MORPHOLOGY, PHYSIOCHEMICAL CHARACTERISTICS, AND FERTILITY OF SOILS FROM QUATERNARY LIMESTONE IN LEYTE, PHILIPPINES

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Very few studies have been conducted on the nature and characteristics of soils from Quaternary limestones in geologically young islands in the humid tropics. This study examined a hillslope in Leyte, Philippines, with soils from Quaternary (Late Pleistocene) limestone and evaluated their morphology, physiochemical characteristics, and fertility constraints. We evaluated six pedons representing different slope positions, such as summit, shoulder, upper backslope, middle backslope, lower backslope, and footslope. Our data indicate that the soils in the upper slopes (summit, shoulder, and upper backslope) have thin solum, black surface horizon, clayey texture, granular structure, high organic matter and N, high Ca and CaCO₃ contents, low contents of nutrients like P, K, Fe, Mn, and B, and are neutral to alkaline pH values. According to Soil Taxonomy, the soils are classified as Typic Calciudolls (summit) and Rendollic Eutrudepts (shoulder and upper backslope), but all three pedons are classified as Calcaric Phaeozems in the World Reference Base system. Conversely, the soils on the lower slopes (fotslope and middle and lower backslopes) have thicker solum and higher clay content. They have subangular blocky structures, which turn hard when dry and become plastic and sticky when wet. Like the soils on the upper slopes, they also have neutral to strongly alkaline pH values, have high organic matter, N, Ca, and CaCO₃ contents, but are generally low in nutrient contents. They are classified as Typic Eutrudepts (source, Soil Taxonomy) or Calcaric Cambisols (source, World Reference Base). Most soils have high rock fragment contents in their profile. Results also show substantial variations of solum depth at short distances along the slope (i.e., from summit to footslope) and across the slope. The solum depth variability helps explain the commonly observed variations of crop growth in limestone areas. The high clay content of these relatively young soils suggests contribution from limestone parent material and possibly volcanic ash from past eruptions of nearby volcanoes. Our results show that soils developed from limestone have both physical and chemical fertility constraints to upland crop production, which differ between soils even in the same landscape. The overall results indicate that the characteristics and fertility constraints of soils from Quaternary limestones in our study site are largely the influence of the slope position, chemical characteristic of the limestone parent material, and human activities. (Soil Science 2006;171: 648–661)

Key words: Quaternary limestone, tropical islands, soil characteristics, soil fertility constraints, tropical soils, calcareous soil.

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COMPARED with the tropical soils in geologically older regions like Africa and the Americas, less pedological research has occurred on the much younger soils on the islands of Southeast Asia (see Sanchez, 1976; Juo and Franzluebbers, 2003). These soils may be

distinct from those in other humid tropical areas because of the unique environmental factors that influenced their formation. Geologically, much of Southeast Asia was the result of recent Cenozoic tectonic events, and many areas emerged from the sea recently (Hall, 2002). This has resulted in the formation of relatively young volcanic and sedimentary landforms (e.g., karst) common around the region. In addition, during the drier period of the Quaternary, the effects of climatic changes on landform development were unique in this region because large areas were under the regime of the monsoonal system (Verstappen, 1997). The present climate that prevails in Southeast Asia is also unique in the sense that it is located in the transitional region between the boreal summer Asian monsoon and the boreal winter Asian monsoon (Chang et al., 2005). Biodiversity, which is related to soil processes (Heemsbergen et al., 2004), is high in the region (Myers et al., 2000) because of the effects of climate and geologic history (Nakashizuka, 2004). For instance, the Philippines has been declared as the second "hottest" of the world's biodiversity hotspots (Myers et al., 2000). This means that the Philippines is second only to Madagascar in concentration of endemic plant and vertebrate species and habitat loss. However, during the last several decades, logging, shifting cultivation, increased upland population, and unsuitable land use systems have caused widespread degradation of upland areas in the Philippines and other parts of Southeast Asia (for examples, see Scholz, 1986; Asio, 1998).

Quaternary limestones are widespread in the islands of Southeast Asia and other tropical regions (for examples, see FAO-UNESCO, 1979). Because of high initial crop productivity and easy accessibility due to generally near or along the coast location and low elevation, limestone areas have a long history of cultivation and other anthropogenic influences, resulting in widespread land degradation (for examples, see Urich et al., 2001; Day and Chenoweth, 2004). Thus, there is a need for studies on the nature and characteristics of these soils for their sustainable management for agriculture or rehabilitation by reforestation or agroforestry. Such studies will also contribute to our better understanding of soils on young tropical islands. We are not aware of any published studies dealing with the characteristics and fertility of soils on Quaternary limestones from the Philippines or any other island in Southeast Asia. In fact,

limited studies have been conducted in other regions also. Rabenhorst et al. (1991) noted that although limestones are quite extensive on a worldwide scale, pedologists have directed less attention toward them. Ironically, the scientific literature abounds with agronomic and plant nutrition studies related to the alleviation of one or a few mineral nutrient problems in calcareous soils (see Mengel and Kirkby, 2001; Braschi et al., 2003).

Studies from other areas have shown that soils from limestones vary from calcareous and shallow young soils to acidic and deep old soils (Legros, 1992; Buol et al., 1997; Muhs, 2001). However, the occurrence of relatively young clayey soil on limestone is, until now, poorly understood. Legros (1992) suggested two hypotheses regarding its origin. The first states that the soil comes from the residue after the carbonate has dissolved; the second states that the soil comes from eolian dust. Other possible sources of clay include fine clay illuviation and clay deposition by fluvial and colluvial processes. In his study on the soils on Quaternary reef terraces in Barbados, Muhs (2001) concluded that the soils were developed from dust derived from the Sahara, volcanic ash from the Lesser Antilles island arc, and detrital carbonate from the underlying reef limestone.

The foregoing review has shown that our understanding of soils on tropical islands in Southeast Asia and of soils from Quaternary limestone is limited despite their widespread occurrence and agricultural importance in the region (limestone areas are estimated to occupy 35,000 km² in the Philippines alone [SWCF-CFTU-IGCI, 2005]). Thus, this study was conducted to evaluate the morphology, physicochemical characteristics, and fertility constraints of soils from Quaternary (Late Pleistocene) limestone in Leyte, Philippines.

MATERIALS AND METHODS

Study Site

The study site is located in a limestone hill along the west-facing coast of Punta, Baybay, Leyte, Philippines (Fig. 1). The hill seems to be a remnant of a reef terrace produced by tectonic uplift. It is underlain by marly limestone up to a height of about 50 m above sea level, and then by coralline limestone up to the summit of 80 m above sea level. In the absence of actual data on the age of the terrace, we estimate its age to be

Fig. 1. Location of study site in Leyte, Philippines.

between 100 and 200 kyr B.P. on the basis of radiometric dating ($^{230}\text{Th}/^{234}\text{U}$) studies on Pleistocene coral reef terraces in the nearby opposite islands of Bohol and Cebu (Omura et al., 2004), although soil development seems to be much younger, probably because of erosion and deposition processes in the past. The topography of the site ranges from moderately sloping to rolling. The original vegetation was dipterocarp rain forest, whereas the present land use is a mosaic of grass fallow (mainly *Panicum maximum* and *Imperata cylindrica*), shrubland, sparse stand of stunted coconut trees, fruit trees, and upland farms planted with corn and root

crops, such as cassava and sweet potatoes. Punta was one of the first places to be inhabited by Spaniards when they came to Leyte in the 17th century (Mollaneda, 1988), implying that the area has a long history of anthropogenic influence. This explains the degraded nature of the landscape. According to the Köppen classification (Köppen, 1923), the climate of Leyte is humid tropical monsoon characterized by an average annual rainfall of 2800 mm, with no distinct dry season and with an average temperature of 28 °C. Two monsoonal winds blow in Leyte and in other parts of the archipelago (Coronas, 1920). From May to October, there is

TABLE 1
Surface morphometry of the limestone soils studied according to the terminology of Schoeneberger et al. (2002)

Characteristics	Pedon					
	1	2	3	4	5	6
Elevation (m)	80	75	65	50	40	20
Slope aspect	135°SE	135°SE	135°SE	135°SE	135°SE	135°SE
Slope gradient (%)	0–5	30–40	30–40	30–40	10–15	5–10
Slope complexity	Curvilinear	Curvilinear	Curvilinear	Curvilinear	Curvilinear	Curvilinear
Slope shape	Flat	Convex, linear	Concave, linear	Concave, linear	Concave, linear	Linear, concave
Hillslope position	Summit	Shoulder	Backslope	Backslope	Backslope	Footslope

- 1) Structure
- Size:
- vf = very fine (<5 mm)
f = fine (5–10 mm)
m = medium (10–20 mm)
c = coarse (20–50mm)
vc = very coarse (>50 mm)
- Type:
- g = granular
abk = angular blocky
sbk = subangular blocky
- 2) Consistency
- Dry:
- l = loose
s = soft
h = hard
- Wet:
- s = sticky
p = plastic
- 3) Rock fragments
- n = none (0%)
v = very few (0%–2%)
c = common (5%–15%)
- m = many (15%–40%)
a = abundant (40%–80%)
d = dominant (>80%)
- 4) Horizon boundary
- a = abrupt
c = clear
d = diffuse

the southwest monsoon (locally called *Habagat*) that blows from the southwest direction, causing high rainfall at the western section of the island. From November to April, the northwest monsoon (*Amihan*) blows from the northwest direction, thus causing high rainfall at the eastern section of the island. In addition, typhoons, generally characterized by strong winds and heavy rainfall, develop several times a year. Measurement of soil temperature at a depth of 10 cm in the meteorological station 8 km away from the study site showed highest temperature (30 °C) in May and lowest (26 °C) in December and January (Asio, 1996). Soil moisture and temperature regimes are udic and isohyperthermic, respectively (Soil Survey Staff, 1999).

Field Soil Description and Sampling

Field soil description and sampling were performed mostly in 2001, with additional field

and laboratory work in 2004. We chose six pedons along the southeast-facing slope of the limestone hill, with one pedon representing each of the following slope positions: summit, shoulder, upper backslope, middle backslope, lower backslope, and footslope (Table 1). To examine and sample the pedons, a pit with surface area measuring 1 × 1 m and having a depth of at least 1 m was dug manually. Soil profile description followed the standard procedures of FAO (1990). About one-half kilogram of composite soil sample was obtained from three subsamples collected from every horizon of each soil profile (Schlichting et al., 1995). Samples were air-dried, ground using wooden hammer, sieved to pass a 2-mm mesh, and stored in glass containers.

To evaluate the variation of solum depth at various positions along the catena, the thickness of the A horizon (including B horizon, if

present) was noted from each pedon and from 2 to 4 points between the pits along the catena, with the aid of a soil auger (interval between points, ≈ 5 –10 m). Moreover, we were also able to evaluate the solum depth variations across the slope using the soil trench constructed by the World Agroforestry Center (ICRAF) researchers in the middle backslope position for soil erosion measurement (in relation to their agroforestry trial). The trench, which was about 40 m long and 80 to 100 cm deep, provided a good opportunity to measure the solum depth variation at the meter scale.

Laboratory Analysis

Particle size distribution was analyzed by the pipette method after pretreatment of soil samples with HCl and H_2O_2 to remove carbonates and organic matter (OM), respectively (Schlichting et al., 1995; USDA-NRCS, 1996). Bulk density was determined by taking three soil cores from each horizon according to Schlichting et al. (1995). Soil pH was determined potentiometrically using water and 0.01 mol/L CaCl_2 at a soil-solution ratio of 1:2.5 (ISRIC, 1995); OM and total N using modified Walkley-Black and modified Kjeldhal methods, respectively (USDA-NRCS, 1996); available phosphorus using NaHCO_3 at pH 8.5 (Olsen method; ISRIC, 1995); cation exchange capacity (CEC) using NH_4OAc at pH 7 (USDA-NRCS, 1996); and CaCO_3 equivalent using the gravimetric procedure based on the reaction of CaCO_3 with HCl (Loeppert and Suarez, 1996). Exchangeable K, Ca, Na, and Mg were extracted by using NH_4OAc (hydrogen ion concentration, pH 7; USDA-NRCS, 1996); Fe, Mn, and Zn by using diethylenetriamine pentaacetic acid–triethanolamine (Martens and Lindsay, 1990); and B by hot water extraction method (Johnson and Fixen, 1990), and then quantified by atomic absorption spectrophotometry. Total Fe and Zn contents of plant leaf samples collected from the site were determined by dry-ashing procedure and then quantified by atomic absorption spectrophotometer (Westerman, 1990).

RESULTS AND DISCUSSION

Morphophysical Characteristics

Results revealed considerable variations in the morphological and physical characteristics of the soils from Quaternary limestone, depending on their geomorphic position in the study site

(Table 2). Soils in the upper slopes (pedons 1, 2, and 3) are more poorly developed, as indicated by their AC profiles. They have thin solum (depth, 15–26 cm), abundant rock fragments, strong granular structure on their A horizons, making them loose and friable, and subangular blocky structure in their subsoils. On the other hand, the soils on the lower slopes (pedons 4, 5, and 6) are more developed, as shown by their A-Bw-C profiles. They also have substantially thicker solum (depth, 35–70 cm) with moderately developed B horizons and subangular blocky structures on both the surface and the subsurface horizons (Fig. 3A). However, all soils have high clay content (composition, $>40\%$) in the fine-earth fraction, although those on the lower slopes seemed to have generally higher clay and silt contents than those on the upper slopes (Fig. 2). In addition, they all have black (color, 10YR 2/1) A horizons and brown to very pale brown (color, 10YR 4/3 to 10YR 8/4) B and C horizons. The stark contrast between the colors of the surface and the subsurface horizons is very clear in the field, especially on non-vegetated areas. All soils become plastic and sticky when wet but turn very hard when dry (except the A horizons of the soils on the upper slopes).

Results showed that solum thickness in the study site varies greatly along the slope (i.e., from the summit to the footslope; Fig. 3A) and across the slope, on the basis of our examination of a portion of the middle slope with uniform topography (Fig. 3B). As can be seen from Fig. 3A, the thinnest solums are found on the shoulder and upper backslope positions, whereas the thickest can be seen in the lower backslope position.

The results generally agree with the literature stating that soils from limestone vary from poorly developed to well-developed soils (Legros, 1992; Buol et al., 1997; Day and Chenoweth, 2004). The differences in profile development and morphological and physical properties of the soils in our study site seem to be largely the effect of parent material, relief, and anthropogenic factors. For instance, the generally thinner solum of the soils on the upper slopes reflects the influence of slope on water movement, which, in turn, determines the rates of weathering, erosion, and soil formation (Johnson, 1985; Sommer and Schlichting, 1997; Chen et al., 1999). Thus, slope positions, which enhance very high runoff and erosion, such as the shoulder and upper slope, produced

TABLE 2
Morphological and physical characteristics of soils from Quaternary limestone

Horizon	Depth (cm)	Color (moist)	Structure	Consistence		Rock fragments	Boundary	Sand*	Silt (%) ^a	Clay ^a	Bulk density (Mg/m ³)	Textural clas
				Dry	Wet							
Pedon 1 (Summit)												
Ap	0–26	10YR 2/1	vf & fsg	1	s & p	m	c	21	24	55	1.35	clay
C1	26–46	10YR 5/3	f & mwsbk	h	s & p	a	d	28	23	49	1.46	clay
C2	>46	10YR 6/3	f & mwsbk	h	s & p	a	d	43	11	46	NID	clay
Pedon 2 (Shoulder)												
Ap	0–17	10YR 2/1	f & msg	1	s & p	m	c	17	38	44	1.44	clay
C1	17–41	10YR 5/3	f & mwsbk	h	s & p	a	d	21	34	45	1.51	clay
C2	41–74	10YR 7/4	mwsbk	h	s & p	a	d	19	29	52	NID	clay
C3	>74	10YR 8/4	m & cwsbk	h	s & p	a	d	31	22	47	NID	clay
Pedon 3 (Upper backslope)												
Ap	0–15	10YR 2/1	f & msg	1	s & p	v	c	2	33	65	1.47	clay
C1	15–52	10YR 4/4	cwsbk	s	s & p	a	d	34	15	51	1.58	clay
C2	>52	10YR 6/6	vcwsbk	s	s & p	a	d	38	16	46	NID	clay
Pedon 4 (Middle backslope)												
Ap	0–12	10YR 2/1	f & msg	h	s & p	v	c	2	9	89	1.35	clay
Bw	12–43	10YR 4/3	m & cmsbk	h	s & p	v	c	1	9	90	1.42	clay
C	>43	10YR 5/3	c & vcwsbk	s	s & p	d	d	5	61	35	NID	silty clay loam
Pedon 5 (Lower backslope)												
Ah	0–15	10YR 2/1	f & mmsbk	h	s & p	v	c	2	9	89	1.26	clay
Bw1	15–44	10YR 3/4	mmsbk	h	s & p	n	d	<1	9	91	1.32	clay
Bw2	44–70	10YR 4/3	mmsbk	h	s & p	v	c	<1	11	89	1.34	clay
C	>70	10YR 5/3	m & cwsbk	s	s & p	d	d	2	72	26	NID	silty clay loam
Pedon 6 (Footslope)												
Ah	0–20	10YR 2/1	msg & sbk	h	s & p	v	c	<1	15	85	1.30	clay
Bw	20–35	10YR 3/2	mmsbk	h	s & p	c	c	<1	16	84	1.25	clay
C	35–70	10YR 5/3	m & cwsbk	s	s & p	a	c	1	46	53	NID	silty clay

ND indicates not determined data.
*Calculated on an organic matter- and calcium carbonate-free basis.
KEY TO ABBREVIATIONS (FAO, 1990).

Fig. 2. Particle size distribution and textural classes of each sampled horizon of the pedons studied based on the USDA textural triangle.

Fig. 3. Variations of solum depth of soils from Quaternary limestone. A, Along the slope from summit to footslope (range, 15–70 cm; mean, 34.7 cm; SD, 17.7; coefficient of variation, 50.9%; $n = 18$). B, Across the slope on a relatively level area in the middle backslope position (range, 15–80 cm; mean, 51.5 cm; SD, 18.5; coefficient of variation, 35.9%; $n = 21$).

the thinnest solum. On the other hand, the lower backslope and footslope positions, which are less subject to erosion and allow for more downward water movement and deposition of surficial materials coming from the upper slopes, showed the thickest solum. The influence of parent material on solum thickness is also evident. The soil on the upper slopes was derived from coralline limestone, whereas the soil on the lower slopes developed from marly limestone; marly limestone contains more fine particles (silt and clay) but slightly lesser calcium carbonate content than does coralline limestone. The higher fine particles content of marly limestone also helps explain the higher clay content of the soils derived from it. The long history of anthropogenic influence in the area may also have contributed to the thinness of solum, especially of the soils on the upper slopes because of enhanced erosion, mixing, and other soil processes. Kleber et al. (2003) have observed the significant role of human influence in changing and slowing down soil development.

The considerable differences in solum thickness at short distances across the slope can be due to the differential solubility of the limestone parent material, as can be observed on limestone outcrops in nearby areas. Soft portions of limestone dissolve easily, resulting in depressions that later become filled with soil (Legros, 1992). The further deepening of the depression, which usually leads to the formation of sinkholes, is enhanced because of the much faster dissolution of limestone when covered with soil than when bare (Urushibara-Yoshino et al., 1999). Such solum thickness variability of soils from limestone has important ecological implications. It helps explain the commonly observed differences in the growth of crops on limestone sites even in areas with uniform surface topography, as we have observed in our study site. Moreover, it may enhance the development of a diverse group of natural vegetation species and soil fauna (Anonymous, 1999).

The black color of the surface horizons with granular structure is related to their high OM content. A comparable soil color (10YR 3/2) was observed on the surface horizons of soils on reef terraces in Barbados (Muhs, 2001). The hard consistency when dry and the plastic and sticky consistency when wet suggests the presence of smectite silicate minerals in the clay fraction. Regarding the high clay contents of the soils, Muhs (2001) attributed the high clay content of the soils on limestone in Barbados

to have come from dust, volcanic ash, and detrital carbonate from the underlying reef limestone. Similarly, the very high clay content of these relatively young soils that we have studied may have been derived from the limestone rock and from eolian addition, particularly volcanic ash. If our estimate of the age of the terrace is correct, which is between 100 and 200 kyr B.P., it puts the origin of the terrace in the Pleistocene epoch, at which time major volcanic eruptions produced the widespread Pleistocene volcanic rocks in the nearby central highlands of Leyte (DENR, 1992; Asio, 1996). Moreover, the marly limestone in the lower part of the catena may have also derived much of its fine particles from volcanic ash.

Chemical Characteristics

Compared with the morphological and physical properties, less dramatic variations in soil chemical properties with landscape position can be seen in Table 3. All soils have high pH_{H_2O} (>7.2), with the general tendency to be slightly higher in the subsurface than in the surface horizons. As expected, pH in $CaCl_2$ is lower than pH_{H_2O} in all soils. OM and total N contents are high in the A horizons and then abruptly decrease with depth, whereas available P and extractable Fe, Mn, and B contents are low in all soils. Available P, exchangeable K and Mg, and extractable Fe contents tend to increase from the soils on the upper slopes to the lower slopes. Exchangeable Na content is low, whereas Ca content is very high as expected because of the presence of $CaCO_3$ in the solum. Thomas (1982) stated that no method is satisfactory for exchangeable Ca in the presence of free $CaCO_3$; hence, the values for Ca are not reflective of the amount of exchangeable Ca. Cation exchange capacity is high in all soils and seems to be higher in the soils in the lower portion of the profile (pedons 4, 5, and 6). $CaCO_3$ content is very high in all soils, particularly in the subsoils. Fine particles of $CaCO_3$ were observed in the A horizons, whereas a mixture of fine and coarse particles of $CaCO_3$ were observed in the lower horizons during the field examination.

The results suggest that most of the chemical properties of the soils from limestone evaluated are directly related to the nature of the limestone parent material. For instance, the neutral to strongly alkaline pH values are caused by the high amounts of $CaCO_3$ in the profiles, which, in turn, are inherited from the limestone rock.

TABLE 3
Chemical characteristics of soils from Quaternary limestone

Horizon	Depth (cm)	pH CaCl ₂	pH H ₂ O	OM (%)	Total N (%)	Avail P (mg/kg)	Exchangeable				Extractable				
							K cmol _c /kg	Mg (cmol _c /kg)	Na (cmol _c /kg)	Ca* (cmol _c /kg)	CEC (cmol _c /kg)	Fe (%)	Mn (%)	B (mg/kg)	CaCO ₃ (%)
Pedon 1 (Summit)															
Ap	0–26	7.6	8.7	8.4	0.41	1.49	0.19	1.49	0.05	89.2	38.4	1.37	0.04	0.63	29
C1	26–46	7.8	8.8	2.3	0.10	1.43	0	0.50	0	69.1	14.5	0.59	0.02	0.19	73
C2	>46	7.7	8.7	1.2	0.08	0.93	0	0.47	0	67.9	12.1	0.54	0.01	0.09	78
Pedon 2 (Shoulder)															
Ap	0–17	7.6	8.2	8.2	0.43	2.76	0.32	1.70	0.08	80.0	34.5	1.29	0.04	0.60	27
C1	17–41	7.8	8.5	1.4	0.08	1.02	0.02	0.52	0.04	72.1	19.2	0.64	0.02	0.10	71
C2	41–74	8.0	8.7	1.8	0.04	0.48	0	0.48	0	70.1	16.6	0.49	0.01	0.06	78
C3	>74	8.1	9.1	0.8	0.03	0.58	0	0.47	0.02	69.1	15.1	0.47	0.01	0.03	80
Pedon 3 (Upper backslope)															
Ap	0–15	7.7	8.1	7.1	0.40	2.33	0.67	1.86	0.02	69.3	38.7	2.14	0.08	0.73	22
C1	15–52	7.9	8.7	1.8	0.05	0.89	0.13	0.36	0.06	77.7	20.1	0.71	0.03	0	67
C2	>52	8.1	8.7	1.4	0.04	0.69	0.08	0.24	0	72.9	21.5	0.57	0.02	0.18	71
Pedon 4 (Middle backslope)															
Ap	0–12	6.4	7.5	9.3	0.44	1.59	0.75	3.34	0.03	54.4	50.2	2.17	0.07	0.51	24
Bw	12–43	7.0	7.8	5.2	0.20	0.50	0.44	1.78	0.07	57.7	60.0	1.53	0.06	0.41	28
C	>43	8.1	8.7	2.4	0.06	0.79	0.19	0.48	0.02	83.5	26.1	1.08	0.03	0.32	71
Pedon 5 (Lower backslope)															
Ah	0–15	5.9	7.1	10.0	0.44	2.24	0.61	4.42	0.17	49.4	40.6	2.54	0.08	0.58	30
Bw1	15–44	5.8	7.2	3.4	0.15	0.30	0.44	2.59	0.07	50.0	62.8	2.40	0.06	0.72	24
Bw2	44–74	6.6	7.3	2.2	0.12	0.56	0.5	2.06	0.06	53.7	65.3	2.11	0.07	0.66	46
C	>74	8.1	8.7	1.8	0.07	1.17	0.24	0.57	0.07	90.1	33.2	1.13	0.04	0.29	67
Pedon 6 (Footslope)															
Ah	0–20	7.4	7.5	6.7	0.40	4.89	2.25	7.11	0.06	55.9	53.4	2.27	0.06	0.71	29
Bw	20–35	7.7	8.0	3.3	0.18	2.63	0.47	1.45	0.11	55.0	54.7	2.17	0.06	0.97	31
C	35–70	7.8	8.6	2.0	0.13	1.31	0.43	0.67	0.06	84.6	40.5	1.85	0.05	0.66	68

*The method used extracts Ca from CaCO₃; thus, the values are not true exchangeable Ca.

The high pH values of the soils agree with the hypothesis that soil pH value does not drop below 7.0 in the presence of CaCO_3 because of its buffering capacity (Ulrich, 1986). Loeppert and Suarez (1996) likewise reported that the pH values of most calcareous soils are within the range 7.5 to 8.5. The high OM content of the surface horizons, which is associated with granular structure and dark color of the soil, is ascribable to the preservation of OM by high Ca (Legros, 1992). The low available P, extractable Fe, Mn, and B contents are due to the alkaline condition of the soil, which causes precipitation of these elements, and probably to the low inherent contents in these elements of the parent limestone rock. The tendency for K and Mg contents to increase from the summit to the footslope suggests possible downslope movement of these materials due to water movement (Sommer and Schlichting, 1997; Tsui et al., 2004). Hence, the sequence of soils we evaluated can be considered as a translocation catena, according to the classification of Sommer and Schlichting (1997). The low exchangeable Na content of the soils reflects the low amount of this element in the parent rock, but the slight tendency for it to be higher on the surface soil may be caused by salt spray from the sea. In his study in the nearby island of Samar, Navarrete (2002) observed much higher amounts of exchangeable Na in soils near the coast than in another comparable soil several kilometers inland. Yaalon (1983) has suggested the important role of salt spray in soil development for coastal areas. The high CEC is related to the high amount of clay of the soils. The occurrence of substantial amounts of fine particles of CaCO_3 in the solum contradicts the report of Legros (1992) and could be due to the mixing effect of frequent cultivation. We observed that coarse fragments of partially weathered limestone materials from the C horizon are brought, in many instances, into the soil surface after plowing with animal-drawn implements.

Soil Classification

According to Soil Taxonomy (Soil Survey Staff, 1999), the soil in the summit (pedon 1) is classified as Typic Calciudoll, implying that it has friable dark surface horizons due to high humus content but has, at the same time, high calcium carbonate content and is poorly developed. The soils in the shoulder and upper backslope positions (pedons 2 and 3) failed the soil depth requirement for the mollic epipedon,

although they also possess the other morphological features of the said diagnostic horizon. Thus, they are classified as Rendollic Eutrudepts, reflecting the free carbonates, which are more than 40%, in their solum. The soils on the middle backslope, lower backslope, and footslope (pedons 4, 5, and 6) are classified as Typic Eutrudepts. According to Soil Taxonomy (Soil Survey Staff, 1999), Eutrudepts are base-rich Udepts of humid areas developed in Holocene or Late Pleistocene deposits, some of which have steep slopes and calcareous parent materials. In the WRB (1998) classification system, the upper three soils are classified as Calcaric Phaeozems, whereas the lower three soils are Calcaric Cambisols. The differences in soil characteristics, primarily caused by the controlling effect of parent material and relief position, resulted in different soil taxa.

Soil Fertility

In view of the fact that soils from limestones are widely used for upland crop production in the Philippines, particularly for corn, root crops like sweet potato and cassava, coconut, and mango, we evaluated the fertility status of the five pedons by matching the values of selected soil properties with published threshold values of the same properties for crop growth or crop production (Tisdale et al., 1985; Landon, 1991; Schlichting et al., 1995). This matching process enables one to identify potential soil fertility constraints to the production of agricultural crops, and thus provides valuable information for the design of appropriate soil management strategies for the sustainable crop production, especially in problem soils such as in our study site. This is in accord with the suggestion that careful assessment of soil constraints is one of the priorities to sustain agricultural production in the tropics (Lal and Ragland, 1993; Lal, 2000).

Table 4 shows that the soils in different slope positions in the study site vary in their fertility characteristics on the basis of the presence or absence of soil fertility constraints. Shallow depth is a constraint in the soil in the upper slopes (pedons 1, 2, and 3), but not in the thicker soils in the lower portion. The clayey texture coupled by blocky structure that turns hard upon drying is a limitation for the soils on the lower slopes, but not for those on the upper slopes because of the good granular structure. The sticky and plastic consistency of the soils on the lower slope is a problem for farm operations

TABLE 4
Fertility constraints to crop production of soils from Quaternary limestone based on the properties of surface horizons*

Soil properties	Threshold pedon value [†]	Pedon					
		1	2	3	4	5	6
Depth (cm) [‡]	>50	—	—	—	+	+	+
Texture [§]	Medium	+	+	+	—	—	—
Bulk density (g/cm ³)	<1.45	+	+	+	+	+	+
Consistence	fr, np, ns	+	+	+	—	—	—
pH (water)	5.5–7.0	—	—	—	—	—	—
OM (%) [¶]	>3.0	+	+	+	+	+	+
Total N (%) [¶]	>0.2	+	+	+	+	+	+
Avail. P (mg/kg) [¶]	>8–15	—	—	—	—	—	—
Exch. K (cmol/kg) [¶]	>0.20	—	—	—	—	—	—
Exch. Ca (cmol/kg) [¶]	>0.40 [#]	—	—	—	—	—	—
Exch. Mg (cmol/kg) ^{**}	>0.50	+	+	+	+	+	+
Extr. Fe (mg/kg) ^{††}	>4.50	—	—	—	—	—	—
Extr. Mn (mg/kg) ^{††}	>0.50	—	—	—	—	—	—
Ext. B (mg/kg) ^{‡‡}	>1.00	—	—	—	—	—	—

Plus sign (+) indicates that soil property is favorable for crop growth; minus sign (—), soil property is a constraint to crop growth/crop production; fr, friable; np, nonplastic; ns, nonsticky.

*Except for depth, which considers solum thickness.

[†]It can also be called “favorable value or condition.”

[‡]Based on Schlichting et al. (1995).

[§]Based on Landon (1991). Clay texture with granular structure is favorable.

^{||}Based on Arshad et al. (1996).

[¶]Based on Landon (1991).

[#]Excessive levels (Ca:Mg ? 7:1) is a constraint (Tisdale et al., 1985).

^{**}Based on Haby et al. (1990).

^{††}Based on Martens and Lindsay (1990).

^{‡‡}Based on Johnson and Fixen (1990).

during dry periods and in the rainy season. This was confirmed by our observations and interviews with farmers in the area. Because of the high CaCO₃ content, the pH level is also a constraint, in addition to the deficiency of the mineral nutrients P, K, Fe, Mn, and B. Braschi et al. (2003) reported that the precipitation of insoluble Ca-P phases is the predominant process that reduces P availability to plants for calcareous soils with a large reservoir of exchangeable Ca. Our field observations of mango and coconut plants growing in the site revealed serious nutritional problems, with Fe deficiency being the most obvious, as indicated by chlorotic leaves. This was confirmed by our analysis of leaf samples of mango and coconut, which revealed Fe contents of 34 and 42 mg/kg, respectively. Both values are below the critical level of 50 to 150 mg/kg Fe in plants (Marschner, 1995). Mengel and Kirkby (2001) mentioned that high bicarbonate concentration from the dissolution of CaCO₃ in calcareous soils induces Fe chlorosis in plants growing in such soil. Srivastava and Gupta (1996) revealed that Mn is also tightly fixed on the surface of CaCO₃

particles by adsorption. Likewise, the presence of free CaCO₃ increases the retention of B but reduces its availability because of precipitation reaction. Excess Ca in the soil is also a constraint because when Ca/Mg ratio exceeds 7:1, Mg becomes deficient (Tisdale et al., 1985). Our analysis of leaf samples of mango and coconut indicated that these plants have Zn deficiency, as revealed by their Zn contents (10 and 9 mg/kg, respectively), which are below the critical level of 15 to 20 mg/kg (Marschner, 1995). Zn is deficient in calcareous soil because it is adsorbed on carbonates (Tisdale et al., 1985; Mengel and Kirkby, 2001).

The results indicate that most of the fertility constraints of the soils studied are directly or indirectly related to the nature and characteristics of the limestone parent material. Moreover, the results indicate that limestone soils in the landscape could vary in their fertility status because of variations in the characteristics of the parent material, slope position, and anthropogenic influence. Contrary to common notion, calcareous limestone soils also have physical fertility constraints (see Lal, 2000) aside from

the nutrient imbalances associated with the alkaline pH. Our results thus imply that agromomic and plant nutrition research, which focuses on only one or two deficient mineral nutrients in calcareous soils, as is commonly practiced, is too simplistic and will contribute little for the sustainable crop production in such soils. Soil management strategies should consider the physical and chemical characteristics and the site conditions. Lal (2000) stressed that soil management should be based on a holistic approach to solve practical problems.

CONCLUSIONS

From the results of this study, the following conclusions may be drawn:

The characteristics of the soils from Quaternary limestone vary with slope position. Those on the upper slopes (summit, shoulder, and upper backslope) have thin solum, black surface horizon, clayey texture, granular structure, high OM and N, high Ca and CaCO_3 contents, low contents of other nutrients like P, K, Fe, Mn, and B, and are neutral to alkaline pH values. Conversely, the soils on the lower slopes (footslope and middle and lower backslopes) have thicker solum and higher clay content subangular blocky structures that turn hard when dry and become plastic and sticky when wet. They also have neutral to strongly alkaline pH values, high OM, N, Ca, and CaCO_3 contents, and are also generally low in the content of nutrients, particularly P, K, Fe, Mn, and B. Most soils have high rock fragment contents in their profile.

The soils possess both physical and chemical constraints to crop production. The most important physical constraints are the shallow depth for the soils on the upper slopes and the plastic and sticky consistence for those on the lower slopes. The chemical constraints, such as the alkaline pH value, and the deficiencies of nutrients like P, K, Fe, Mn, B, and Zn, are directly related to the calcareous nature of the soils, which, in turn, is closely linked to the chemical characteristic of the limestone parent material.

The soils show substantial variations in solum depth at short distances along the slope (i.e., from summit to footslope) and across the slope, which are probably the effect of the slope position and the differential solubility

of the limestone. This solum depth variation has tremendous implication for the use and management of the soils.

The high clay content of the soils suggests a possible eolian contribution, particularly from volcanic ash, considering that the area is close to volcanic mountains. This is in addition to the contribution of the limestone parent material and deposition, particularly for the soils in the lower slopes.

Slope position, chemical characteristic of parent material, and anthropogenic influence (cultivation) seem to be the major factors that contributed to the differences in the characteristics and fertility status among the limestone soils studied.

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