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REVIEW

The Factors and Assumed Mechanisms of the Hardening of Red Soils and Yellow Soils in Subtropical Okinawa Island, Japan

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Abstract

Red soils and Yellow soils in Okinawa Island have the problem of severe hardening in dry conditions. It is important for the improvement and management of these soils to make the factors and mechanisms that affect the soil hardening clear. For this purpose, the properties and the degree of hardening of 43 topsoil samples in upland fields in the central area of Okinawa Island were determined. The results showed that the clay content and pH values were positively related to the degree of hardening. It is well known that clayey soils become very hard by air-drying because of the remarkable shrinkage, however, the pH-dependency of soil hardening has not been reported. Some investigations on the cause of the pH-dependency suggested that some physico-chemical conditions such as charge on the surface of soil particles in high-pH conditions, and the remarkable shrinkage of alkaline soils due to a large amount of calcium ions, enhance the hardening of these soils. The pH-dependency of hardening was also observed in the Red soils and Yellow soils in Kyushu Island, and this phenomenon probably occurs in soils with properties similar to the Red soils and Yellow soils in Okinawa, such as some Ultisols, Alfisols or Inceptisols in tropical, subtropical or temperate regions in the world.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: overliming, soil management, soil physics

Introduction

So-called Maji-soils are widely distributed in the Southwestern Islands, Japan. Maji-soils are divided into two types: the Red soils and Yellow soils called "Kunigami-Maji" that corresponds to Udults, Aquults, Udepts, or Aquepts, and the Dark Red soils called "Shimajiri-Maji" that corresponds to Udalfs, Udepts or Udolls in the USDA Soil Taxonomy[13]. These soils show problematic physical properties such as low water holding capacity, high erodibility and poor tilth. Especially, severe hardening of soil blocks under dry conditions causes a serious problem on tillage.

The degree of hardening of the Red soils and Yellow soils in Okinawa is remarkably varied among the soils[4], however, the cause of differences in hardening and a measuring method have not been known. It is important for the improvement of the agricultural productivity of the Red soils and Yellow soils to make the factors and mechanisms of hardening clear.

The degree of soil-hardening can be determined accurately and easily by an unconfined compression test using soil blocks that were shaped into small-size square prisms[3]. The objective of this paper is to show the degree of hardening of the Red soils and Yellow soils by this method to elucidate the factors that have influences on the degree of hardening and to make the mechanisms of hardening of these soils clear[4–7].

Materials and methods

The examined Red soils and Yellow soils were collected from 43 upland fields in Ginoza Village that is located in the central area of Okinawa Island (coordinates: 26º29´N and 127º59´E).

The climatic condition observed at Naha City, 40 km southwest from Ginoza, is as follows[9]. Mean annual temperature is 22.4ºC, the highest and lowest values of 28.3 and 16.0ºC are observed in July and January, respec-

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tively. Annual rainfall is 2,037 mm and in any month rainfall is greater than 100 mm.

Subsurface geology is diverse with limestone, sandstone, phyllite, and Kunigami gravels distributed in this area[2,8]. Therefore, the physical and chemical properties of the collected soils were expected to be various, reflecting the diversity of parent materials. The topography of the investigated area was coastal terraces ranging from about 20 to 50 m above sea level. The dominant soils in this area are Fine-textured Haplic Red soils, Fine-textured Mountain Yellow soils, Fine-textured Terrace Yellow soils, Skeletal Calcaric Dark Red soils, and Typic Calcaric Dark Red soils[11], according to the classification of cultivated soils in Japan[1]. Sugarcane is the dominant crop and vegetables, grass and flowers are also cultivated. Disturbed soils for the measurement of hardening and chemical analysis and 100 mL core samples for physical analysis were collected in 43 plots of these fields. Samples were collected from topsoil within the depth of 10 cm.

Degree of the hardening was measured by an unconfined compression test as follows. Disturbed soil samples were wetted by capillary action, and then shaped into prisms with a blade. This treatment was intended to simulate the hardening of plowed soils with air-drying after the wetting by rain. The size of a shaped sample was approximately 1 × 1 × 2 cm. The shaped samples were air-dried in an oven at 40ºC and the unconfined compression test was conducted. Accurate size of samples was measured by a vernier caliper before and after the drying in order to measure the shrinkage of the soils by air-drying. The physical and chemical properties of soils were measured by the methods as follows; ① particle size: pipette method and wet sieving, ② three phase: actual volumetric method, ③ water retention curve: pressure plate method, ④ pH: glass electrode by 1:2.5 extraction, ⑤ total carbon: dry combustion method, and ⑥ cation exchange capacity (CEC) and exchangeable cations: Schollenberger method. The clay mineral analysis by X-ray diffraction, detailed particle-size analysis by laser diffraction and micromorphology observation in thin sections were also conducted using selected samples.

Results and discussion

1. Factors that influence soil hardening

The degree of hardening (unconfined compressive strength in air-dried state), physical and chemical properties of the samples are shown in Table 1. The correlation coefficient between the strength of hardening and the physical and chemical properties are also shown in the lower column of Table 1.

Table 1. Degree of hardening, physical and chemical properties of the examined soils

Degree of hardening (MPa)		Hue		Value		Chroma		Clay (%)		Solid phase (%)		Bulk density (Mg m^{-3})	
class	n	class	n	class	n	class	n	class	n	class	n	class	n
<1	1	5YR	9	3.5–4.5	8	1–4	5	<30	5	<45	1	<1.2	2
1–2	9	7.5YR	23	5	29	6	23	30–40	14	45–50	13	1.2–1.3	8
2–3	14	10YR	11	6	6	8	15	40–50	10	50–55	9	1.3–1.4	7
3–4	11							50–60	9	>55	5	1.4–1.5	8
>4	8							>60	5			>1.5	3
r		0.269		–0.141		–0.257		**0.745***		–0.123		–0.313*	

Table 1. (continued)

Degree of hardening (MPa)		Total carbon (g kg^{-1})		pH (H_2O)		CEC ($cmol_c\ kg^{-1}$)		Exchangeable calcium ($cmol_c\ kg^{-1}$)		Base saturation (%)		Bray2-phosphate (Mg $P_2O_5\ kg^{-1}$)	
class	n	class	n	class	n	class	n	class	n	class	n	class	n
<1	1	<10	27	<5	11	<10	6	<5	15	<20	4	<100	1
1–2	9	10–20	14	5–6	7	10–15	25	5–10	11	20–50	10	100–500	12
2–3	14	>20	2	6–7	9	15–20	10	10–20	12	50–100	12	500–1,000	22
3–4	11			>7	16	>20	2	>20	5	>100	17	>1,000	8
>4	8												
r		0.314*		**0.486*****		**0.549*****		**0.415*****		0.252		0.004	

n : Number of the samples. r : Correlation coefficient between the degree of hardening and each property.
* Statistically significant at 5% level, *** 0.1% level.

If the degree of hardening of a soil becomes larger than 0.5 MPa, the ratio of harrowing by rotary tillers decreases. The degree of hardening was larger than this threshold in all samples, however, the value was various among the samples: the maximum was 6.4 MPa and the minimum was 0.6 MPa. Dominant soil color was 7.5YR 5/6 to 5/8, bright brown. Classification of cultivated soils in Japan[1] defines the Red soils and Yellow soils by color of subsurface soils as follows: if it is 5YR or redder in hue with a value of more than 3 and chroma of 3 or more, exclusive of value/chroma of 4/3 and 4/4, it is Red soil; and if it is more yellow than 5YR with a value of 3 or more and chroma of 6 or more, exclusive of value/chroma of 3/6 and 4/6, it is Yellow soil. According to these definitions, most of the examined soils were classified into Yellow soils. Particle size analysis showed that most samples were fine-textured, HC or LiC. Bulk density ranged from 1.2 to 1.5. Carbon content was smaller than 15 g kg^{-1} in most samples. The pH-values were various: the highest and the lowest values of pH (H_2O) were 8.1 and 3.9 respectively, reflecting the diversity of soil parent materials and soil management. Exchangeable calcium content was also various and showed a clear positive relationship to the pH values with correlation coefficient of 0.878 (statistically significant at 0.1% level). Other exchangeable cation contents were smaller than 3 $cmol_c$ kg^{-1}. CEC was in the range of 10 to 20 $cmol_c$ kg^{-1} and positively related to clay content with correlation coefficient of 0.639 (statistically significant at 0.1% level).

Among the physical and chemical properties, clay content, CEC, pH, and exchangeable calcium content showed an intimate (statistically significant at 0.1% level) positive relationship to the degree of hardening (Table 1). Fig. 1 shows the strong positive relationships among clay content, pH value and the degree of hardening. If the clay content is similar, soils with higher pH-values become harder than the lower pH soils. This tendency is especially remarkable in soils with large contents of clay.

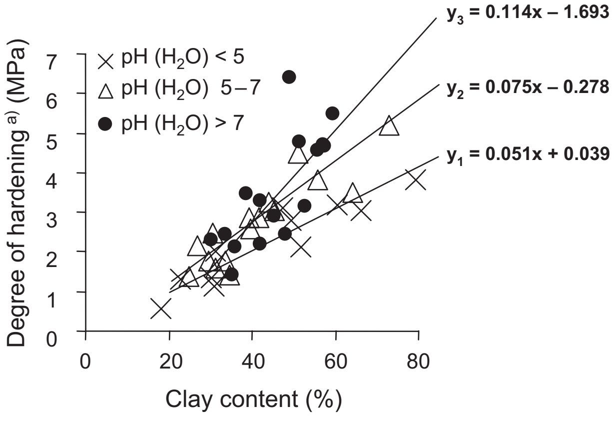

Fig. 1. Relationships among clay content, pH values and degree of soil hardening

a): Unconfined compressive strength of air-dried soil blocks.

2. The cause of pH-dependent soil hardening

It is well known that clayey soils, which commonly show high CEC values due to the large surface area of particles, become hard by air-drying. The remarkable hardening of clayey soils is attributed to the shrinkage caused by a capillary suction that works at the meniscus of soil water in fine pores during the air-drying process. The positive relationship between clay content and the degree of shrinkage of soil blocks (Fig. 2) indicates that the above-mentioned mechanism was the cause of strong hardening of fine-textured Red soils and Yellow soils.

Whereas, the cause of the strong hardening of high-pH soils (Fig. 3), which usually contain a large amount of

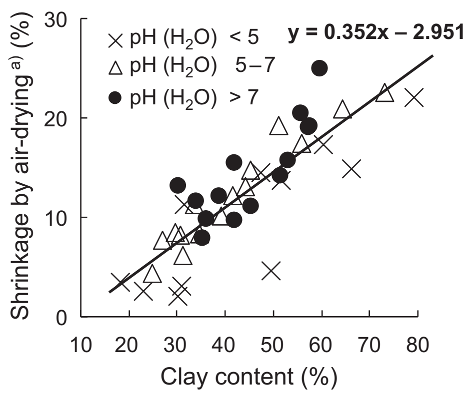

Fig. 2. Relationship between clay content and shrinkage of soil blocks by air-drying

a): Decrease of the volume of moist soil blocks by air-drying.

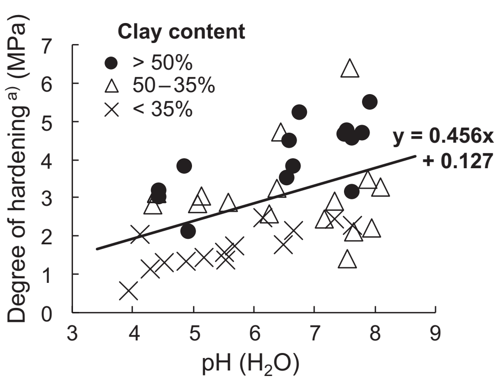

Fig. 3. Relationship between pH values and degree of soil hardening

a): Unconfined compressive strength of air-dried soil blocks.

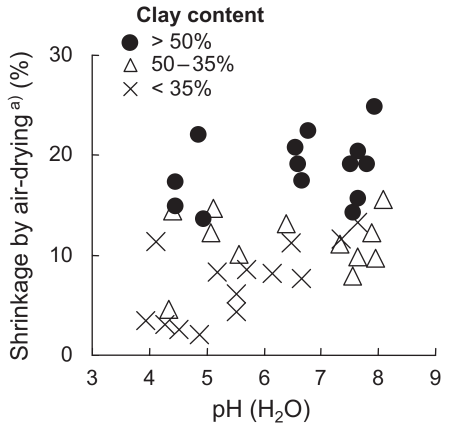

Fig. 4. Relationship between pH values and shrinkage of soil blocks by air-drying

a): Decrease of the volume of moist soil blocks by air-drying.

exchangeable calcium, was not clear. No significant relationship was observed between pH-values and the degree of shrinkage by air-drying of the studied soils (Fig. 4). Therefore the investigations on the cause of pH-dependent soil hardening were conducted based on the following four hypotheses.

① Clay mineral composition, which can influence soil physical properties, is different between the high-pH soils and low-pH soils.
② Subtle differences of particle size that could not be detected by a pipette method exist among the soils with different pH values.
③ A high-pH state itself enhances the hardening through some physico-chemical conditions on soil particles.
④ Abundant exchangeable calcium works as an enhancer of hardening.

(1) Clay mineral composition

X-ray diffraction analysis was conducted for 14 selected samples with pH (H_2O) values ranging from 4.3 to 7.9. The results (Fig. 5: representative charts of a

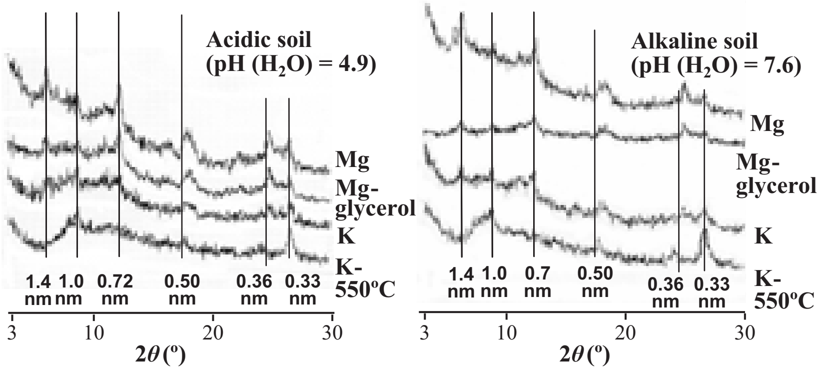

Fig. 5. XRD Charts of clay fraction

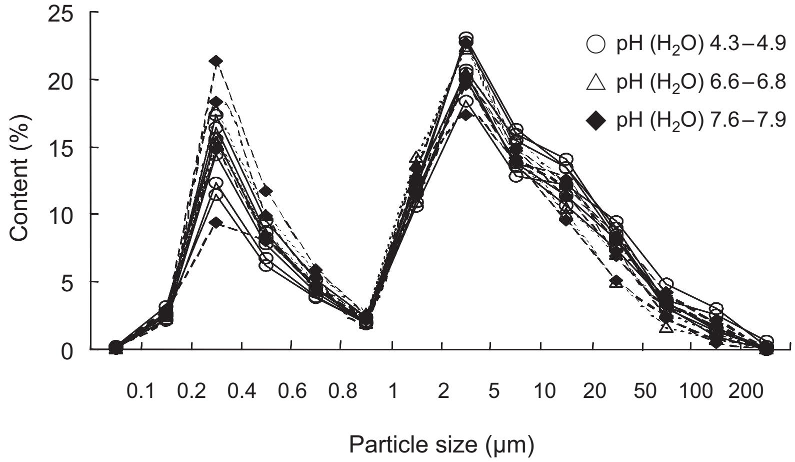

Fig. 6. Detailed particle size distribution determined by laser diffraction method

high-pH soil and a low-pH soil are shown) indicated that the dominant clay minerals were similar in all samples; i.e. 2:1-2:1:1 intergrade, illite and 0.7 nm kaolin minerals were dominant. Therefore, clay mineral composition is not the cause of pH-dependent soil hardening.

(2) Particle size distribution

Detailed particle-size distribution analysis by a laser diffraction analyzer was conducted for the same 14 samples used in X-ray diffraction. This analysis also showed similar patterns in all samples; i.e. bimodal distribution with peaks of 0.2 to 0.4 μm and 2 to 5 μm (Fig. 6). It means that the particle size distribution is not the cause of pH-dependent soil hardening, either.

(3) Effect of high-pH condition itself

Degree of hardening of an acidic soil, with pH (H_2O) value of 4.9, increased by the addition of an alkaline solution (sodium hydroxide) that raised soil pH (Fig. 7). The degree of hardening increased to 4.9 MPa when pH (H_2O) was raised to 7.8; in this state the degree of hardening exceeded that of an alkaline soil that showed a pH (H_2O) value of 7.6. The effect of hardening enhancement caused by this treatment, which raised both pH-value and exchangeable cation content, was larger than that caused by the addition of neutral salts such as calcium chloride shown below, which increased exchangeable cation content but did not raise pH-value. This result showed that the higher-pH condition itself increased the degree of hardening.

This treatment did not increase the degree of shrinkage of soil blocks by air-drying; therefore the enhancement of soil hardening in high-pH conditions is not related to the shrinkage. Furthermore, this treatment did not affect the micromorphological characteristics of the soil: both the treated and untreated soils showed vughy microstructure[12] with common vughs and a small amount of interconnected zigzag planes as shown in Fig. 8.

At this point, the author suggests that some physicochemical states, such as charge of the clay mineral surface under high-pH conditions, enhance the hardening through some structural change such as the three-dimensional arrangement of particles in clay flocs or the degree of dispersion. However, this hypothesis should be investigated by further studies.

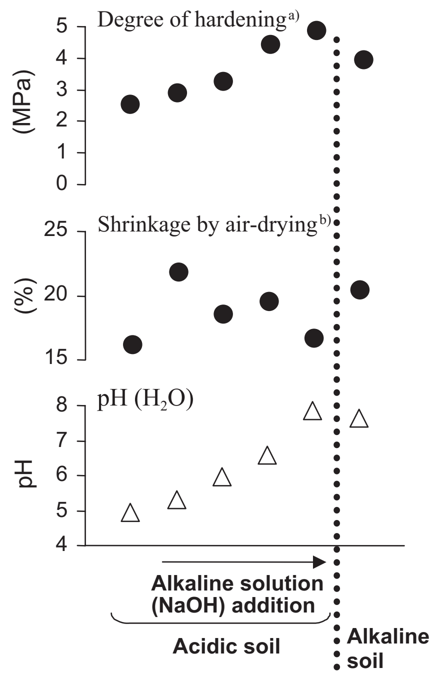

Fig. 7. Enhancement of hardening of an acidic soil by alkali-addition treatment

a): Unconfined compressive strength of air-dried soil blocks.

b): Volume of soil blocks in the moist state is 100%.

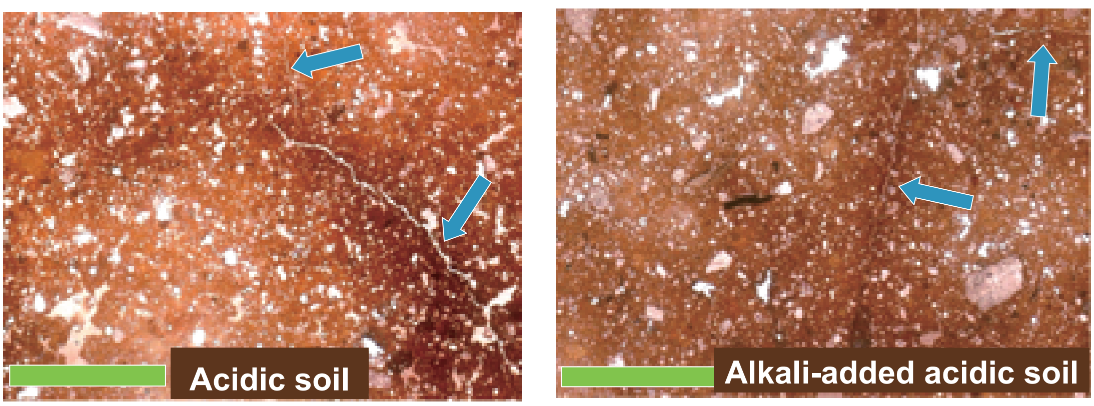

Fig. 8. Micromorphology

Bar: 5 mm. Arrow: Interconnected zigzag planes.

(4) Effect of calcium ion

The addition of the solution of calcium chloride, that increased the content of calcium ion in soils without raising pH-values, also increased the degree of hardening of the acidic soil (Fig. 9). In addition to the hardening, this treatment regularly enhanced a little the shrinkage of soil blocks by air-drying. This effect was not observed in the alkali-addition treatment. The enhancement of hardening accompanied with the increase of shrinkage occurred also in cases of the addition of other neutral salts such as magnesium chloride, potassium chloride or sodium chloride[4].

Watanabe and Ogawa[14] showed that the unconfined compressive strength of heavy clay soil in Hokkaido increased by lime application. They assumed that the calcium ion increased the amount of water bound among the clay particles, and therefore enhanced soil shrinkage by air-drying that caused a strong hardening. Nishimura and Toride[10] elucidated that gypsum application to Kunigami-Maji enhanced the formation of crust, which is the thin hard layer formed on the soil surface. Nishimura and Toride attributed this effect to the enhanced dispersion of aggregates as a result of the ion exchange from aluminum to calcium; this mechanism may also relate to the effect of calcium ion on the soil hardening shown above.

The enhancement of hardening shown in Fig. 9 was probably due to the processes suggested in these papers, however, the precise mechanisms should be investigated by further studies.

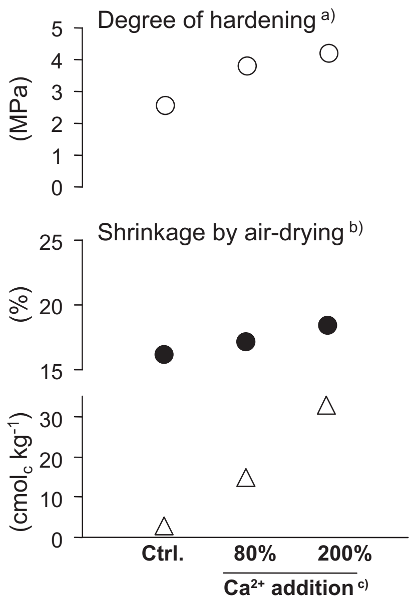

Fig. 9. Enhancement of hardening and shrinkage of an acidic soil by addition of calcium ion

a): Unconfined compressive strength of air-dried soil blocks.
b): Volume of soil blocks in the moist state is 100%.
c): Amounts of added Ca^{2+} was 80% and 200% of examined soil CEC.

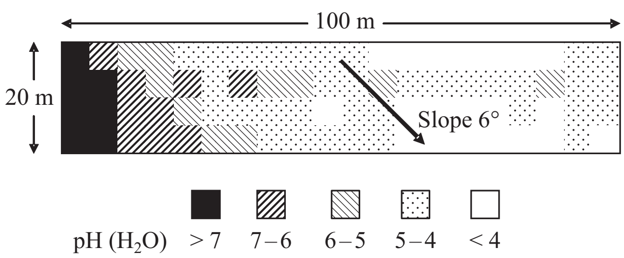

Fig. 10. Various soil pH values observed in a sugarcane field

3. A recommendation on soil management

As shown above, the pH-dependent hardening of the Red soils and Yellow soils by air-drying is not related to the native properties of soils such as clay mineral composition or particle size distribution. It may be due to the difference of some physico-chemical states of the surface of clay particles under different pH conditions. The chemical properties such as pH are easily changed; therefore, acidic soils will become very hard if the pH-value is artificially raised.

In the case of the study field, soils with various pH values have been generated from diverse parent materials. In addition, these soils have been artificially disturbed by land reclamation. As a result, the soil pH value of a plot and that of an adjacent one were often different to a large extent. In some cases, soil pH values ranged from strongly acidic to alkaline even in a narrow field, as shown in Fig. 10. It is difficult to maintain a suitable soil pH for cultivation in such areas. Interviews with the farmers revealed that some of them have applied lime to their fields with alkaline soils because of the misunderstanding; they believed that the fields were strongly acidic. This kind of inadequate soil management will cause not only the deficiency of micronutrients or enhancement of some soil diseases but also the problem of soil-hardening. Therefore, soil management based on a soil pH test, which should be conducted at a few different points in a plot, if possible, is strongly recommended for such areas.

In addition, a similar result was obtained in the Red soils and Yellow soils in Nagasaki Prefecture, western area of Kyushu Island with a warm temperate climate of 16.7ºC mean annual temperature, also. This kind of soil, i.e. Ultisols, Alfisols or Inceptisols with a large content of clay dominated by kaolin and non-expanding 2:1 or 2:1:1 minerals and a small amount of carbon, are widely distributed in tropical, subtropical and temperate areas all over the world. These soils may show the same property of pH-dependent hardening as the Red soils and Yellow soils in Okinawa and Nagasaki Prefectures, therefore the prevention of unsuitable soil-pH management such as overliming should be stressed in order to prevent soil hardening for all these soils.

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