

# Characterization, classification, and crop suitability of selected soils in the Ragain Subwatershed, Philippines

EDGEL O. ESCOMEN<sup>1,\*</sup>, ABDUL RACMAN M. MAPANDI<sup>1</sup>, ALLYSA JOIE A. AMBOS<sup>1</sup>, FELIX KENT NEIL J. SAN JOSE<sup>1</sup>, ANALIZA C. OUANO<sup>1</sup>, ALBERTO L. AMBOS<sup>1</sup>, MELENCIO C. JALOVA JR.<sup>2</sup>

<sup>1</sup>College of Agriculture, Mindanao State University. Marawi City 9700, Lanao del Sur Mindanao, Philippines.

Tel.: +63-9064203396, \*email: edgel.escomen@msumain.edu.ph

<sup>2</sup>College of Forestry and Environmental Studies, Mindanao State University. Marawi City 9700, Lanao del Sur Mindanao, Philippines.

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**Abstract.** *Escomen EO, Mapandi ARM, Ambos AJA, Jose FKNJS, Ouano AC, Ambos AL, Jalova Jr. MC. 2026. Characterization, classification, and crop suitability of selected soils in the Ragain Subwatershed, Philippines. Asian J Agric 10 (1): g100153. <https://doi.org/10.13057/asianjagric/g100153>. Sustainable agricultural development requires site- and soil-specific technologies. This study aimed to characterize, classify, and assess the land suitability of select soils in the Ragain Subwatershed, Philippines, derived from three representative pedons. Reconnaissance surveys, soil pedon identification and preparation, soil sampling, and physico-chemical analyses were conducted on select areas within the Ragain Subwatershed. Three representative pedons were analyzed through field characterization and physico-chemical analyses, followed by classification using the USDA Soil Taxonomy and land evaluation based on the FAO framework coupled with the parametric square-root method. Land suitability assessment of the three representative pedons indicated that no areas were highly suitable (S1) for the selected crops. Oil palm and banana showed moderate suitability (S2; LSI up to 67.19 and 56.68, respectively), primarily limited by drainage and soil texture. Several crops, including sugarcane and mango, were classified as marginally suitable (S3) due to constraints in texture and organic carbon. Meanwhile, Arabica coffee and cocoa were not suitable within the evaluated pedons because of combined climatic and physico-chemical limitations. These overarching constraints—particularly poor drainage, strong soil acidity, and low phosphorus availability—highlight the limitations of blanket agricultural recommendations and emphasize the necessity of targeted amelioration strategies to enhance productivity and sustainability.*

**Keywords:** FAO framework, Lanao del Sur, parametric land evaluation, pedon characterization, soil taxonomy

## INTRODUCTION

Healthy soil is a fundamental necessity for sustainable global food consumption and ecosystem maintenance (Shah et al. 2005). Consequently, achieving sustainable agriculture involves studying soil attributes and properties through comprehensive soil characterization (Tahat et al. 2020). Soil characterization provides information that enriches understanding of the physical, chemical, mineralogical, and microbiological features of soils. Such data are important for managing crop production, forests, and grasslands (Ajala et al. 2021). In addition, soil classification is useful for predicting the most suitable land use and production potential. It also aids for technology transfer and information sharing among soil scientists, policymakers, planners, and researchers working closely with agricultural extension agents (Assen and Yilma 2010). The combination of soil characterization, soil classification, and soil mapping is a powerful tool for agricultural development, especially for food security and environmental sustainability (Sharu et al. 2013). For instance, a recent land suitability assessment of selected soil series in Ilocos Norte, Philippines, demonstrated the value of identifying ideal soil profiles. This process enables targeted interventions, such as specific fertilizer applications, to overcome fertility constraints and maintain soil health (Watson et al. 2025).

Lanao del Sur is a province with a well-suited climate and vast arable area in the Philippines, projecting tremendous agricultural potential (Ministry of Finance and the Budget and Management 2025). Various regional and provincial development framework plans identified 15 soil types common in the Province of Lanao del Sur, but their properties were not well defined and adequately documented (Japan International Cooperation Agency (JICA) 2016). The past soil surveys have mapped adjacent regions in Mindanao at a broad reconnaissance scale. Furthermore, regional assessments in nearby Cotabato Province have largely focused on macro-climatic suitability rather than in-depth soil morphology (Basan et al. 2020). Consequently, these general inventories lack the high-resolution, pedon-level data required for modern agronomic planning. Recent comprehensive soil characterizations have been conducted in other Philippine landscapes (Watson et al. 2025). Unlike those areas, foundational pedological data detailing the precise morphological and physico-chemical constraints of local soils in the Ragain Subwatershed are virtually nonexistent. This hinders the development of site-specific agricultural strategies. The assessment of the three chosen pedons used in this research is important since they represent the major topographical and drainage differences of the active agricultural landscape. The definition of these three differentiated profiles offers the most important missing

foundation necessary to shift generalized regional assumptions toward accurate and specific land assessment.

At present, diverse agricultural technologies and inputs are prescribed at a few locations in the country. These are often projected to other locations varying in morphological and physico-chemical properties. Consequently, systems and technologies may be recommended across sites with dissimilar capabilities and limitations (Dinssa and Elias 2021; Hadiyan et al. 2026), rather than being site- or soil-specific. Data-driven, site-specific evaluation is necessary to implement agricultural technologies effectively. The overall classification of soils has become an essential procedure for reducing the adverse effects of climate change (Griffel et al. 2022). On-site data will also enable the identification of appropriate soil health indices, supporting accurate nutrient management and resource optimization (Mondal et al. 2025). In the long run, this process can empower key stakeholders, such as farmers and policymakers, to adopt climate-smart strategies that safeguard long-term regional food security (Kabato et al. 2025). This aligns with broader policy frameworks such as the Sustainable Development Goals (SDGs)-specifically No Poverty (SDG 1), Zero Hunger (SDG 2), Climate Action (SDG 13), and Life on Land (SDG 15). Therefore, the specific objectives of this study were to characterize the physico-chemical properties, classify the soil taxonomy, and evaluate the crop suitability of selected soils in the Rmain Subwatershed.

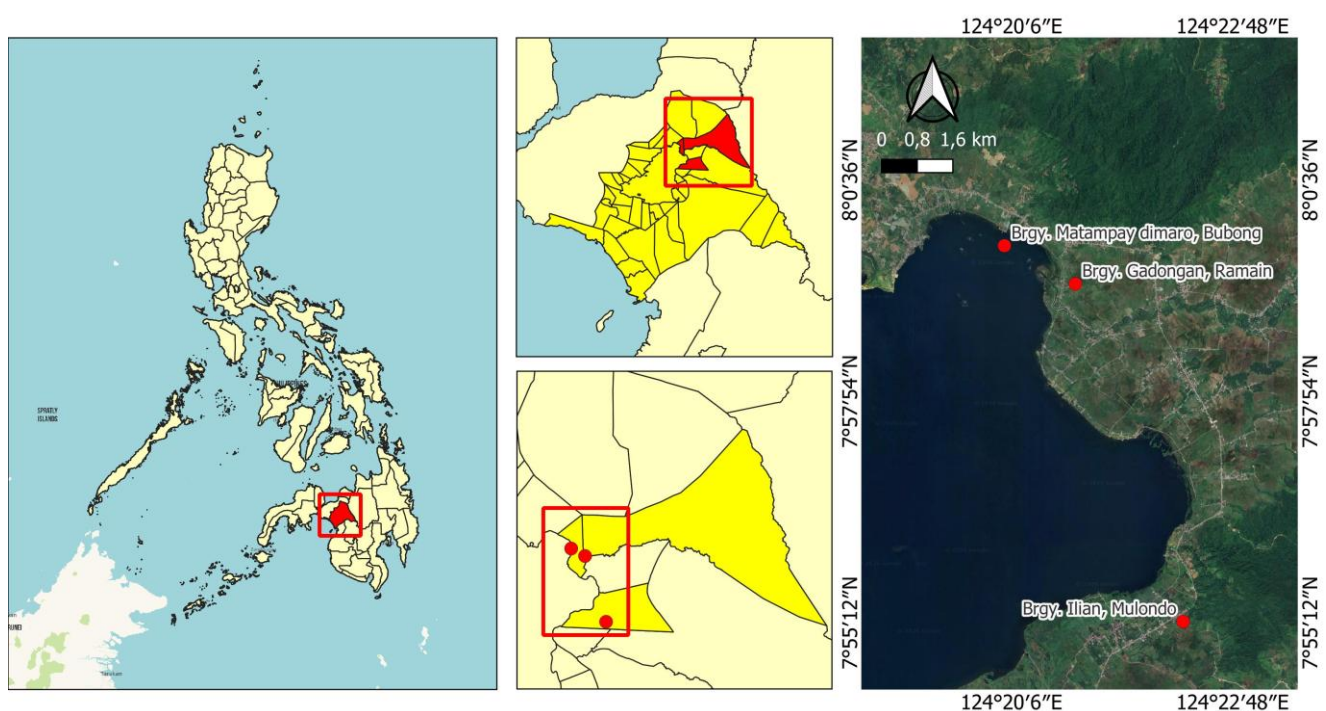
Despite the recognized importance of soil characterization for sustainable land use planning, the extent to which pedon-level variability influences crop suitability and management decisions in the Rmain Subwatershed remains insufficiently understood.

Therefore, this study addresses the following research question: How do differences in soil morphological and physico-chemical properties among representative pedons affect soil classification and crop suitability under local climatic conditions? Specifically, the study examines how variations in drainage, soil acidity, nutrient status, and texture translate into differing land suitability classes and agricultural constraints.

## MATERIALS AND METHODS

### Description of the study area

The study was conducted in the selected areas in the Rmain Subwatershed, namely Brgy. Gadongan, Ditsaan Rmain (7.988889 N 124.348056 E; elevation: 700.60 masl, slope: 0-1%, land use: crop land), Brgy. Matampay Dimaro, Bubong (7.996667 N 124.333611 E; elevation: 829.70 masl, slope: 6-7%, land use: crop land), and Brgy. Ilian, Mulondo (7.920278 N 124.370000 E; elevation: 715.70 masl, slope: 0-1%, land use: crop land), Lanao del Sur, Philippines (Figure 1). These specific sites were purposively selected during the reconnaissance survey because they represent the major topographical and drainage differences of the active agricultural landscape. Three major soil types covered the area. These were Rugnan clay loam, Aduyon clay loam, and Rmain loam. Although these are the general areas, in this analysis, the individual soil pedon will serve as the fundamental unit of observation to produce site-based pedological information.



**Figure 1.** Location of the study sites in the Rmain Subwatershed, Philippines

### Pedon selection and representativeness

During the reconnaissance survey, the active agricultural landscape of the Ragain Subwatershed was evaluated to identify major topographical and drainage variations. To check within-site variability and ensure soil homogeneity before the final pit selection, random auger borings were conducted across each target area. Specifically, these preliminary auger samples demonstrated consistent soil color and texture across the targeted boundaries, verifying the lack of significant spatial variability. Based on this spatial assessment, one representative, typifying pedon was purposively selected per barangay, yielding a total of 3 pedons for the entire study. Following standard pedological protocols for baseline characterization, a single, carefully sited soil pit was utilized to define each uniform mapping unit. Because the evaluated mapping units exhibited highly uniform geomorphological and surface characteristics during the preliminary borings, a single pedon per unit was deemed sufficient to represent the broader soil series accurately. Therefore, it must be explicitly stated that this research is a baseline pedological characterization study rather than a statistical regional survey. The purposive sampling methodology also helped ensure that each sampled pedon is considered the central diagnostic profile. This approach provided an overview of the major geomorphology, drainage patterns, and slope with respect to the selected agricultural zone to support a taxonomic classification. As such, the resulting pedological and agronomic inferences apply primarily to these representative mapping units rather than capturing the full spatial variability of the entire watershed.

### Soil morphological characterization

The soil physical analyses were conducted in every pedon within the identified areas of the selected soil in the Ragain Subwatershed. A 1 m<sup>2</sup> pit was dug to a depth of >1 m. The soil horizons were identified and marked after the soil pit was dug and cleared. Soil morphological data, including matrix color, structure, consistency, and horizon boundaries, were collected in situ following the Guidelines for Soil Description (FAO 2006). The explicit criteria for assigning master and diagnostic horizons followed the USDA Keys to Soil Taxonomy (Soil Survey Staff 2022), using observed morphological features and subsequent laboratory data. Soil samples were collected from each identified horizon. The collected samples were then bagged, labelled, and transported to the Soil Laboratory at Mindanao State University Main Campus, Marawi, Lanao del Sur, and the Department of Agriculture-Regional Soils Laboratory-10. To ensure methodological clarity, it should be noted that two distinct frameworks were applied for different analytical purposes: the USDA Soil Taxonomy was used for soil classification (including diagnostic horizon identification), while the FAO Soils Bulletin 32 framework was applied for land suitability evaluation. This distinction ensures consistency between the methodological description and the analytical objectives of the study.

### Soil sampling and analysis

The soil samples from each horizon were air-dried, ground to a fine fraction of  $\leq 2$ mm, sieved, and labelled before submission to the Department of Agriculture-Regional Soils Laboratory-10 for analyses of pH (unitless), OM (%), and exchangeable bases (cmol<sub>c</sub>/kg). To ensure laboratory precision, each laboratory procedure consisted of three analytical repeats (technical replicates) performed on the single homogenized soil sample collected from each horizon. Therefore, it should be noted that these represent analytical precision rather than independent field or pedon replication. Standard Quality Assurance and Quality Control (QA/QC) were strictly observed, including the use of method blanks on a routine basis, calibration standards, and certified reference soil materials. Particle size distribution analysis (% sand, % silt, and % clay) was conducted at the Soils Laboratory of the College of Agriculture, Mindanao State University Main Campus, Marawi City, Lanao del Sur, Philippines. The list of physicochemical analyses, reporting units, and the methods used are shown in Table 1. The analytical tools used in the testing facilities include a calibrated digital pH meter for studying soil reaction, an Atomic Absorption Spectrophotometer (AAS) for determining exchangeable bases, and a UV-Vis Spectrophotometer for determining available phosphorus (ppm). In the reporting of results, parameters falling below the standard method detection limit (MDL)-specifically <1.0 ppm for Olsen-P-are explicitly designated as "Not Detected" (ND).

### Time and location of the study

This study was conducted from December 2024 to April 2025, with a duration of 92 days: 12 days for reconnaissance and soil sampling in the Brgy. Gadongan, Ditsaan Ragain, Brgy. Matampay Dimaro, Bubong, and Brgy. Ilian, Mulondo, Lanao del Sur, Philippines, and 80 days for chemical analyses at the Department of Agriculture-Regional Soils Laboratory-10, Cagayan de Oro, and Soils Laboratory, College of Agriculture, Mindanao State University Main Campus, Marawi City, Lanao del Sur.

**Table 1.** Soil properties used for physicochemical analyses of the study area

Soil properties	Methods	Units
Chemical		
Soil pH	Potentiometric method	unitless
Organic Matter	Walkley and Black (1934)	%
Exchangeable Bases (Ca, Mg, Na, and K)	Ammonium Acetate Method (Black 1982)	cmol <sub>c</sub> /kg
Available Phosphorus	Olsen-P (Olsen et al. 1954)	ppm
Physical		
Particle Size Analysis	Hydrometer method (Bouyoucos 1962)	%
Soil color	Munsell color chart	Munsell notation

### Soil classification

The soils were classified from the epipedon to family level according to the United States Department of Agriculture (USDA) Soil Classification System “Keys to Soil Taxonomy 13<sup>th</sup> Edition 2022” (Soil Survey Staff 2022).

### Climatic data

The National Aeronautics and Space Administration (n.d.)-Prediction of Worldwide Energy Resources (NASA-POWER) provided a 20-year summary of available data on rainfall, relative humidity, and mean temperature for 2005-2024. Only Precipitation (PRECTOTCORR), Temperature at 2 Meters (T2M, T2MMAX, T2MMIN), and Relative Humidity at 2 Meters (RH2M) were extracted at 8.000 N 124.375 E. Climate data were used to assess suitability and matched with the crop’s climatic requirements to determine suitability under specified agro-climatic conditions (Basan et al. 2020). The growing cycle evaluated for each specific crop was defined according to its distinct physiological maturity period, spanning from planting or active vegetative growth to harvest, as prescribed by the FAO crop suitability framework.

### Land evaluation

The selected soil series in Romain Subwatershed was evaluated using a system approach based on the Food and Agriculture Organization framework for land suitability evaluation using FAO Soils Bulletin 32 (FAO 1976). The data gathered was found in Table 2. The FAO Land Suitability classification is shown in Table 3. Three categories were derived from the framework, namely: order, class, and subclass.

The suitability order for land determines if the land unit is suitable (S), moderately suitable (S2), marginally suitable (S3), or not suitable (N). Classes indicate the level of suitability. Subclass indicates the types of limitation caused by climate (annual precipitation, relative humidity, and mean annual temperature), topography (slope), soil wetness (flooding and drainage), soil physical properties (texture, coarse fragments and soil depth), soil fertility (apparent CEC, base saturation, and soil pH), and salinity & alkalinity (ECE, and ESP). Each subclass was designated a letter suffix: *t* for topography, *w* for wetness, *s* for physical properties, *f* for fertility, *c* for climate, and *n* for salinity and alkalinity.

### Crop suitability assessment

The specific crops evaluated in this study were purposively selected based on their high economic importance and established local agricultural relevance within the region. These crops-including Arabica coffee, banana, cocoa, guava, mango, oil palm, papaya, pineapple, Robusta coffee, and sugarcane-also demonstrated potential for climatic adaptation to support regional food security and commercial viability. The evaluation process includes identifying and matching Land Use Requirements (LUR) and Land Qualities (LQ) to come up with sound and viable recommendations (Sys et al. 1993). The specific crop requirements and corresponding optimal growth parameters used for this matching process are detailed in Table 4, derived from Sys et al. (1993). Each individual land characteristic was assigned a numerical rating (e.g., 100 for highly suitable/S1, 85 for moderately suitable/S2, 60 for marginally suitable/S3, and 40 or below for currently not suitable/N) based on its deviation from these optimal LURs. Climate and land indices were calculated using a weighing factor. It was carried out using the Square Root Method (Khiddir 1986) following the formula:

$$I = R_{\min} \times \sqrt{\frac{A}{100} \times \frac{B}{100} \times \frac{C}{100} \dots}$$

Where, I: Index,  $R_{\min}$ : Minimum rating, A, B, C...: other ratings besides the minimum rating.

**Table 2.** Climatic and land characteristics used in crop suitability assessment

Climatic characteristics (NASA-POWER)	Land characteristics
Precipitation of growing cycle (mm)	a. Topography (% slope)
Mean temperature of the growing cycle (°C)	b. Wetness (flooding and drainage)
Mean annual maximum temperature (°C)	c. Physical soil characteristics (Texture, coarse fragments, and soil depth)
Mean daily temperature of coldest month (°C)	d. Soil fertility characteristics (Apparent CEC, base saturation, sum of basic cations, pH, and organic carbon)
Length of dry months	e. Salinity and Alkalinity (ECe, and ESP)
Relative Humidity	

**Table 3.** The FAO land suitability classification and Land Suitability Index

Order	Class	Description	Land Suitability Index
Suitable	S1	Highly Suitable-land units with no or only 4 slight limitations.	76-100
Moderately Suitable	S2	Moderately Suitable-land units with more than 4 slight limitations, and/or no more than 2 severe limitations.	51-75
Marginally Suitable	S3	Marginally Suitable-land units with more than 3 moderate limitations, and/or no more than 2 severe limitations.	26-50
Not Suitable	N	Not Suitable (Currently)-land units with severe limitations that can be corrected.	0-25

The derivation of the minimum rating ( $R_{min}$ ) is determined by identifying the single lowest numerical score among all evaluated land characteristics. This acts as the primary weighting factor because the most limiting parameter exerts the greatest constraint on overall crop performance. As an actual field-derived example from this study, the evaluation for banana in Brgy. Gadongan, Ditsaan Rmain identified drainage as the most limiting factor, yielding an  $R_{min}$  of 60. Applying the formula with the other evaluated parameter ratings (e.g., a secondary texture rating of 89.24), the index is calculated as:

$$I = 60 \times \sqrt{\frac{100}{100} \times \frac{85}{100}} \times \frac{85}{100} \times \frac{95}{100} \times \frac{85}{100} = 60 \times 0.7638 = 45.83$$

This final index of 45.83 directly corresponds to the Marginally Suitable (S3) classification—specifically designated as S3f due to organic carbon constraints—matching the site-specific results based on the standard index ranges provided in Table 3.

**Geospatial analysis and suitability mapping workflow**

A land suitability mapping process was undertaken through ArcGIS 10.3. The spatial model was on a polygonal base and on baseline homogeneity across the three large soil mapping units, i.e., Rugnan clay loam, Adtuyon clay loam, and Rmain loam. The suitability maps for individual crops are shown in Figures 5. A-I.

**Uncertainties and limitations**

The suitability maps generated in this study assume homogeneity within the boundaries of the three major uniform soil mapping units. While the purposively selected pedons act as central diagnostic profiles, this qualitative extrapolation method inherently masks micro-topographical and micro-climatic variations that may exist within a single soil series.

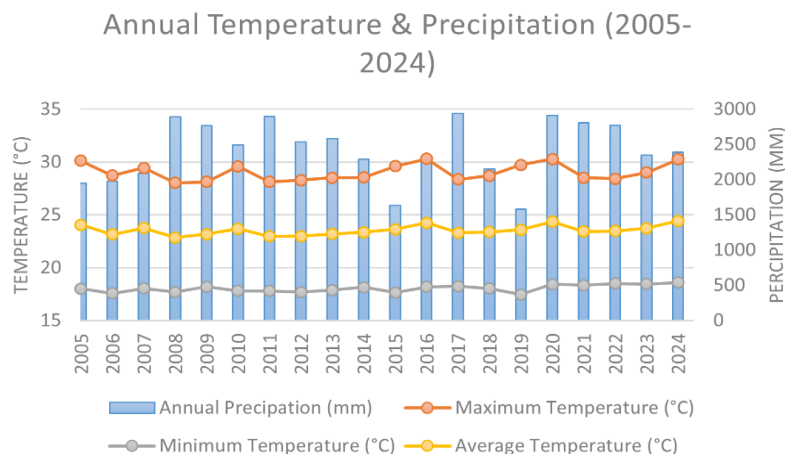
**RESULTS AND DISCUSSION**

**Climate data**

The 20-year record of climate data from NASA-POWER (<https://power.larc.nasa.gov/data-access-viewer/>) shows annual variability in temperature, precipitation, and relative humidity. As shown in Figure 2, the highest maximum Mean Annual Temperature (MAT) recorded was in 2016 at 30.31°C, followed by 30.27°C in 2020, and 30.26°C in 2024. The lowest maximum MAT recorded was in 2008 at 28.03°C. The minimum MAT was recorded in 2019 with 17.4°C and in 2008 with 18.5°C. The average temperature ranged from 22.85°C in 2008 to 24.42°C in 2024. These temperatures, specifically the lowest maximum temperatures reaching below 18°C, limit the physiological range of strictly tropical crops that need warmer base temperatures to grow vegetatively and flower. This thermal constraint contributes to the marginal and inappropriate climate scores of temperature-sensitive crops such as Robusta coffee in this part of the area (Chemura et al. 2021).

As shown in Figure 2, annual precipitation fluctuated significantly from 1,578.17 mm in 2019 to 2,941.02 mm in 2017, with no clear trend. It was relatively high in 2008, 2011, 2017, 2020, 2021, and 2022, and lower in 2005, 2015, and 2019. These high precipitation regimes (often exceeding 2,000 mm/year) have posed major constraints on crops sensitive to excessive moisture. This precipitation alters the necessary dry seasons during which pineapple needs to flower and fruit. Consequently, these conditions support the marginally appropriate (S3c) climatic category for pineapple (Williams et al. 2017).

Lastly, relative humidity data ranged from 82% to 88% in a year-to-year basis, suggesting that the Rmain Subwatershed has had a continuously humid climate over the past 20 years, as shown in Figure 3. This sustained elevated relative humidity constitutes an extreme bioclimatic constraint, as it favors fungi and reduces optimal crop respiration. As a result, this climatic parameter influences the not suitable (Nc) classification for cocoa cultivation, which requires lower humidity to develop its pods and avoid diseases (Lahive et al. 2019).



**Figure 2.** Annual temperature and precipitation of the study area

**Table 4.** Sample table of land use requirement for Arabica coffee

	<b>S1 (Rating: 100-95)</b>	<b>S2 (Rating: 85)</b>	<b>S3 (Rating: 60)</b>	<b>N1 (Rating: 40-25)</b>	<b>N2 (Rating: 0)</b>
<b>Climatic Requirements</b>					
Annual precipitation (mm)	1500-1600 / 1500-1400	1600-1800 / 1400-1200	1800-2000 / 1200-1000	> 2000 / 1000-800	< 800
Length dry season (months: P < 1/2 PET)	2.5-3 / 2.5-2	3-4 / 2-1	4-5 / 1-0	5-6	> 6
Mean annual max. temp. (°C)	25-26 / 25-24	26-28 / 24-22	28-30 / 22-20	30-32 / 20-18	> 32 / < 18
Mean daily min. temp. of coldest month (°C)	15-17 / 15-14	17-19 / 14-10	19-21 / 10-7	21-23 / 7-4	> 23 / < 4
Mean annual temp. (°C)	19-18 / 19-20	18-16 / 20-22	16-15 / 22-24	15-14 / 24-26	< 14 / > 26
Mean rel. humidity dryest month (%)	55-60 / 55-50	60-70 / 50-40	70-80 / 40-30	80-90 / 30-20	> 90 / < 20
n/N of the 5 driest months	> 0.65	0.65-0.5	0.5-0		
<b>Land and Soil Requirements</b>					
<b>Topography (Slope %)</b>					
Irrigated agriculture (1)	0-1 / 1-2	2-4	4-6	> 6	
High-level management (2)	0-2 / 2-4	4-8	8-16	> 16	
Low-level management (3)	0-4 / 4-8	8-16	16-30	30-50	> 50
<b>Wetness</b>					
Flooding	F0	F0	F0		F1+
Drainage	good; groundwater > 50 cm / 100-150 cm	moderate	imperf.	poor but drainable	poor not drainable
<b>Physical Soil Characteristics</b>					
Texture / Structure	C<60s, Co, SiCL, CL / C>60s, SC, L	SCL	SL, LfS		Cm, Sicm, C>60v, LS, LcS, cs, fs
Coarse fragments (vol%)	0-3 / 3-15	15-35	35-55	> 55	
Soil depth (cm)	> 200 / 200-150	150-100	100-50	< 50	
CaCO <sub>3</sub> (%)	0-1 / 0	1-2	2-5	> 5	
Gypsum (%)	0 / 0-0.5	0.5-2	2-3	> 3	
<b>Soil Fertility Characteristics</b>					
Apparent CEC (cmol(+)/kg clay)	24-16 / > 24	<16(-)	<16(+)		
Base saturation (%)	> 80 / 80-50	50-35	35-20	< 20	
Sum of basic cations (cmol+)/kg soil)	> 6.5 / 6.5-4	4-2.8	2.8-1.6	< 1.6	
pH H <sub>2</sub> O	6.0-5.8, 5.8-5.6 / 6.0-6.2, 6.2-6.6	5.6-5.4 / 6.6-7.4	5.4-5.2 / 7.4-7.8	< 5.2 / > 7.8	
Organic carbon (%)	> 2.4 / 2.4-1.2	1.2-0.8	< 0.8		
<b>Salinity and Alkalinity</b>					
E <sub>Ce</sub> (dS/m)	0-0.5	0.5-2	2-6	> 6	

Note: C<60s: Clay (less than 60%), blocky structure; Co: Clay, oxisol structure; SiCL: Silty clay loam; CL: Clay loam; C>60s: Very fine clay (greater than 60%), blocky structure; SC: Sandy clay; L: Loam; SCL: Sandy clay loam; SL: Sandy loam; LfS: Loamy fine sand; Cm: Massive clay; Sicm: Massive silty clay; C>60v: Very fine clay (greater than 60%), vertisol structure; LS: Loamy sand; LcS: Loamy coarse sand; cs: Coarse sand; fs: Fine sand. For complete climatic and land requirements of crops, please refer to Land evaluation part III: Crop requirements (Sys et al. 1993)

**Physiographic characteristic and land use**

The physiographic characteristics and land use are shown in Table 5. All pedons were utilized for agricultural purposes. They were well-drained, except in Brgy. Gadongan, Ditsaan Ramin, which had imperfect drainage, was classified according to the drainage criteria outlined by Sys et al. (1991). Under this framework, good drainage (GD) indicates that water is removed from the soil readily but not rapidly, leaving the upper profile free of wetness indicators. Imperceptible drainage (IMD), on the contrary, is the process that results in the slow removal of water. Therefore, the soil remains wet for extended periods. This classification is directly related to the field morphology observed in the Brgy. Gadongan pedon with pronounced gleying and a distinct hydromorphic color resulting from prolonged saturation. Brgy. Gadongan, Ditsaan Ramin, and Brgy. Ilian, Mulondo had flat terrain, while Brgy. Matampay Dimaro, Bubong had an undulating to gently sloping landscape. The elevation of the area ranged from 700.60 to 829.70 masl, as determined from Google Earth observations.

**Soil morphological properties**

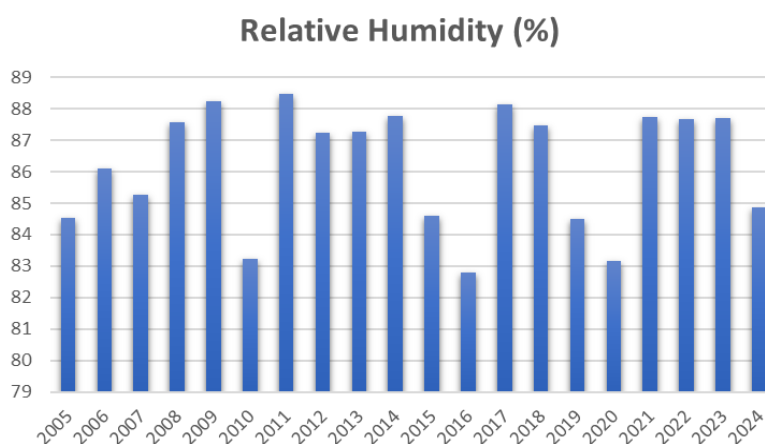
All three pedons in the Ramin Subwatershed exhibited distinct soil physical properties highlighting their developmental contrasts. For instance, the soil profile of Brgy. Gadongan, Ditsaan Ramin had distinct hydromorphic features indicating prolonged saturation and poor drainage (Vepraskas and Craft 2016). The Apg horizon (0-30 cm) is a gray (7.5R 6/0), strong, coarse sub-angular blocky soil that is very hard when dry and very sticky/plastic when wet (Table 6). Below this, the parent material shows strong gleying. The C1g horizon (30-48

cm) is reddish-gray (5R 5/1) with a weak subangular blocky structure and remains very firm when moist. The deeper C2g (48-77 cm) and C3g (77 cm-below) horizons transition to red (10R 5/8) and reddish-brown (2.5YR 5/1), respectively. These deeper layers degrade into a weak, single-grain structure with a soft, loose, and non-sticky/non-plastic consistency. This suggests a coarser texture lacking cohesion. All boundaries in this profile are clear and smooth. The topsoil (Ap, 0-30 cm) is a sandy clay loam (Table 7). Immediately below the tillage layer, the soil loses its fine particles and becomes almost entirely sand in the C1g horizon (30-48 cm). The lower parent material remains coarse throughout the deeper horizons, fluctuating between sandy loam and pure sand. Scientifically, this highly sandy profile indicates very rapid drainage and poor water retention, leading to quick drying and requiring careful irrigation management (Libohova et al. 2018). However, in this particular landscape, what would have been expected to be a swift internal drainage is completely negated by a high regional water table. The sudden shift in texture, when the heavy, sandy clay loam layer on the surface is replaced by pure sand subsoil, is a typical mark of recent alluvial deposits and stratification. Since this stratified profile is located in an endoaquic zone, it is periodically flooded with groundwater. As a result, the otherwise overly permeable sands are continuously saturated for long periods, leading to imperfect drainage and severe gleying as observed. The lack of any diagnostic subsurface horizon beneath the surface layer, coupled with these prominent aquic conditions, provides the explicit morphological justification for classifying this pedon as an Entisol.

**Table 5.** Site characteristics of the selected soils in Ramin Subwatershed, Philippines

Location	Coordinates	Slope (%)	Elevation (masl)	Slope position	Drainage class	Land use
Brgy. Gadongan, Ditsaan Ramin	7°59'20" N 124°20'53" E	0-1	700.60	Flat	IMD	Crop land
Brgy. Matampay Dimaro, Bubong	7°59'48" N 124°20'1" E	6-7	829.70	Undulating to gently sloping	GD	Crop land
Brgy. Ilian, Mulondo	7°55'13" N 124°22'12" E	0-1	715.70	Flat	GD	Crop land

Note: masl: Meter above sea level, Drainage: GD: Good drainage, IMD: Imperfect drainage



**Figure 3.** Annual relative humidity (%) of the study area

In stark diagnostic contrast to the unweathered Gadongan profile, the profile at Brgy. Matampay Dimaro, Bubong, demonstrates argillaceous development with highly uniform consistency. This physical trait is generally favorable for moisture retention in upland agricultural systems (Buol et al. 2011). The undisturbed A horizon (0-27 cm) is dark brown (10YR 3/3) with a weak, fine, sub-angular blocky structure and a highly workable, friable consistency when moist (Rabot et al. 2018). The underlying subsoil layers indicate an accumulation of silicate clay (Buol et al. 2011), fulfilling the strict morphological criteria for an argillic diagnostic horizon. The identification of this well-developed argillaceous horizon directly drives its taxonomic classification as an Ultisol. The Bt1 (27-58 cm), Bt2 (58-103 cm), and Bt3 (103-133 cm) horizons progressively shift from strong brown (7.5YR 4/6 to 7.5YR 5/8) while upgrading to a strong, coarse sub-angular blocky structure. Interestingly, this workable, friable, and slightly sticky/slightly plastic consistency is maintained uniformly throughout the subsoil and into the transitional BC horizon (133 cm below), with all horizons separated by clear, smooth boundaries. The topsoil (A, 0-27 cm) is a loam, making it an excellent, workable planting medium (Rabot et al. 2018). As depth increases, the Bt1 horizon (27-58 cm) transitions into a sandy clay loam. All deeper subsoil layers beneath 58 cm uniformly classify as sandy clay due to high clay content. This specific progression provides excellent topsoil for roots, paired with a subsoil with a strong capacity to hold moisture (Libohova et al. 2018).

Representing an intermediate weathering stage compared to the previous pedons, the pedon at Brgy. Ilian, Mulondo, demonstrates a clear texturo-pedological progression where stickiness and plasticity increase with depth. This confirms the active illuviation of clays (Schaetzl and Anderson 2005) and establishes a distinct argillic diagnostic horizon. The presence of this argillaceous horizon is the definitive morphological feature linking this profile to its Alfisol classification. The tilled topsoil (Ap, 0-40 cm) is light yellowish-brown (10YR 6/4) with a moderate, very coarse sub-angular blocky structure and a friable, moist consistency, separated by a clear, wavy boundary. Deeper in the profile, the Bt2 (63-87 cm) and Bt3 (87-127 cm) horizons darken to 10YR 5/8 and 10YR 4/6, respectively, while the structure becomes strong and coarse. The consistency in these lower layers becomes noticeably heavier and more restrictive, transitioning from firm/plastic in Bt2 to hard, firm, sticky, and plastic in Bt3, with both lower boundaries being clear and smooth. The topsoil (Ap, 0-40 cm) starts as a well-draining sandy loam. The soil then smoothly transitions into a sandy clay loam through the middle subsoil horizons (40-87 cm), before classifying as a heavier sandy clay in the deepest evaluated layer. This gradual increase in clay means the lower horizons will hold water much more effectively than the well-draining surface layer (Weil and Brady 2016).

### Soil chemical properties

The pedon in Brgy. Gadongan, Ditsaan Raman, is divided into four distinct layers. The topsoil A<sub>pg</sub> horizon (0-30 cm) and the three deeper subsoil layers, namely, C<sub>1g</sub>

(30-48 cm), C<sub>2g</sub> (48-77 cm), and C<sub>3g</sub> (77 cm below). The topmost layer is strongly acidic (pH 5.41), but the soil becomes moderately acidic in the deeper horizon (reaching pH 5.84 in the C<sub>3g</sub> layer) (Table 8). Organic Matter (OM) and Total Nitrogen (TN) are moderate in the surface and low to very low in subdominant horizons. In particular, the available P is extremely low throughout the profile. However, the soil is rich in important nutrients, such as calcium and magnesium, which are rated high to very high at all depths (Table 8). This pedon had a high Cation Exchange Capacity (CEC), meaning the soil is excellent at holding onto nutrients, and a base saturation that increases with depth, indicating a good reserve of basic nutrients in the deeper horizons (Penn and Camberato 2019; Wiesmeier et al. 2019) (Table 9). This high base saturation (increasing from 59.75% to 89.68%) is pedologically consistent with its classification as a relatively young alluvial Entisol. In this environment, periodic groundwater saturation prevents complete leaching and actively replenishes basic cations within the profile.

The pedon in Brgy. Matampay-Dimaro, Bubong features a deeper, highly weathered soil profile with five layers: the surface A horizon (0-27 cm), three subsoil clay layers Bt1 (27-58 cm), Bt2 (58-103 cm), Bt3 (103-133 cm), and BC horizon (133 cm below). The soil is strongly acidic throughout, with a pH ranging from 4.67 to 5.14. The surface horizons (A) contain a very high concentration of organic matter (6.50%) and nitrogen, while these are reduced significantly in the lower horizons. Available phosphorus is completely undetectable at all horizons (Penn and Camberato 2019). Although the surface horizon had moderate levels of calcium and potassium, deeper horizons show extreme leaching of exchangeable bases (Sanchez 2019). This severe nutrient leaching is reflected in the very low base saturation, ranging from 2.79% to 6.21% in the deeper horizons. Such a characteristic pattern of moderately high CEC in combination with perceived low base saturation is indicative of its taxonomic classification as a highly weathered Ultisol. It represents an older topography in which simple cations have long since been washed out by natural processes and replaced by acidic cations. The soil in this horizon had the capacity to retain alkaline nutrients, but it is quite poor despite its moderately high CEC.

In Brgy. Ilian, Mulondo, the pedon consists of four layers: the surface A<sub>p</sub> horizon (0-40 cm) and three consecutive subsoil layers, Bt1 (40-63 cm), Bt2 (63-87 cm), and Bt3 (87-127 cm). The entire profile is strongly acidic, with pH values ranging from 5.00 to 5.14. It has low organic matter (0.80%), which decreases further in the deeper horizons (Wiesmeier et al. 2019). Like several other sites, available phosphorus is completely undetected (MDL <1.0 ppm). However, the soil compensates somewhat with its mineral content, maintaining moderate calcium and high magnesium levels throughout all depths. Additionally, it maintains a medium to very high CEC. It shows a high to very high base saturation in the lower horizons (87.17% in the Bt3 layer), indicating that the nutrients present are basic rather than acidic cations (Sanchez 2019). This contrasts with the intensely leached profile in Brgy. Matampay

Dimaro, Bubong. Here, the pronounced accumulation of basic cations at depth maintains a base saturation well above the 35% taxonomic threshold. This acts as the diagnostic pedological signature of an Alfisol, indicating active illuviation of clays in an environment that has not yet undergone extreme base depletion.

**Soil taxonomic classification**

As shown in Figure 4, the soil in Brgy. Gadongan, Ditsaan Ramin, Lanao del Sur is classified in the order Entisols (Table 10), which are essentially young soils that lack distinct, developed subsurface horizons-linking

directly to the absence of a diagnostic subsurface horizon noted in the morphological evaluation and have a base saturation greater than 35% (Buol et al. 2011). Moving down the taxonomic hierarchy, it falls under the suborder Aquents because the soil experiences continuous wetness (aquic conditions) and shows signs of gleying (a grayish color due to waterlogging) within the top 50 cm of the mineral surface. Because it is saturated by a regional water table rather than a perched water table, it is classified into the great group Endoaquents (Soil Survey Staff 2022) (Table 11).

**Table 6.** Soil morphological properties: soil color, structure, consistency, and horizon boundary of the selected soil in Ramin Subwatershed, Philippines

Horizon	Depth (cm)	Color	Structure	Consistency	Horizon boundary
		Dry	Type/Grade/Class	Dry/Moist/Wet	
Brgy. Gadongan, Ditsaan Ramin					
Ap	0-30	7.5R 6/0	SAb/St/C	VH/VFi/VS/P	CS
C1g	30-48	5R 5/1	SAb/We/C	SH/VFi/SS/SP	CS
C2g	48-77	10R 5/8	Sg/We/C	So/L/NS/NP	CS
C3g	77-below	2.5YR 5/1	Sg/We/C	So/L/NS/NP	CS
Brgy. Matampay Dimaro, Bubong					
A	0-27	10YR 3/3	SAb/We/F	SH/Fr/SS/SP	CS
Bt1	27-58	7.5YR 4/6	SAb/Mo/M	SH/Fr/SS/SP	CS
Bt2	58-103	7.5YR 5/6	SAb/St/C	SH/Fr/SS/SP	CS
Bt3	103-133	7.5YR 5/8	SAb/St/C	SH/Fr/SS/SP	CS
BC	133-below	7.5YR 5/8	SAb/St/C	SH/Fr/SS/SP	CS
Brgy. Ilian, Mulondo					
Ap	0-40	10YR 6/4	SAb/Mo/VC	SH/Fr/SS/SP	CW
Bt1	40-63	10YR 5/6	SAb/Mo/C	SH/Fr/SS/SP	CW
Bt2	63-87	10YR 5/8	SAb/St/C	SH/Fi/SS/P	CS
Bt3	87-127	10YR 4/6	SAb/St/C	H/Fi/S/P	CS

Note: Horizon: A: Topsoil, B: Subsoil, C: Parent material, p: Tillage or other artificial disturbances, g: Strong gleying, w: Weak color or structure within B horizon, t: Accumulation of silicate clay. Color: 7.5R 6/0: Gray, 5R 5/1: Reddish gray, 10R 5/8: Red, 2.5YR 5/1: Reddish brown, 10YR 3/3: Dark brown, 7.5YR 4/6, 7.5YR 5/6 and 7.5YR 5/8: Strong brown, 10YR 6/8: Brownish yellow, 10YR 6/4: Light yellowish brown, 10YR 5/6 to 10YR 5/8: Yellowish brown, 10YR 4/6: Dark yellowish brown. Structure: St: Strong, We: Weak, Mo: Moderate, M: Medium, F: Fine, C: Coarse, G: Granular, Sg: Single Grain, Ab: Angular Blocky, SAb: Sub-Angular Blocky. Consistency: H: Hard, SH: Slightly Hard, VH: Very Hard, Fi: Firm, SFi: Slightly Firm, VFi: Very Firm, Fr: Friable, SFr: Slightly Friable, VFr: Very Friable, L: Loose, So: Soft, NS: Non-Sticky, S: Sticky, SS: Slightly Sticky, VS: Very Sticky, NP: Non-Plastic, P: Plastic, SP: Slightly Plastic, VP: Very Plastic. Boundary: C: Clear, S: Smooth, G: Gradual, T: Topography, W: Wavy

**Table 7.** Soil's physical properties: particle size distribution and textural class of the selected soils in Ramin Subwatershed, Philippines

Horizon	Depth (cm)	Particle size distribution			Textural class
		%Sand	%Silt	%Clay	
Brgy. Gadongan, Ditsaan Ramin					
Ap	0-30	52.63	24.49	22.89	SCL
C1g	30-48	95.76	0.19	4.05	S
C2g	48-77	72.00	16.00	12.00	SL
C3g	77-below	88.87	7.34	3.79	S
Brgy. Matampay Dimaro, Bubong					
A	0-27	44.81	30.50	14.31	L
Bt1	27-58	57.57	8.37	34.06	SCL
Bt2	58-103	45.65	4.17	50.18	SC
Bt3	103-133	52.98	5.54	41.48	SC
BC	133-below	52.75	6.46	40.79	SC
Brgy. Ilian, Mulondo					
Ap	0-40	56.00	34.00	15.00	SL
Bt1	40-63	58.00	21.00	21.40	SCL
Bt2	63-87	53.00	24.00	23.00	SCL
Bt3	87-127	45.00	17.80	37.20	SC

Note: Texture: SL: Sandy loam, L- Loam, S: Sand, SC: Sandy clay, SCL: Sand clay loam, SiL: Silt loam, SiCL: Silty clay loam

At the subgroup level, it is classified as Typic Endoaquents due to its sandy clay loam surface texture and an irregular decrease in organic carbon, which indicates water deposits stratified the soil layers. Furthermore, it represents the central concept of the great group by meeting these key criteria. Specifically, it strictly lacks additional diagnostic horizons or features such as a histic epipedon, sulfidic materials within 50 cm, or a shallow lithic contact. Finally, its family classification is coarse-loamy over sandy, mixed, superactive, nonacid, isohyperthermic Typic Endoaquents because the texture contrasts sharply between the coarse-loamy upper layers and sandy deeper layers, while maintaining a nonacid reaction class due to a base saturation above 50% (Soil Survey Staff 2022).

The soil in Brgy. Matampay Dimaro, Bubong, Lanao del Sur, features a much more weathered soil profile classified as an Ultisol. The soil is defined by the presence of an argillaceous subsurface horizon with very low saturation (<35%) (Sanchez 2019), matching the morphological identification of the argillic diagnostic horizon. It further indicates that the cations present are easily replaceable basic cations. It belongs to the Humults suborder because it is highly enriched with organic matter in the upper 15 cm of the argillic horizon, is 1.57%, easily exceeding the 0.9% requirement (Soil Survey Staff 2022). It is further classified into the Haplohumults great group and down to the subgroup Typic Haplohumults because its clay content does not decrease by 20% from its maximum as it goes deeper into the profile. It also lacks other

diagnostic horizons or aberrant features such as aquic conditions within the upper 60 cm, a fragipan, or a lithic contact. These key criteria securely anchor it in the central concept. At the family level, it is described as fine, mixed, superactive, isohyperthermic Typic Haplohumults. The superactive designation for Cation Exchange Capacity (CEC) to clay ratio is exceptionally high (0.885-0.988) (Buol et al. 2011).

The soil profile in Brgy. Ilian Mulondo represents a different path of development, classified as an Alfisol, directly tied to the aforementioned diagnostic argillic horizon. Alfisols are similar to Ultisols in that they have a prominent argillic (clay-accumulated) subsurface horizon. However, they are generally more fertile because they retain a base saturation of greater than 35% deep in the profile (Sanchez 2019). Experiencing a moderately wet climate, it falls into the Udalfs suborder and the Hapludalfs great group. It strictly meets the central concept for these soils, placing it in the Typic Hapludalfs subgroup (Soil Survey Staff 2022). This is specifically because it meets the key criteria of lacking redoximorphic features indicating wetness in the upper horizons. Additionally, it does not possess a shallow lithic contact or other diagnostic horizons like glossic features. At the most specific family level, it is categorized as fine-loamy, mixed, superactive, isohyperthermic Typic Hapludalfs. Similar to the other clay-rich sites in this study, the high CEC-to-clay ratios (1.57-1.78) indicate the superactive class, meaning the specific clay types present are highly effective at holding onto moisture and nutrients (Buol et al. 2011).

**Table 8.** Soil's chemical properties: total exchange bases, % base saturation, and cation exchange capacity of the selected soil in Ramin Subwatershed, Philippines

Horizon	Depth (cm)	Total exchange bases (cmol/kg)	CEC (Sum) (cmol/kg)	Base saturation (%)
Brgy. Gadongan, Ditsaan Ramin				
Apg	0-30	24.51 (H)	41.02 (VH)	59.75 (M)
C1g	30-48	26.00 (H)	30.15 (H)	86.24 (VH)
C2g	48-77	24.16 (M)	27.13 (H)	89.05 (VH)
C3g	77-below	25.02 (H)	27.90 (H)	89.68 (VH)
Brgy. Matampay Dimaro, Bubong				
A	0-27	5.73 (M)	24.88 (M)	23.03 (L)
Bt1	27-58	2.09 (VL)	33.67 (H)	6.21 (VL)
Bt2	58-103	1.37 (VL)	44.45 (VH)	3.08 (VL)
Bt3	103-133	1.25 (VL)	36.23 (H)	3.45 (VL)
BC	133-below	1.00 (VL)	35.86 (H)	2.79 (VL)
Brgy. Ilian, Mulondo				
Ap	0-40	15.74 (H)	24.17 (M)	65.12 (H)
Bt1	40-63	15.85 (H)	33.70 (H)	47.03 (M)
Bt2	63-87	19.19 (H)	40.99 (VH)	46.82 (M)
Bt3	87-127	18.82 (H)	21.59 (M)	87.17 (VH)

Note: VL: Very Low, L: Low, M: Moderate, H: High, VH: Very High, ND: Not Detected. Values presented for chemical properties represent the mean of three analytical laboratory repeats

**Table 9.** Soil taxonomic classification of the selected soil series in Ramin Subwatershed, Philippines

Pedon	Diagnostic horizon			Soil classification		
	Surface	Subsurface	Temperature	Moisture	Order	Suborder
Brgy. Gadongan, Ditsaan Ramin	Ochric	None	Isohyperthermic	Aquic	Entisols	Aquents
Brgy. Matampay Dimaro, Bubong	Ochric	Argillic	Isohyperthermic	Udic	Ultisols	Humults
Brgy. Ilian, Mulondo	Ochric	Argillic	Isohyperthermic	Udic	Alfisols	Udalfs

**Table 10.** Soil taxonomic classification of the selected soil series in Rmain Subwatershed, Philippines

Pedon	Family		Soil classification			
	Great group	Subgroup	Particle-size	Mineralogy	Cation exchange activity	Soil reaction
Brgy. Gadongan, Ditsaan Rmain	Endoaquents	Typic Endoaquents	Coarse-loamy over sandy	Mixed	Superactive	Nonacid
Brgy. Matampay Dimaro, Bubong	Haplohumults	Typic Haplohumults	Fine	Mixed	Superactive	-
Brgy. Ilian, Mulondo	Hapludalfs	Typic Hapludalfs	Fine-loamy	Mixed	Superactive	-

**Table 11.** Crop suitability assessment of Brgy. Gadongan, Ditsaan Rmain, Brgy. Matampay, Dimaro, Bubong, and Brgy. Ilian, Mulondo, Philippines

Crops	Brgy. Gadongan, Ditsaan Rmain		Brgy. Matampay Dimaro, Bubong		Brgy. Ilian, Mulondo	
	Land Suitability Index	Land suitability classification	Land Suitability Index	Land suitability classification	Land Suitability Index	Land suitability classification
Arabica Coffee	2.78	Nw (drainage/flooding)	7.87	Nf (pH)	6.25	Nf (pH)
Banana	56.68	S2ws (drainage and texture)	19.91	Nf (pH)	27.18	S3sf (texture and %OC)
Cocoa	8.79	Nc (relative humidity)	11.66	Nf (pH)	14.67	Nsf (texture and pH)
Guava	29.83	S3w (drainage/flooding)	38.50	S3f (pH)	45.83	S3f (%OC)
Mango	17.83	Nw (drainage/flooding)	36.58	S3f (pH)	53.17	S2f (%OC)
Oil Palm	56.68	S2ws (drainage and texture)	67.19	S2f (pH)	37.69	S3s (texture)
Papaya	14.17	Nw (drainage/flooding)	22.91	Nf (pH)	43.35	S3f (%OC)
Pineapple	8.48	Nw (drainage/flooding)	35.5	S3c (rainfall)	33.33	S3cf (rainfall and %OC)
Robusta Coffee	19.72	Nws (drainage and depth)	30.3	S3f (pH)	49.49	S3csf (rainfall, texture, and pH)
Sugarcane	31.09	S3w (drainage/flooding)	29.07	S3f (pH)	64.92	S2sf (texture, and %OC)

Note: t: Topography, w: Wetness, s: Physical properties, f: Fertility, c: Climate, and n: Salinity and alkalinity



**Figure 4.** Soil profile in the Philippines: A. Brgy. Gadongan, Ditsaan Rmain; B. Brgy. Matampay Dimaro, Bubong; and C. Brgy. Ilian, Mulondo

### Crop suitability assessment

The crop suitability assessment categorizes the land into four distinct classes, namely highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N) (Shaloo et al. 2022). Scientific analysis of these pedons reveals substantial spatial variability in soil physico-chemical properties and climatic factors, which control the potential for different agricultural integrations, as detailed in the final crop suitability assessment (Table 12).

To establish analytical coherence and address the fragmentation of soil property datasets, Table 12 provides an integrative synthesis. It directly consolidates key soil chemical indicators (specifically pH, organic matter, cation exchange capacity, and base saturation extracted from Tables 8 and 9) and morphological constraints, linking them explicitly with the final crop suitability rankings and their corresponding spatial distribution outputs (Figures 5. A-I).

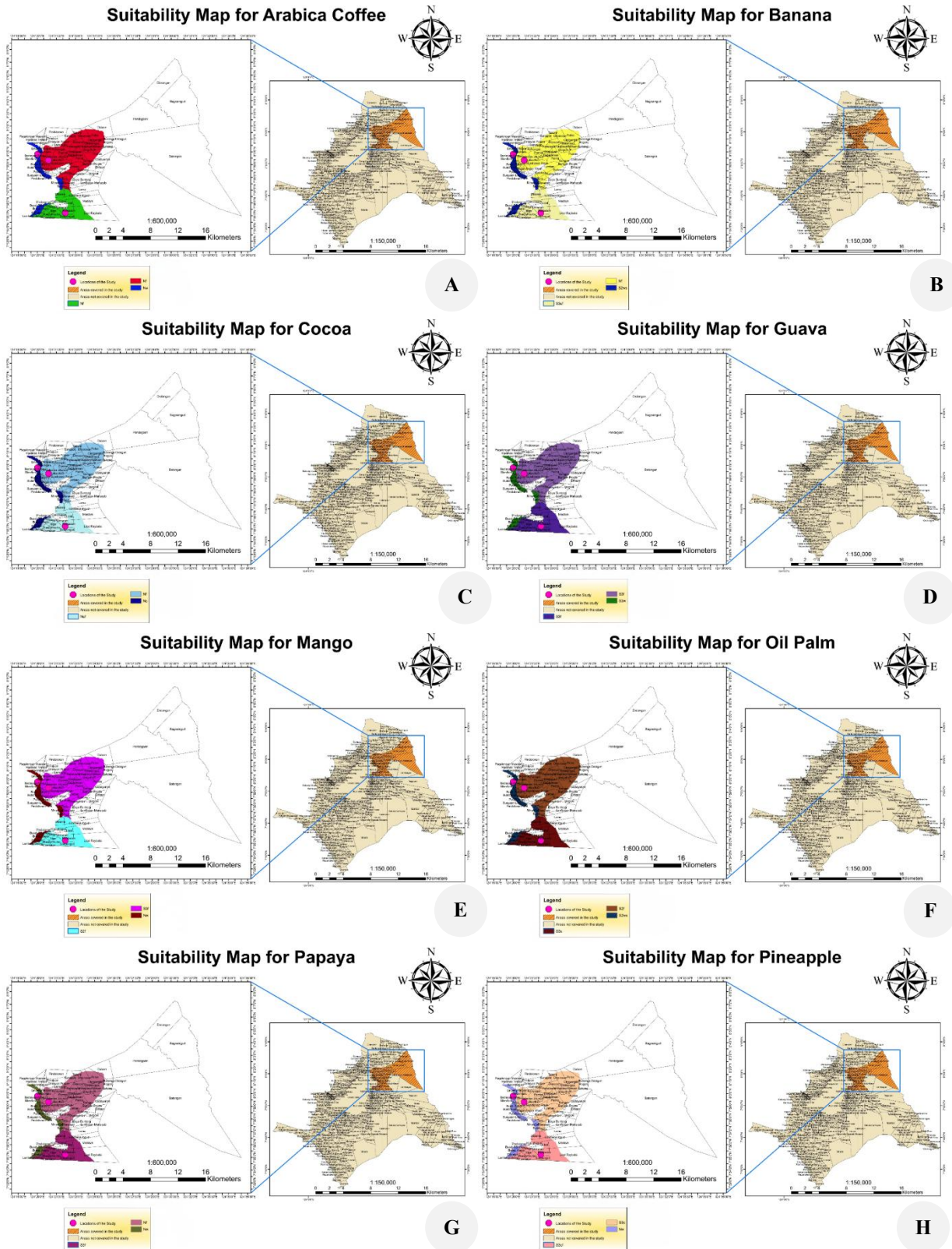
### Site-specific crop suitability constraints

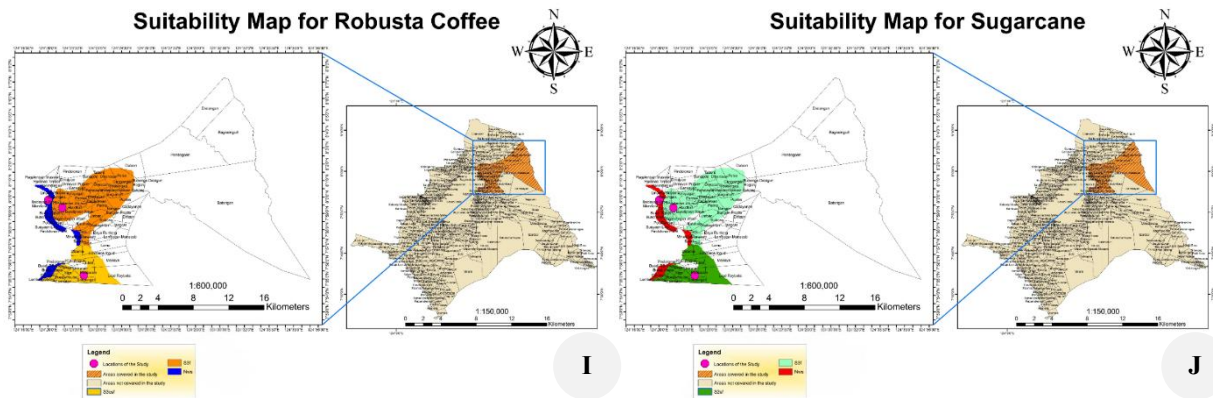
In Brgy. Gadongan, Ditsaan Ramin, crop limitations are distinctly divided into soil-based and climate-based constraints. The major agronomic limitation is poor drainage and flooding (w) in the land suitability classification. Only banana (*Musa* spp.) and Oil palm (*Elaeis guineensis* Jacq.) attained a moderately suitable (S2ws) rating because they are still constrained strictly by soil drainage (imperfect drainage; Table 5) and texture (up

to 95.76% sand; Table 7). Sugarcane (*Saccharum officinarum* L.) and guava (*Psidium guajava* L.) are categorized as marginally suitable (S3w) exclusively due to these soil-water limitations. Continual hydrological problems make many crops completely not suitable (Nw), such as Arabica coffee (*Coffea arabica* L.), mango (*Mangifera indica* L.), papaya (*Carica papaya* L.), and pineapple (*Ananas comosus* (L.) Merr.). Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) is also not suitable specifically due to its soil drainage and depth (Nws) requirements. Climatic limitations operate independently to restrict other crops; for instance, cocoa (*Theobroma cacao* L.) is not suitable for the pedon environment specifically due to its requirement for relative humidity (Nc). These results are consistent with reports that long-term waterlogging has a very strong negative effect on root respiration and nutrient uptake of non-hydrophytic crops, which requires intensive drainage systems to become commercially viable. This localized hydrological constraint closely parallels the land-suitability profiles of similar lowland Aquents across Southeast Asia specifically in Indonesia and Vietnam, where drainage engineering is a common requirement. For instance, in the heavily monsoonal alluvial plains of Vietnam and Indonesia, prolonged saturation in young tropical soils can be analogous. This severely restricts non-hydrophytic cash crops. It dictates that agricultural viability relies almost entirely on large-scale drainage engineering or raised-bed systems.

**Table 12.** Integrative summary linking key soil indicators and climatic constraints to overall crop suitability rankings and corresponding spatial map outputs

Location in the Philippines (Pedon)	Key soil indicators (Tables 8 and 9)	Key climatic and morphological constraints	Moderately suitable (S2)	Marginally suitable (S3)	Not suitable (N)
Brgy. Gadongan, Ditsaan Ramin	pH: 5.41-5.84 (Strongly to moderately acidic) OM: Moderate (surface) to Low CEC: 27.90-41.02 cmol/kg (High-Very High) BS: 59.75%-89.68% (Moderate-Very High)	Soil: Poor drainage (IMD), sandy subsurface (Texture), very low Avail. P (1.2 ppm); Climate: High relative humidity	Banana (Figure 5.B) Oil Palm (Figure 5.F)	Guava (Figure 5.D) Sugarcane (Figure 5.J)	Arabica Coffee (Figure 5.A), Cocoa (Figure 5.C), Mango (Figure 5.E), Papaya (Figure 5.G), Pineapple (Figure 5.H), Robusta Coffee (Figure 5.I)
Brgy. Matampay Dimaro, Bubong	pH: 4.67-5.14 (Strongly acidic) OM: 6.50% (Very high in surface) to low CEC: 24.88-44.45 cmol/kg (Moderate-Very High) BS: 2.79%-23.03% (Very Low-Low)	Soil: Extreme base leaching, undetected Avail. P; Climate: Excessive rainfall	Oil Palm (Figure 5.F)	Guava (Figure 5.D), Mango (Figure 5.E), Pineapple (Figure 5.H), Robusta Coffee (Figure 5.I), Sugarcane (Figure 5.J)	Arabica Coffee (Figure 5.A), Banana (Figure 5.B), Cocoa (Figure 5.C), Papaya (Figure 5.G)
Brgy. Ilian, Mulondo	pH: 5.00-5.14 (Strongly acidic) OM: 0.80% (Low) CEC: 21.59-40.99 cmol/kg (Moderate-Very High) BS: 46.82%-87.17% (Moderate-Very High)	Soil: Texture (clay illuviation), undetected Avail. P; Climate: Excessive rainfall	Mango (Figure 5.E), Sugarcane (Figure 5.J)	Banana (Figure 5.B), Guava (Figure 5.D), Oil Palm (Figure 5.F), Papaya (Figure 5.G), Pineapple (Figure 5.H), Robusta Coffee (Figure 5.I)	Arabica Coffee (Figure 5.A), Cocoa (Figure 5.C)





**Figure 5.** Suitability map for A. Arabica coffee, B. Banana, C. Cocoa, D. Guava, E. Mango, F. Oil palm, G. Papaya, H. Pineapple, I. Robusta coffee, J. Sugarcane. The spatial distribution depicted in this crop suitability maps is derived from the qualitative extrapolation of data from three purposively selected pedons across their respective representative soil mapping units. The mapping assumes baseline landscape homogeneity and the use of homogeneous soil polygons within these boundaries rather than utilizing continuous geostatistical interpolation

The crop suitability evaluation for Brgy. Matampay Dimaro, Bubong indicates a clear distinction between soil constraints and climatic restrictions. Soil pH is the primary limiting factor for agricultural development, directly linked to the strongly acidic values (pH 4.67-5.14) in Table 8. Of the crops assessed, Oil palm (*E. guineensis*) has a moderate suitability, with a Land Suitability Index (LSI) of 67.19. This crop is limited exclusively by soil pH (S2f). A few crops like guava (*P. guajava*), mango (*M. indica*), Robusta coffee (*C. canephora*), and sugarcane (*S. officinarum*), with an LSI of 38.50, 36.58, 30.3, and 29.07, respectively, are marginally suitable due to soil fertility constraints, specifically pH (S3f). Some crops are completely not suitable (N) due to extreme soil pH restriction (Nf) for Arabica coffee (*C. arabica*), banana (*Musa* spp), and papaya (*C. papaya*). It implies substantial soil amelioration before cultivation for these crops. This extreme acidity, combined with the high leaching typical of Ultisols, restricts phosphorus availability and promotes aluminum toxicity. This phenomenon is widely documented as a primary barrier to tropical agriculture. These findings are highly consistent with pedological assessments of upland Ultisols in neighboring Southeast Asian countries, such as Malaysia and Thailand, highlighting the shared bottlenecks of base depletion and acidity. In those similarly weathered tropical landscapes, profound base depletion and strong acidity are the primary bottlenecks to crop expansion, mandating strict liming and phosphorus management protocols before establishing sensitive plantation crops. Beyond soil fertility, pineapple (*A. comosus*) is classified as marginally suitable (S3) with an LSI of 35.5, but its primary limitation is completely climatic, specifically rainfall (S3c).

In Brgy. Ilian, Mulondo, the agronomic limitations of the zone are mainly controlled by soil physical and chemical characteristics, namely texture (Table 7), % OC (0.80%; Table 8), and pH (5.00-5.14; Table 8), though distinct climatic constraints also affect specific crops. Both sugarcane (*S. officinarum*) and mango (*M. indica*) are

classified as moderately suitable based strictly on soil limitations. Sugarcane is constrained by soil-specific factors, namely texture and organic carbon (S2sf), while mango growth is limited exclusively by organic carbon (S2f). A large cluster of crops falls into the marginally suitable (S3) category due to similar soil-based nutrient and textural restrictions; guava (*P. guajava*) and papaya (*C. papaya*) are limited by %OC (S3f). Arabica coffee (*C. arabica*) and cocoa (*T. cacao*) are not suitable (Nf and Nsf, respectively) due to severe soil pH and textural limitations. Beyond soil properties, climatic limitations further constrain pineapple (*A. comosus*) and Robusta coffee (*C. canephora*), which must be explicitly separated: these crops are inherently restricted by soil constraints (texture, pH, and %OC). Independent of these soil properties, both crops face distinct climatic limitations (rainfall), resulting in their cumulative S3cf and S3csf classifications, respectively. The observed pedological pattern-maintaining moderate subsoil base saturation while suffering from severe topsoil organic carbon depletion-typifies intensively tilled Alfisols across the Southeast Asian highlands. Much like the cultivated sloping landscapes of Java and Northern Luzon, linking organic carbon findings to regional patterns of surface degradation in Alfisols. The mechanical loss or rapid oxidation of surface organic matter fundamentally degrades the soil's physical suitability. This underscores that the baseline fertility of these Alfisols can be fully unlocked only through aggressive organic residue integration.

### Suitability mapping

The multiple crop suitability maps presented in the subsequent figures (Figures 5) illustrate the spatial distribution of the identified land suitability classes across the study area. To clarify the spatial model's parameters and validity, it must be noted that these maps are derived entirely from the evaluation of the three purposively selected pedons, rather than from continuous geostatistical interpolation. The mapping process utilized a polygonal

base that assumes baseline landscape homogeneity across the three large soil mapping units (Rugnan clay loam, Aduyon clay loam, and Ragain loam). Consequently, the specific suitability data calculated for each pedon were qualitatively extrapolated across the entire boundaries of its respective mapping unit. While this methodology provides a practical and generalized regional baseline, its validity is strictly tied to the assumption of uniform landscape conditions. Consequently, this approach inherently masks potential microtopographical, localized drainage, or microclimatic variations within the broader mapped zones.

### Uncertainties and limitations

Though the FAO framework, along with the parametric square-root technique, offers a powerful standardized methodology for crop suitability assessment, this paper acknowledges some shortcomings. To begin with, the assessment will be based on predefined parameters for optimal growth that may not account for the changing phenotypic plasticity of newly developed, climate-resistant crop varieties. Moreover, the technique, which evaluates one typifying pedon in each agricultural area, though pedologically stable in determining the basic taxonomic classification, introduces spatial ambiguity due to microtopographical differences within larger mapping units. Lastly, the climatic parameters were based on 20 years of retrospective data. Hence, the future projection of the effects of climate change on extreme temperatures and rainfall was not implemented, which could also alter the long-term suitability indices of the considered crops.

In conclusion, this study characterized, classified, and assessed the land suitability of three pedons within the Ragain Subwatershed of the Province of Lanao del Sur. Substantial spatial variability within the evaluated pedon environments reveals the soil properties that influence agricultural potential across these representative mapping units. Physico-chemical analyses showed that the Brgy. Gadongan, Ditsaan Ragain pedon, classified as Entisols specifically Typic Endoaquents, had poor drainage and a sandy subhorizon with very low available phosphorus. However, its CEC and %BS were high. The pedon of Brgy. Matampay Dimaro, classified as Ultisols (specifically Typic Haplohumults), had an argillaceous subsurface horizon. It was severely limited by strong acidity, extreme deep-soil nutrient leaching, and undetected phosphorus. The Brgy. Ilian, Mulondo pedon, classified as Alfisols, specifically Typic Hapludalfs, had an argillic subsurface horizon, high base saturation, but was low in organic matter.

Consequently, crop suitability assessment using the FAO framework revealed that no crops achieved a highly suitable (S1) classification. For these specific sites, the crops require significant interventions before they can be suitable for production. Common constraints as observed in the studied profiles included drainage, pH, and textural class for crops such as oil palm, banana, sugarcane, and mango. Arabica coffee and cocoa were not suitable in the assessed pedons due to combined climatic, physiological, and physicochemical constraints.

The study confirms that soil heterogeneity and site-specific constraints strongly govern agricultural potential, emphasizing that soil amelioration must be tailored to these localized pedological findings. However, this study is limited by the use of only three representative pedons without spatial replication. It is also limited by the assumption of landscape homogeneity in suitability mapping, which may overlook micro-scale variability. Future research should incorporate additional pedons and geostatistical approaches to improve spatial representativeness and validation. Long-term field trials are also recommended to refine these crop suitability assessments and directly evaluate the identified pedon-level constraints.

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