.19	2,5Y 5/4 (light olive brown)	6.60	3.87	6.54	2.84	0.32	0.45	22.34	45
	30–50	5	67	28	Silty clay loam	15.41	1.43	2,5Y 5/4 (light olive brown)	6.33	1.78	6.53	2.75	0.25	0.39	18.33	54
5M	0–20	16	73	10	Silt loam	17.43		10YR 5/6 (yellowish brown)	6.29	2.04	6.78	3.54	0.14	0.41	21.93	50
	20–40	13	70	17	Silt loam	15.78	1.28	2,5 5/6 (light olive brown)	6.71	3.43	5.82	2.94	0.32	0.25	16.09	58
	40–60	13	70	17	Silt loam	16.33	1.40	2,5 5/4 (light olive brown)	6.78	2.04	5.59	2.27	0.25	0.32	15.42	55
6M	0–10	15	82	3	Silt	13.39	1.41	2,5 5/6 (light olive brown)	6.81	2.36	8.57	1.39	0.14	0.41	24.28	48
	10–30	15	76	9	Silt loam	11.38	1.43	2,5 5/6 (light olive brown)	6.49	2.14	5.53	2.51	0.32	0.25	20.29	42
	30–60	25	66	9	Silt loam	15.78		2,5 5/6 (light olive brown)	6.38	1.56	3.71	1.96	0.28	0.21	10.74	57

M Maros District, BD bulk density, CEC cation exchange capacity, BS base saturation

carbonate minerals in the formed soil. Even for lowland morphologies, an intensive washing process in areas with sufficient rainfall can free calcite minerals from the soil. The free carbonate in the soil did not show an even distribution; however, it was observed only in isolated spots, indicating a high hydrogeological activity. This led to the formation of the 2:1 type of clay mineral content and accelerated the formation of the 1:1 clay mineral content. According to Hazen et al. (2013), the intensive hydrogeology activity accelerates the transformation of the 2:1 clay mineral content into the 1:1, forming polymorphs of kaolinite with excessive H<sub>2</sub>O in the crystal layer as halloysite (Al<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>·nH<sub>2</sub>O) (Fig. 6). Zhang et al. (2016) found that a soil environment with a low C-organic level causes the 2:1 type clay mineral content to transform into kaolinite mineral more quickly than in an environment with a high C-organic level (Table 1). However, Kowalska et al. (2021) showed that carbonate minerals in the soil do not affect the formation and transformation

of clay minerals in temperate climates. Carbonate minerals were found in all soil layers; thus, their contribution to the formation of clay minerals was insignificant.

In Bangkala District with the D-3 climate (Fig. 3), the parent rock was less affected by the relatively dry climate on mineral recrystallization; hence, less mineral recrystallization was observed. Calcite made a minor contribution to the soil quality; however, the environment caused the accumulation of free carbonate in the soil, aiding the formation of secondary 2:1 type clay mineral content, which was more dominant than the 1:1 clay mineral content. The condition of this study site is suitable for rainfed rice paddies because it can store water for long duration and reducing water consumption.

The result showed that the process of mineral transformation in the soil is strongly influenced by hydrogeological activity, which accelerates the soil genesis process. Owing to different climates, iron oxide undergoes both reduction and oxidation (Vepraskas and Lindbo 2012). The hydrogeology

**Table 2** Soils physical and chemical characteristic in Bangkala District, Jenepono Regency

Profile	Depth	Sand	Silt	Clay	Texture	Water content	BD	Color	pH	C-organic	Ca	Mg	K	Na	CEC	BS
	cm	%				%	g/cm <sup>3</sup>		H <sub>2</sub> O	%	(cmol (+)kg <sup>-1</sup> )				%	
1J	0–5	11	28	61	Clay	15.41	1.17	10YR 2/1 (black)	7.04	4.33	13.68	2.42	0.41	0.51	28.56	60
	5–25	3	34	63	Clay	15.05	1.16	10YR 3/1 (very dark grey)	7.03	4.12	9.56	2.77	0.36	0.35	22.00	59
	30–50	11	47	42	Clay	14.68		10YR 3/1 (very dark grey)	7.06	3.52	8.82	1.17	0.22	0.41	20.20	53
	>60	14	34	52	Clay	14.31		10YR 4/1 (dark grey)	7.00	2.88	6.27	1.08	0.15	0.28	17.16	45
2J	0–20	8	32	60	Clay	13.95	1.20	10YR 2/1 (black)	6.15	3.92	14.55	3.28	0.39	0.41	35.54	52
	20–40	2	26	72	Clay	13.58	1.16	10YR 4/2 (dark grayish brown)	6.13	3.71	10.24	3.15	0.32	0.32	27.58	51
	40–60	9	44	47	Clay	13.21		10YR 3/3 (dark brown)	6.27	3.82	8.50	2.56	0.25	0.29	21.72	53
3J	0–10	2	52	46	Clay	12.84	1.16	10YR 2/1 (black)	7.10	3.96	14.46	3.36	0.42	0.36	29.69	63
	10–30	19	30	50	Clay	12.48	1.23	10YR 2/1 (black)	7.08	4.38	12.37	2.31	0.19	0.21	25.65	59
	30–70	19	33	48	Clay	12.11		10YR 2/1 (black)	7.08	3.53	10.95	1.17	0.32	0.19	22.42	56
	>70	22	30	46	Clay	12.01		10YR 2/1 (black)	7.20	3.33	12.95	1.21	0.22	0.19	23.40	62
4J	0–15	18	51	32	Silty clay loam	11.01	1.26	2,5Y 2,5/1 (black)	7.30	3.71	14.75	1.69	0.38	0.39	31.02	55
	15–30	13	55	32	Silty clay loam	10.64	1.23	2,5Y 4/1 (dark gray)	7.22	3.91	11.72	3.27	0.26	0.24	28.95	54
	30–60	10	32	59	Clay	10.28		2,5Y 4/1 (dark gray)	7.22	3.22	10.45	2.15	0.24	0.22	25.11	52

J Jenepono District, *BD* bulk density, *CEC* cation exchange capacity, *BS* base saturation

activity attributed to the inundation process enhances the transformation of primary and secondary minerals into mineral oxides (Rabenhorst and Parikh 2000). The transformation of mineral oxides in the soil affects the availability of nutrients and toxicity in rice paddies (Pezeshki and Delaune 2012). The

rained lowlands of Bantimurung District showed a medium category BS with values of 33 to 58%, which is in line with pan-oxide plow formation. This indicates that the soil's ability to provide nutrients for plants decreased (Table 1). The rainfall significantly influences the pH, BS, CEC, and water content

**Table 3** Pearson correlation for soil parameters in Bantimurung District, Maros Regency

	Precipitation	Sand	Silt	Clay	Water content	Bulk density	pH	C-organic	Ca	Mg	K	Na	CEC	BS
Precipitation	1													
Sand	-0.359	1												
Silt	-0.096	-0.634**	1											
Clay	0.384	0.114	-0.840**	1										
Water content	0.523*	-0.066	-0.301	0.439	1									
Bulk density	-0.236	0.181	-0.137	0.053	-0.396	1								
pH	-0.660*	0.553*	-0.054	-0.326	-0.126	0.014	1							
C-organic	0.103	-0.022	0.225	-0.277	0.268	-0.952**	0.113	1						
Ca	-0.077	0.388	0.021	-0.288	0.095	0.111	0.579*	0.002	1					
Mg	0.070	-0.552*	0.504*	-0.280	-0.277	-0.234	-0.186	0.228	-0.260	1				
K	0.089	0.112	-0.216	0.197	0.585*	-0.425	0.094	0.408	0.039	0.151	1			
Na	0.308	-0.434	0.204	0.052	-0.053	-0.210	-0.275	0.085	0.228	0.150	-0.406	1		
CEC	0.502*	-0.129	-0.299	0.478	0.543*	-0.542*	-0.141	0.353	0.183	-0.045	0.232	0.598*	1	
BS	-0.483*	0.191	0.401	-0.651**	-0.577*	0.448	0.345	-0.214	0.312	0.263	-0.059	-0.331	-0.780**	1

\* Correlation is significant at the 0.05 level (2-tailed)

\*\* Correlation is significant at the 0.01 level (2-tailed)

**Table 4** Pearson correlation for soil parameters in Bangkala District, Jeneponto Regency

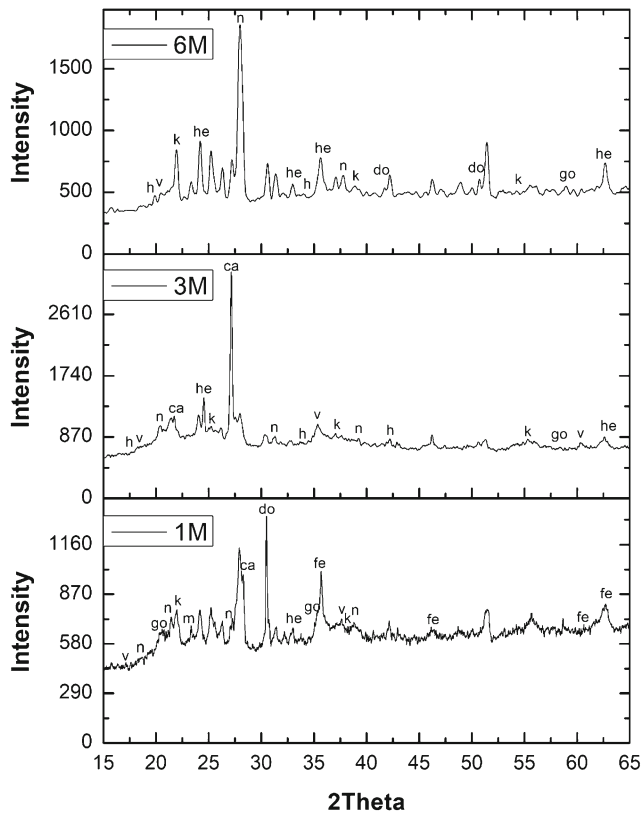
	Precipitation	Sand	Silt	clay	Water content	BD	pH	C-organic	Ca	Mg	K	Na	CEC	BS
Precipitation	1													
Sand	-0.060	1												
Silt	0.076	-0.030	1											
Clay	-0.029	-0.548	-0.819**	1										
Water content	-0.331	-0.471	-0.392	0.594*	1									
BD	0.016	0.757**	0.063	-0.481	-0.770**	1								
pH	-0.052	0.482	0.346	-0.566*	-0.178	0.337	1							
C-organic	0.312	-0.134	-0.176	0.226	0.067	0.132	0.008	1						
Ca	0.371	0.039	0.147	-0.141	-0.368	0.516	0.122	0.609*	1					
Mg	0.369	-0.725**	-0.123	0.521	0.126	-0.280	-0.543	0.612*	0.464	1				
K	0.292	-0.400	0.115	0.139	-0.041	0.100	-0.022	0.479	0.762**	0.571*	1			
Na	-0.062	-0.374	0.155	0.088	0.496	-0.275	-0.008	0.262	0.391	0.267	0.559*	1		
CEC	0.286	-0.168	0.017	0.088	-0.263	0.371	-0.249	0.510	0.913**	0.638*	0.744**	0.446	1	
BS	0.405	-0.095	0.185	-0.100	-0.125	0.166	0.416	0.800**	0.625*	0.401	0.593*	0.154	0.358	1

\* Correlation is significant at the 0.05 level (2-tailed)

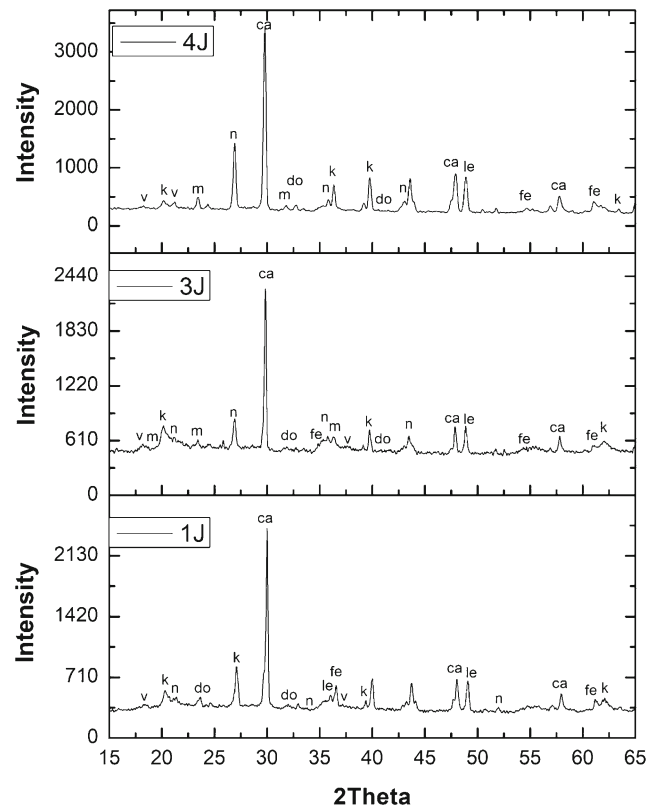
\*\* Correlation is significant at the 0.01 level (2-tailed)

both negatively and positively (Table 3). If left unchecked, this can decrease the productivity of rainfed agricultural soil and have repercussions on the local community income.

The presence of oxide minerals influenced the soil color in Bantimurung District. Alternatively, the soil color in Bangkala District was considerably affected by the



**Fig. 6** X-ray diffractometer data in Bantimurung District with clay mineral: kaolinite (k), halloysite (h), vermiculite (v), montmorillonite (m), nontronite (n). Carbonate minerals: calcite (ca), and dolomite (do). Oxide mineral: hematite (he), goethite, and ferrihydrite (fe)



**Fig. 7** X-ray diffractometer data in Bangkala District with clay mineral: kaolinite (k), vermiculite (v), montmorillonite (m), nontronite (n). Carbonate minerals: calcite (ca) and dolomite (do). Oxide mineral: ferrihydrite (fe) and lepidocrocite (le)

**Table 5** Oxide component in a layer of oxide-pan in Bantimurung District

Profile	Fe <sub>2</sub> O <sub>3</sub> m/m%	Al <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	MnO	TiO <sub>2</sub>	CaO	ZrO <sub>2</sub>	BaO	ZnO	MoO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>
1M	43.56	31.97	14.39	4.07	3.81	1.62	0.32	0.2	0.05	x	x
3M	25.87	31.24	32.88	3.39	2.93	4.02	0.41	0.16	0.07	0.04	x
6M	33.42	43.91	13.24	2.22	3.33	2.6	0.47	x	0.07	0.04	0.71

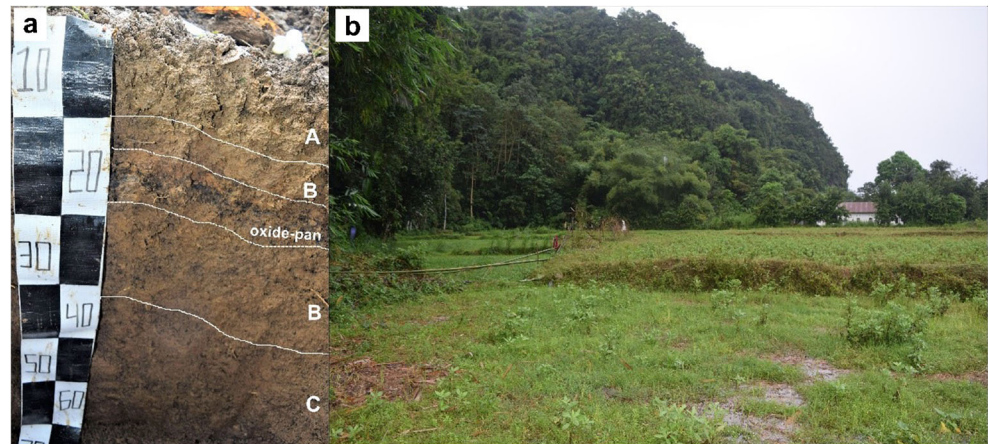
The data has been recalculated in 100%

x no data

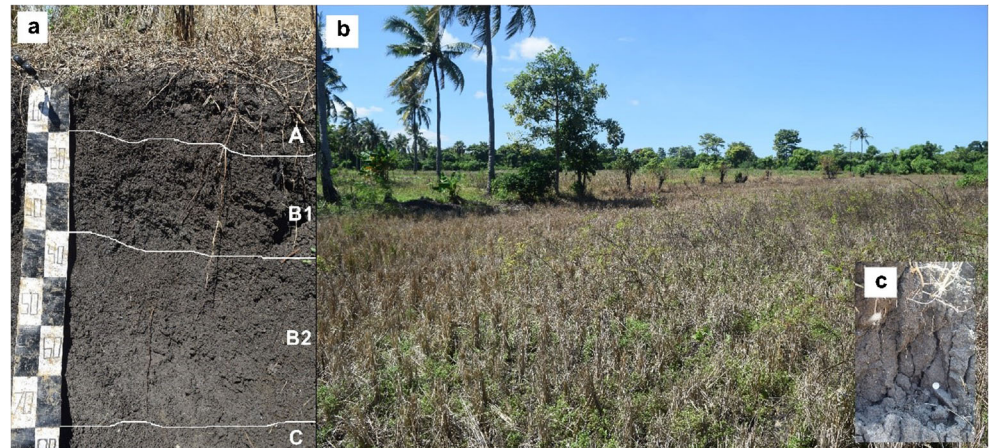
accumulation of organic matter, resulting in a low chroma value (Table 2). High organic matter and 2:1 clay mineral contents increased the water-holding capacity of the soil (Diatta et al. 2020) but caused the soil cracks under dry conditions (Fig. 9c). Soil cracks reduce crop productivity, and the crop productivity increases when the soil is well irrigated (Pal et al. 2012). In the D-3 climate, the implementation of drip or sprinkle irrigation can improve soil productivity in Vertisols order soils (Crescimanno et al. 2007).

In Bantimurung District, intensive land cultivation decreased organic matter content, as demonstrated by the increase in soil bulk density (Table 1). It will decrease the productivity of rainfed cultivation. This was exacerbated by farmers who sell leftover crops to breeders as animal feed rather than returning them to the soil as a source of organic matter. Instead, farmers prefer to use chemical fertilizers as a nutrient source for rice paddies. Excessive use of chemicals fertilizer can endanger the soil quality and sustainability (Chuan-chuan

**Fig. 8** Soil profile (1M) in Bantimurung District showed an oxide-pan layer between the B horizon (a) and the land use for rainfed (b)



**Fig. 9** Soil profile (3J) in Bangkala District showed a soil profile with A, B1, B2, and C horizons (a), the land use for rainfed (b), and fracture in soil when it dried (c)



et al. 2017). Soil fertility must be maintained by increasing the C-organic level so that nutrients are not quickly lost because of high levels of eluviation (Aprile and Lorandi 2012). In Bangkala District, increasing the water content in dry areas can increase the soil bulk density. This can be performed by collecting and storing water in pools (Kiros et al. 2016), during the rainy season (Li 2003). The use of perennial rivers for irrigation increases the soil water content and lengthens the planting period, thus increasing the crop production in this district.

## Conclusions

Soil genesis from carbonate rocks in rainfed agriculture lowlands is affected by climatic factors, which must be understood to successfully develop and land use for increased crop production. Based on the result of this study, the soil formation in the study site with the C-2 climate was sufficiently quick because of the intense hydopedological activity and twice-yearly inundation process. This was evidenced by the formation of the pan-oxide plow, kaolinite, and a low C-organic level. Soil fertility can be maintained at this study site by increasing the C-organic level so that nutrients are not quickly lost because of high levels of eluviation. Alternatively, the study site with D-3 climate showed high levels of soil fertility but also tended to undergo soil cracking under dry conditions. This study site requires management in terms of increased water content through rainfall harvesting during the rainy season and the use of perennial rivers for irrigation to improve crop productivity.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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