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Comparison of Soil Taxonomy (2022) and WRB (2022) Systems for Classifying Paddy Soils with Different Drainage Grades in South Korea

Dan-Bi Lee [1,2], Young-Nam Kim [3,4], Yeon-Kyu Sonn [2] and Kye-Hoon Kim [1,*]

[1] Department of Environmental Horticulture, University of Seoul, Seoul 02504, Republic of Korea
[2] Division of Soil and Fertilizer, National Institute of Agricultural Science, Rural Development Administration, Wanju 55365, Republic of Korea
[3] Division of Applied Life Science (BK21), Gyeongsang National University, Jinju 52828, Republic of Korea
[4] Institute of Agriculture and Life Science (IALS), Gyeongsang National University, Jinju 52828, Republic of Korea
* Correspondence: johnkim@uos.ac.kr

Abstract: Soil classification is the systematic classification of soils based on distinguishing the characteristics of soil, aiding in understanding the properties of soils through soil survey and establishing appropriate strategies for effective soil utilization and management. Globally, the Soil Taxonomy (ST) and the World Reference Base for soil resources (WRB) are widely used for soil classification. However, the two classification systems have differences in criteria, thus exhibiting difficulties in exchanging classification results. In South Korea, soil classification has been steadily implemented to provide useful soil information to farmers for efficient soil management, contributing to the sustainability of paddy lands, but it has not been easy to establish an accurate classification system due to intensive soil management and variation in soil redox conditions. In this study, two paddy soils with different drainage grades, pedon 1 and pedon 2, were classified using the ST and WRB, and based on the comparative results, a classification criterion for paddy soil in Korea was recommended. According to ST, pedon 1 was classified as a coarse loamy, mesic family (the mean annual soil temperature, 11–14 °C) of Anthroaquic Eutrudepts (artificially irrigated, base saturation > 60%), whereas pedon 2 was a coarse loamy, mesic family of Fluvaquentic Endoaquepts (organic carbon content > 0.2%, water-saturated across the soil profile). Based on the WRB, the two soils were categorized as follows: Stagnic Hydragric Anthrosols (Eutric, Loamic, Oxyaquic) (saturated with surface water, subsurface horizon that is wet-field and human-affected) for pedon 1 and Stagnic Gleyic Hydragric Anthrosols (Eutric, Loamic, Oxyaquic) (saturated with surface and ground water, subsurface horizon that is wet-field and human-affected) for pedon 2. Overall, the two classification systems categorized these pedons consistently by judging the soil properties according to depth, but there was a difference in layer classification upon saturation by water across the soil horizons. Poor soil drainage hinders rice growth in paddies due to lowering soil and water temperature and the occurrence of harmful reduction products. In this regard, we proposed a draft of the classification criteria specialized for paddy soils in Korea based on drainage grades. This will contribute to sustainable paddy soil management by accurately classifying paddy soils and providing better soil information to farmers.

Keywords: soil classification; rice field; soil characteristics; artificial hydromorphism; agricultural sustainability

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Citation: Lee, D.-B.; Kim, Y.-N.; Sonn, Y.-K.; Kim, K.-H. Comparison of Soil Taxonomy (2022) and WRB (2022) Systems for Classifying Paddy Soils with Different Drainage Grades in South Korea. *Land* **2023**, *12*, 1204. https://doi.org/10.3390/land12061204

Academic Editors: Marco Criado, Antonio Miguel Martínez-Graña and Leticia Merchan

Received: 13 May 2023
Revised: 1 June 2023
Accepted: 8 June 2023
Published: 9 June 2023

1. Introduction

Soil investigation is generally performed through filed observation and laboratory analysis. This involves cataloging soil characteristics, such as topography, stoniness, texture, degree of drainage and erosion, parent materials, soil moisture, pH, salinity, soil color, etc., as well as studying their spatial distribution in the landscape [1,2]. Soils can be categorized into similar types for soil classification, and each soil type exhibits unique characteristics related to physics, chemistry, biology, and mineralogy. The information obtained through soil investigation allows farmers to better understand the overall characteristics of agricultural soils, which is helpful in determining the quality and suitability of soils for farming practices. Additionally, it establishes appropriate strategies for effective soil utilization and management, such as fertilization, organic amendment input, pest control, and pollutant remediation, consequently improving soil fertility and crop yield [1]. In general, based on the soil survey laboratory methods manual of USDA [3], soil investigation is performed through a process that involves visually inspecting the characteristics of the soil profile and field site (e.g., terrain, slope, drainage, soil color, structure, mottle, horizon boundaries, stickiness, plasticity, plant root system, etc.), determining the properties of the soil (e.g., pH, soil organic matter, base saturation, cation exchange capacity, extractable bases, particle size distribution, etc.), and organizing these results to create a soil map [4]. Subsequently, for various land use purposes, the assembled data and the created soil map can be used by scientists or land owners to predict and evaluate the suitability, limitation, and potential of soil behavior [5,6] that are the key consideration for successful agricultural activities. Moreover, the collected soil samples and related databases via the soil survey are of great importance for the conservation of soil resources, as well as further application in estimating soil carbon stock, water capacity, and soil loss [7], thereby contributing to sustainable agriculture.

Soil classification is performed using a soil profile description through visual observation and determining the physicochemical characteristics of each soil layer [3,4]. Soil classification is aimed at clearly understanding the characteristics of soil and helping soil management through soil commentary; therefore, an accurate investigation and classification of the soil are essential. Although many countries manage soil by creating a separate classification system suitable for the characteristics of soil in their country, Soil Taxonomy (ST) [8] and the World Reference Base for Soil Resources (WRB) [9] are the most used soil classification systems worldwide [10]. ST is a soil classification system developed by the United States Department of Agriculture (USDA), which classifies into 12 orders by considering the physical, chemical, and biological characteristics of soil [8]. On the other hand, the WRB is developed by the Food and Agriculture Organization of the United Nations (FAO) and classified into 32 reference soil groups (RSGs) according to the soil environment and soil formation process [9]. These two classification systems are useful for classifying soil by determining soil characteristics by depth [11]. However, due to differences in the classification criteria, diagnostic horizons, and layer naming, it is difficult to implement mutual studies between the ST and WRB systems [12]. For the WRB, in particular, it is not a hierarchical taxonomy, and each major taxon does not overlap with each other. As if reflecting this, some studies suggested that the WRB classification system is more flexible to demonstrate the soil conditions, such as soil depth limitation for plant growth, salinity, and contamination [10,13].

In South Korea, soil surveys had been carried out in detail throughout the country, and based on the survey results, the Taxonomical Classification of Korean Soils was published in 2000 [14]. Then, the Rural Development Administration (RDA) developed a soil information system using soil database and soil maps accumulated over 40 years of soil surveys across the country, which was digitized and provided to the public online in 2006 [7]. Currently, RDA soil researchers are performing to rework soil classification according to the updated ST and WRB systems, in order to publicize soil classification information globally [2,4,12]. Nevertheless, with the lack of existing classification data and the recent changes in land use and consumption, vegetation, and climate, it is not possible to satisfy most of the classification criteria that conform to the current ST and WRB systems [2,15]. Therefore, through the development of customized classification systems, soil scientists and land managers can better understand the characteristics of their own soils and also ensure the effectiveness of soil management practices such as agriculture, forestry, land development, and environmental conservation.

Paddies throughout South Korea account for approximately 46% of the total agricultural area [16] and are distributed mainly in fluvio-marine, alluvial plain, valley, and alluvial fan areas. Additionally, most of them are soils with alluvial or colluvial deposits as parent material [2]. However, there are many practical difficulties in developing soil classification systems, particularly for soils of rice fields, because they are distributed over a large area with different soil formation characteristics and topography. Moreover, the difference in water saturation across the soil profile is an additional factor that introduces difficulties in the soil classification of paddy lands. In particular, the criteria of ST mainly used in Korea is thought to be inappropriate for paddy soil classification due to it not distinguishing the impacts of flooding conditions caused by irrigation and the groundwater level on the characteristics of the soil profile. Therefore, this study was performed to establish a paddy soil classification system suitable for Korea. For this, we selected two paddy soils of different regions with different drainage grades, and classified the soils using the ST and WRB systems. Then, the comparative information obtained from the present study was reviewed to propose a classification method for paddy soil in Korea.

2. Materials and Methods

2.1. Study Site

The soil used for classification is paddy soil distributed in Korea, and the two representative pedons located in Gyeongsangbuk-do were selected (Figure 1). Pedon 1 was located in Oksu-dong, Heungpyeong-ri, Guseong-myeon, and Gimcheon-si (128°3′33.7′′ E, 36°3′52.5′′ N), and characterized as a sandy loam with a moderately well drainage grade. Pedon 2 was a coarse loamy soil at a very poorly drained grade, located in Muju-ri, Yonggung-myeon, and Yecheon-gun (128°18′42.9′′ E, 36°36′40.0′′ N). The average annual temperature (11–14 °C) and precipitation (1032–1291 mm) of the two regions are similar.

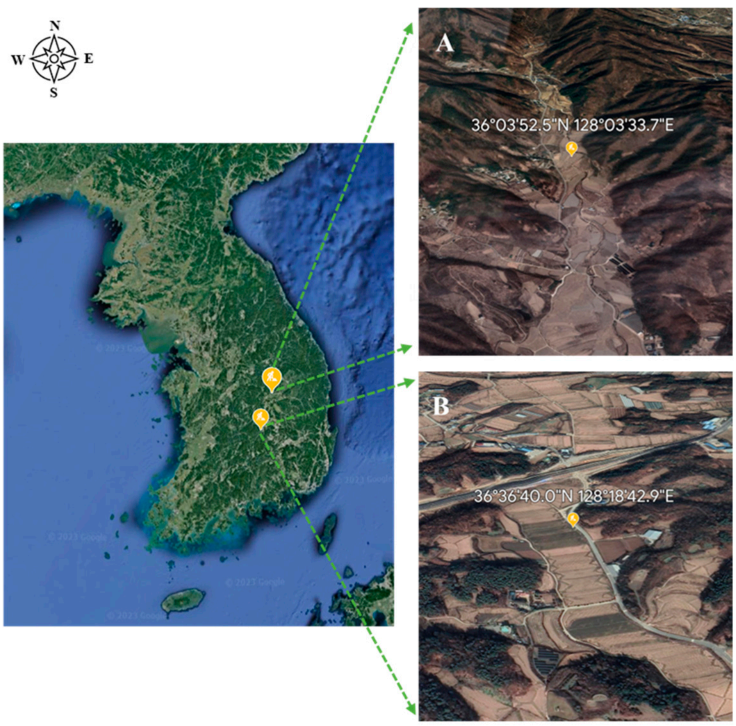

Figure 1. Study area with locations of the soil survey sites: pedon 1 (**A**) and pedon 2 (**B**).

2.2. Soil Survey and Properties

For the soil classification, data on field survey and physicochemical properties of the two pedons were obtained from the Taxonomical Classification of Korean Soils (2014), published by the RDA [17]. The fieldwork was conducted according to the Soil Survey

Manual [18], which is the standard survey method for soil taxonomy. Through the field survey, the soil color, texture, and structure of the pedons were identified, and based on the survey results, the soil horizon of each pedon was classified. Then, the soil of each layer was collected, air-dried, and sieved by passing through a 2 mm sieve before analyzing the properties of the soil. Soil analysis was conducted according to the soil survey laboratory methods manual prescribed in the Soil Survey Investigation Report (SSIR) No. 42 Version 4.0, which is the standard analytical method for application in Soil Taxonomy classification [3]. Twenty grams of the sampled soil was mixed with 20 mL of reverse-osmosis water (1:1 = w:v), with occasional stirring for 1 h, and the suspension pH was measured. To calculate the total carbon per unit area, soil organic carbon was quantified by the $FeSO_4$ titration method and then this weight percentage was converted to volume percentage. After that, each value was calculated by multiplying the bulk density Dbm (m is usually 1/3 bar or 30 cm) and the thickness (in inches) of the corresponding horizon. Soil texture was analyzed with a pipet method after removing organic matter (OM) using hydrogen peroxide (H_2O_2) and dispersing with sodium hexametaphosphate $(NaPO_3)_6$. The exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ were extracted with a 1 N NH_4OAc (pH 7.0) solution. The cation exchange capacity (CEC) was measured by saturating the soil with 1 N NH_4OAc (pH 7.0), removing excess NH_4^+ with ethanol, and distilling. The effective CEC was calculated by adding extractable acidity to the sum of the NH_4OAc extractable base. The base saturation was (BS) calculated as follows: (total NH_4OAc-extractable bases/CEC) $\times$ 100%. The physical and chemical properties of the soils are represented in Tables 1 and 2, respectively.

Table 1. Chemical properties of the two pedons by soil horizon.

	Depth (cm)	pH †		Organic Carbon	NH_4OAc Extractable Bases					
		H₂O	KCl ‡	(g kg^{-1})	Ca^{2+} (cmol kg^{-1})	Mg^{2+} (cmol kg^{-1})	K^+ (cmol kg^{-1})	Na^+ (cmol kg^{-1})	CEC § (cmol kg^{-1})	BS ¶ (%)
Pedon 1	0–20	5.8	4.6	1.12	4.3	0.6	0.6	0.1	7.3	77.4
	20–49	6.4	5.0	0.64	5.2	1.0	0.6	0.1	7.5	91.7
	49–76	7.0	5.1	0.10	3.5	1.0	0.6	0.1	5.3	96.0
	76–160	7.0	5.0	0.08	2.9	0.9	0.1	0.1	4.6	86.5
Pedon 2	0–19	7.7	6.3	0.70	6.7	1.6	0.1	0.2	8.3	100
	19–36	8.1	6.1	0.27	7.2	1.8	0.1	0.2	7.7	100
	36–72	6.1	4.3	0.39	5.3	1.5	0.2	0.2	8.4	86.8
	72–150	5.9	4.1	0.25	3.5	1.5	0.1	0.1	7.9	66.7

† Saturated paste extract; ‡ 0.1 M KCl; § Cation exchange capacity; ¶ Base saturation.

2.3. Soil Classification System

Soil classification was performed according to the criteria of the ST and WRB systems, using data on the field survey and physicochemical properties. The ST is a hierarchical taxonomy with six categorical levels as follows: order, suborder, great group, subgroup, family, and series [8]. There are a total of 12 orders, with the top hierarchical level that further applies the soil properties, including depth, moisture, temperature, texture, structure, OM content, cation exchange capacity, salt content, base saturation, and clay mineralogy [8]. Table 3 shows the detailed information on 12 orders in ST. On the other hand, the WRB classification system is performed in the order of the diagnostic horizon, diagnostic properties and diagnostic materials, and the field measurement and observation of soil characteristics considering the soil formation process are required. This classification system is categorized into two levels: reference soil groups (RSGs) and soil units [9]. In the first level, there are 32 RSGs that are categorized by reflecting similar pedogenesis, parent material formation, or major ecological regions (Table 4). An RSG is selected as a major characteristic for the generation and development of soil. Afterwards, in the second level, 185 qualifiers are selected based on the properties of soil physics, chemistry, biology, and mineralogy, which are defined and divided into two groups, i.e., principal and supplementary qualifiers. For naming the soil, a set of qualifiers was combined with RSG; the principal qualifiers are listed from right to left in order of importance before the RSG, and the supplementary qualifiers are listed alphabetically in parentheses after the RSG. The WRB soil classification system [9], which was a newly revised fourth edition at the World Congress of Soil Science 2022 in Glasgow, was used in this study. The principal qualifiers represent the main characteristics that determine the RSG, so they are major factors in evaluating soil formation and development process. In the revised WRB [9], changes in the classification wording criteria, such as the movement of 'gleyic' and 'stagnic' related to soil water saturation from supplementary to principal qualifiers, was applied to the present study.

Table 2. Physical properties of the two pedons by soil horizon.

	Depth (cm)	Particle Size Distribution (mm)			Sand Fraction (mm)				
		Clay (<0.002)	Silt (0.002–0.05)	Sand (0.05–2.0)	Very Fine (0.05–0.10)	Fine (0.10–0.25)	Medium (0.25–0.50)	Coarse (0.50–1.00)	Very Coarse (1.00–2.00)
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Pedon 1	0–20	10.5	21.6	67.8	6.0	13.1	14.8	20.1	13.9
	20–49	10.8	20.1	69.1	5.0	10.8	15.6	21.8	16.1
	49–76	10.4	17.6	72.0	5.8	12.5	16.0	22.9	14.9
	76–160	7.6	19.0	73.4	6.2	13.7	14.6	21.9	17.0
Pedon 2	0–19	12.1	24.0	63.8	5.6	10.8	11.0	17.4	19.0
	19–36	11.9	24.0	64.1	5.8	10.4	11.6	18.6	17.7
	36–72	15.7	27.0	57.3	6.2	10.4	10.8	15.7	14.2
	72–150	18.1	29.9	52.0	5.4	9.7	9.6	14.6	12.7

Table 3. Twelve soil orders, with the top hierarchical level, in the USDA Soil Taxonomy [8].

Soil Order	Major Criterion	Code
Gelisols	Cold, permafrost	GEL
Histosols	Organic soil materials	HIS
Spodosols	Spodic horizon, forest, low BS%	SPO
Andisols	Volcanic ash materials	AND
Oxisols	Oxic horizon, highly weathered	OXI
Vertiesols	Dominance of swelling clays	VER
Aridisols	Soils of arid areas	ARI
Ultisols	Argillic horizon, low BS%, forest	ULT
Mollisols	Dark, grassy, high OM and BS%	MOL
Alfisols	Diagnostic horizon, medium BS%, forest	ALF
Inceptisols	Few diagnostic horizons	INC
Entisols	No genetic horizons	ENT

Table 4. Thirty-two reference soil groups (RSGs) in the WRB soil classification system [9].

RSG	Major Criterion	Code
Histosols	Soils with thick organic layers	HS
Anthrosols	With long and intensive agricultural use	AT
Technosols	Containing significant amounts of artefacts	TC
Cryosols	Permafrost-affected	CR
Leptosols	Thin or with many coarse fragments	LP
Solonetz	With a high content of exchangeable Na	SN
Vertisols	Alternating wet-dry conditions, shrink-swell clay minerals	VR
Solonchaks	High concentration of soluble salts	SC
Gleysols	Groundwater-affected, underwater or in tidal areas	GL
Andosols	Allophanes and/or Al-humus complexes	AN

Table 4. *Cont.*

RSG	Major Criterion	Code
Podzols	Subsoil accumulation of humus and/or oxides	PZ
Plinthosols	Accumulation and redistribution of Fe	PT
Planosols	Stagnant water, abrupt textural difference	PL
Stagnosols	Stagnant water, structural difference and/or moderate textural difference	ST
Nitisols	Low-activity clays, P fixation, many Fe oxides, strongly structured	NT
Ferralsols	Dominance of kaolinite and oxides	FR
Chernozems	Very dark topsoil, secondary carbonates	CH
Kastanozems	Dark topsoil, secondary carbonates	KS
Phaeozems	Dark topsoil, no secondary carbonates (unless very deep), high base status	PH
Umbrisols	Dark topsoil, low base status	UM
Durisols	Accumulation of, and cementation by, secondary silica	DU
Gypsisols	Accumulation of secondary gypsum	GY
Calcisols	Accumulation of secondary carbonates	CL
Retisols	Interfingering of course-textured, lighter-colored material into a finer-textured, stronger colored layer	RT
Acrisols	Low-activity clays, low base status	AC
Lixisols	Low-activity clays, high base status	LX
Alisols	High-activity clays, low base status	AL
Luvisols	High-activity clays, high base status	LV
Cambisols	Moderately developed	CM
Fluvisols	Stratified fluviatile, marine, or lacustrine sediments	FL
Arenosols	Sandy	AR
Regosols	No significant profile development	RG

3. Results and Discussion

3.1. Description of the Two Paddy Soil Characteristics

The geographical properties of the two pedons used in this study are shown in Table 5. Pedon 1 was a paddy soil developed in a narrow valley with a slope of 7–15%, and the topsoil was saturated with irrigation water for more than 90 days of the year. The soil moisture regime was udic and anthraquic according to ST and WRB, respectively. Since the average annual temperature (AAT) in the area of pedon 1 was 13.4 °C, the soil temperature regime was classified as mesic when the AAT was under 15 °C and the temperature difference between summer and winter was more than 5 °C. Pedon 1 parent material was alluvium–colluvium from granite, and the surface and subsurface soils were categorized as follows: ochric epipedon (0–20 cm) and cambic horizon (49–76 cm), respectively, by ST, and anthraquic (0–49 cm) and hydragric (49–76 cm) horizons, respectively, by WRB.

Table 6 presents the morphological properties of pedon 1 by horizon. The soil profile was developed in four layers and classified by being named Ap, Bag, Bw, and BC, from the topsoil to the bottom (Figure 2A). The topsoil layer (Ap) has been currently used as agricultural land, so the suffix ‘p’ (plow) was added to the soil name A (eluvial horizon). The Ap layer (0–20 cm) was a dark gray 10YR 4/1, sandy loam that is structureless, slightly sticky, and slightly plastic. The soil color of the second layer (20–49 cm) was dark gray (10YR 4/1) and the soil texture was loam. There was a 2–20% distribution of small, clear, and brown (7.5YR 4/3) mottle on the surface, with a weak and platy structure. Like the Ap layer, it was slightly sticky and plastic, with fine gaps and few roots. Thus, the second layer was named Bag, which is a transitional layer formed between the eluvial horizon (A) and the accumulation layer (B) relatively more dominant. Additionally, this layer was in a reduced state, thus, the suffix ‘g’ was added. Herein, the use of the suffix ‘g’ is somewhat different between the ST and WRB systems. Soil Taxonomy categorizes the suffix for soil reduced by water as ‘g’ (strong gley), whereas the WRB subdivides it into ‘g’ (stagnic condition), ‘l’ (capillary water), and ‘r’ (strong reduction) [19]. The third layer, Bw (49–76 cm), represented a weakly developed (w) accumulation layer (B). This layer was a brown (7.5YR 4/3) sandy loam, with prominent dark brown (7.5YR 3/3) mottles and a weak platy structure. It also had low stickiness and plasticity. The final layer was

BC (76–160 cm), a transition layer that has features of both the accumulation layer (B) and parent material (C). It was a brown (7.5YR 4/3) sandy loam with distinct dark brown (5YR 3/4) mottles. It was non-sticky and had a weak subangular blocky structure and pores small in both size and quantity.

Table 5. Geographical properties of the two pedons used in this study.

Site	Classification System	Slope (%)	Soil Moisture Regime	Soil Temperature Regime	Parent Material	Diagnostic Feature (by Horizon)
Pedon 1	ST	7–15	Udic	Mesic	Alluvium–colluvium from granite	• 0–20 cm †: ochric epipedon • 49–76 cm ‡: cambic horizon
	WRB		Anthraquic			• 0–49 cm †: anthraquic horizon • 49–76 cm ‡: hydragric horizon
Pedon 2	ST	2–7	Aquic	Mesic	Local alluvium from granite	• 0–19 cm †: ochric epipedon • 36–72 cm ‡: cambic horizon
	WRB					• 0–36 cm †: anthraquic horizon • 36–72 cm ‡: hydragric horizon

ST, soil taxonomy; WRB, the World Reference Base for soil resources. † Surface horizon; ‡ Subsurface horizon.

As a result of examining the characteristics of pedon 2 soil profile, it was a paddy soil formed in a narrow valley with a slope of 2–7% and very poor drainage. Since it was saturated by water, the soil moisture regime was classified as aquic. In addition, the soil temperature regime (AAT: 14.1 °C) of the pedon 2 area was classified as mesic. Pedon 2 parent material was local alluvium from granite, and the surface and subsurface soils were categorized as follows: ochric epipedon (0–19 cm) and cambic horizon (36–72 cm), respectively, by ST, and anthraquic (36–72 cm) and hydragric (49–76 cm) horizons, respectively, by WRB. Pedon 2 consisted of four layers, as shown in Figure 2B. The first layer was the topsoil layer (Ap) formed between 0 and 19 cm depths. It was a dark grayish brown (2.5Y 4/2) sandy loam with no structure, slightly sticky, and low plastic (Table 6). The second layer (BAg) had dark olive–gray-colored soil, and the soil texture was sandy loam. The brown (7.5YR 4/4) mottle with marked definition was distributed over 20% of the surface and had a weak prismatic structure. It was slightly sticky and plastic, with few pores and roots. The third layer (49–76 cm) was a black (5Y 2.5/1) sandy loam with some clear olive brown (2.5Y 4/3) mottles. It was also an accumulation layer (B horizon) weakly developed (w) as a somewhat angular blocky structure. The final level (76–150 cm) was classified as BC, a transition layer that has features of both B and C (parent material) horizons, and had a brown sandy loam with distinct dark reddish brown (5YR 3/4) mottles. It had a weak subangular blocky structure, as well as poor adhesion and plasticity. Unlike pedon 1, the third layer name is Bg according to ST, because it has been reduced by the influence of the groundwater level rather than irrigation [19]. Meanwhile, WRB classifies this layer as Bl with the suffix 'l' that represents a layer reduced by the groundwater level. The final one (72–160 cm) was a layer of the parent material and was a black (5YR 2.5/1) sandy loam, with light olive brown (2.5Y 4/4) mottles. It had no structure, moderate stickiness, and strong plasticity. Since the layer was saturated by groundwater, the layer was named Cg according to ST, while WRB was Cl (Figure 2B).

Table 6. Twelve soil orders, with the top hierarchical level, in the USDA Soil Taxonomy [8].

	Depth (cm)	Horizon		Color		Structure		Boundary	Sticky	Plastic
		ST	**WRB**	**Main**	**Mottle**	**Shape**	**Grade**			
Pedon 1	0–20	Ap	Ap	10YR 4/1	10YR 4/4	Massive	Structureless	Clear	Slightly Sticky	Slightly plastic
	20–49	BAg	BAg	10YR 4/2	7.5YR 4/3	Platy	Weak	Clear	Slightly Sticky	Slightly plastic
	49–76	Bw	Bw	7.5YR 4/3	7.5YR 3/3	Platy	Weak	Gradual	Slightly Sticky	Slightly plastic
	76–160	BC	BC	7.5YR 4/3	5YR 4/3	Subangular blocky	weak	-	Non	Non
Pedon 2	0–19	Ap	Ap	2.5Y 4/2	-	Massive	Structureless	Clear	Slightly Sticky	Slightly plastic
	19–36	BAg	BAg	5Y 4/2	7.5YR 4/4	Prismatic	Weak	Abrupt	Slightly Sticky	Slightly plastic
	36–72	Bg	Bl	5Y 2.5/1	2.5Y 4/3	Subangular blocky	Weak	Diffuse	Slightly Sticky	Slightly plastic
	72–150	Cg	Cl	5Y 2.5/1	2.5Y 4/4	Massive	Structureless	-	Slightly Sticky	Very plastic

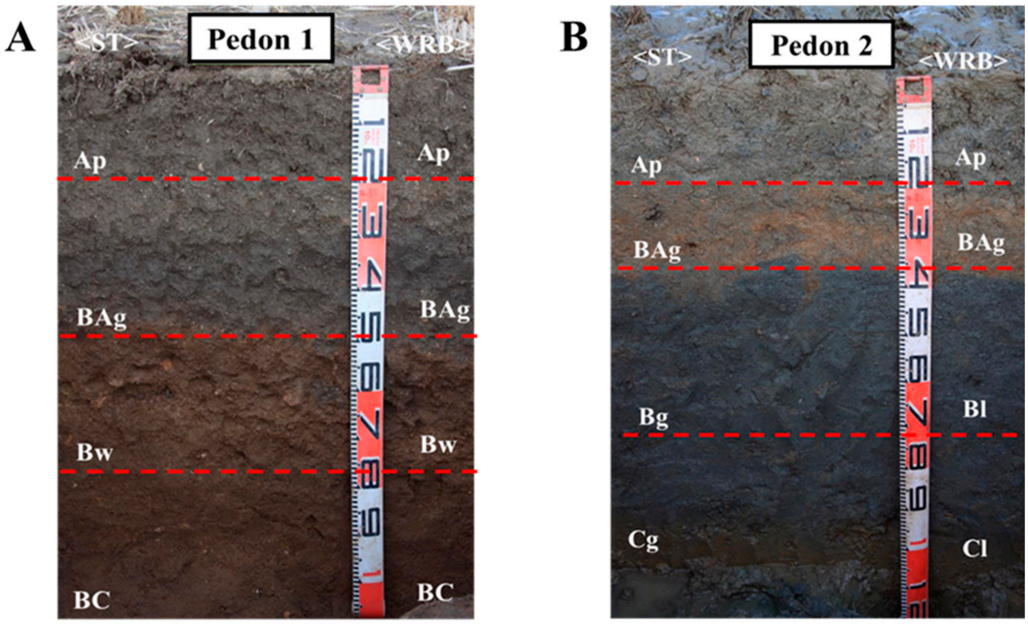

Figure 2. Classification of soil horizon for pedon 1 (**A**) and pedon 2 (**B**) according to the ST and WRB systems.

As such, it was demonstrated that there are some differences between the two classification systems, ST and WRB, in assigning the layer names. WRB made it especially possible to classify paddies more precisely according to the factors causing the water saturation across the soil profile, using different suffixes [19]. Although this study compared only two pedons of the rice field, considering the situation in which the paddies are distributed in diverse terrains throughout Korea, it is necessary to develop a soil classification system suitable for the Korean environment by taking advantage of ST and WRB, and further conducting accurate soil surveys on more paddy soils.

3.2. Soil Classification with the ST System

Figure 3 shows the soil classification for two paddy soils based on the ST system. According to the soil orders as the highest level of the soil classification system, pedon 1 was classified as Inceptisols based on the cambic horizon (Figure 3A), a subsurface layer of pedogenic change without visible illuviated materials, and seasonal high-water table within 100 cm depth [20,21]. Inceptisols consist of six suborders categorized depending on the temperature and moisture regimes: Aquepts (aquic; a water table at or near the surface for many years), Gelepts (gelic; very cold climates), Cryepts (cryic; cold climates), Ustepts (ustic; semiarid and subhumid climates), Xerepts (xeric; very dry summers and moist winters), and Udepts (udic; humid climates). Given the well-draining characteristic of pedon 1, it was classified as Udepts. Next, the great group of Udepts was categorized as Sulfudepts (sulfuric; highly acid horizon within 50 cm), Durudepts (duripan; silica-cemented layer within 100 cm), Fragiudepts (fragifan; firm and brittle not cemented layer within 100 cm), Humudepts (umbric or mollic epipedon; rich in humus with low or moderate base saturation, respectively), Eutrudepts (base saturation of more than 60% in >75 cm), and Dystrudepts (base saturation of less than 60% in >75 cm) [21]. Based on this, pedon 1 belonged to Eutrudepts. Subsequently, according to the soil subgroup of Eutrudepts [8] that includes Humic Lithic (a value of less than 3 and containing stone material within 50 cm), Lithic (stone material), Aquertic (aquic conditions), Vertic (a slickenside or wedge structure), Andic (andic properties; volcanically produced material), Vitrandic (containing volcanic glass), and Anthroaquic (artificially irrigated), pedon 1 belonged to the Anthroaquic category. In a report by Han (2018) [22], several paddy soils with long-term irrigation practices in Korea were classified as Anthroaquic Eutrudepts. Since the soil temperature regime of pedon 1 was mesic and the soil texture was coarse loamy, taking these together, the final taxonomic name according to the ST system was a coarse loamy, mesic family of Anthroaquic Eutrudepts (Figure 3A).

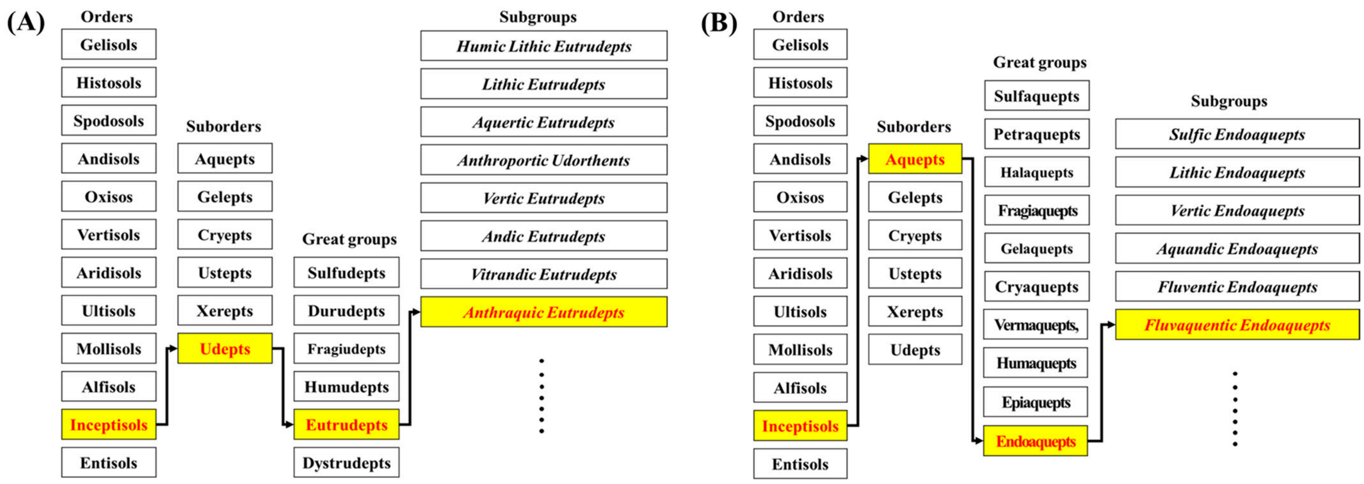

Figure 3. Soil classification for the two paddy soils, pedon 1 (**A**) and pedon 2 (**B**), with Soil Taxonomy [8].

Like pedon 1, the soil order of pedon 2 was Inceptisols, but its suborder was recognized as Aquepts (Figure 3B) because of the aquic horizon with very poor drainage [21]. The great group of Aquepts is composed of Sulfaquepts (sulfuric horizon within 50 cm), Petraquepts (cemented horizon or plinthite within 100 cm), Halaquepts (salic horizon within 50 cm), Fragiaquepts (fragipan within 100 cm), Gelaquepts (gelic; very cold soil temperature regime), Cryaquepts (cryic; cold soil temperature regime), Vermaquepts (bioturbation within 100 cm), Humaquepts (histic, melanic, mollic, or umbric epipedon), Epiaqyeots (episaturation; perched water table), and Endoaquepts (endosaturation; saturated across soil profile). Pedon 2 with high BS was classified as Endoaquepts. There are six soil subgroups of Endoaquepts: sulfic, lithic, vertic, aquandic (andic properties), fluventic (anthropogenic disturbance), and fluvaquentic (organic carbon content >0.2% and no hardpan layer), and pedon 2 met the characteristics of fluvaquentic. Hence, the final soil classification for pedon 2 using the ST system was a coarse loamy, mesic family of Fluvaquentic Endoaquepts (Figure 3B).

As such, it was demonstrated that there are some differences between the two classification systems, ST and WRB, in assigning layer names. WRB made it especially possible to classify paddies more precisely according to the factors causing the water saturation across the soil profile, using different suffixes [19]. Although this study compared only two pedons of rice field, considering the situation in which the paddies are distributed in diverse terrains throughout Korea, it is necessary to develop a soil classification system suitable for the Korean environment by taking advantage of the ST and WRB, and further conducting accurate soil surveys on more paddy soils.

3.3. Soil Classification with the WRB System

According to the WRB classification system [9], pedon 1 and pedon 2 were classified as Anthrosols because they have been constantly and intensively used for rice yield in a reduced state by artificial irrigation. There are a total of 11 principal qualifiers describing Anthrosols: Hydragic (paddy soil), Irragic (high OM due to sediment deposition by irrigation water), Hortic (high OM and phosphorus due to agricultural activity), Plaggic (high base saturation, with artefacts), Pretic (high cation content), Terric (contains artefacts), Gleyic (saturated with groundwater, a chroma ≤ 2), Stagnic (soil reduced by water, oxidized), Ferralic (highly weathered, low in CEC), Sideralic (weakly developed and low in CEC), and Andic (andic properties). Based on this, the principal qualifiers for pedon 1 were recognized as hydragic and stagnic, and those for pedon 2 were hydragric, stagnic, and greyic. Next, the supplementary qualifiers are divided into features that describe detailed soil profiles. For Anthrosols, there are a total of 35 supplementary qualifiers to distinguish based on the characteristics of soil chemistry and physics. The supplementary qualifiers for both pedons 1 and 2 were identical: Eutric (sum of exchangeable Ca, Mg, K, and Na is greater than exchangeable Al), Loamic, and oxyaquic (saturated with water for more than 20 days of the year). This is because the two soils belonged to the same catena, had different drainage depending on the terrain, and also had similar soil characteristics. Therefore, pedon 1 was classified as Stagnic Hydragric Anthrosols (Eutric, Loamic, Oxyaquic) (Figure 4A) and pedon 2 was Stagnic Gleyic Hydragric Anthrosols (Eutric, Loamic, Oxyaquic) (Figure 4B).

3.4. Proposal for Paddy Soil Classification accroding to Drainge Grade

The two soil classification systems, ST and WRB, distinguish soil horizons based on the soil characteristics, such as topography, structure, color, and biogeochemistry, mineralogy, etc., by soil depths, but their classification criteria are somewhat different [11,12]. In particular, exemplary studies on the classification of paddy soil flooded by irrigation long term can be found in very few countries. Among them, in South Korea, soil classification of various agricultural lands has been successfully performed by referring to the ST and WRB systems, but there are still difficulties in establishing a paddy soil classification system, primarily due to extreme variation in the water saturation status by region. In paddy lands, rice growth and yield are highly dependent on the redox state of the belowground. The poor drainage condition in paddy soils especially influences soil and water temperature, as well as the generation of toxic products (i.e., Fe^{2+}), eventually impairing the growth and productivity of rice plants [23,24]. Recently, in this regard, the WRB system has changed the classification wording criteria for reduced and oxidized soils, such as paddy soils, i.e., stagnic and gleyic were moved from supplementary to principal qualifiers [9]. Accordingly, by simultaneously evaluating the drainage conditions of topsoil and subsoil, paddy soils greatly affected by surface irrigation and the groundwater level in the principal qualifiers level can be subdivided, as in pedon 2 of this study. For accurate soil classification, other wording criteria changes in the newly updated WRB system include: removed (e.g., fulvic, melanic, aridic, geric, and sulfidic) and added words (e.g., cohesic, imonic, panpaic, tsitelic, protogypsic, Aeolic, mulmic, and organotechnic) [9]. However, despite such changes, it may not still be applicable as an appropriate soil classification criterion globally due to differences in soil characteristics and landscape environments that exist by country and region. Hence, the RDA has judged that it is necessary to develop a soil classification system tailored to Korean conditions, and so is making efforts for research on this. Currently, pedologists in the RDA recommend additional soil classification criteria for rice fields, as represented in Table 7. In general, the main color of soil can change according to its redox state. That is, moderately well-drained soils do not have reduced-colored mottles (i.e., grey spots), whereas poorly drained soils have oxidized-colored mottles (i.e., red spots) on the reduced-colored background [4]. Hence, this suggests that the color and quantity of mottle in soil horizon can be an indicator of classifying soil drainage grade which is an important factor for recommending land use. As such, it is judged that the draft criteria proposed here (Table 7) will be helpful for efficient land use and management by making the paddy soil classification system more precise.

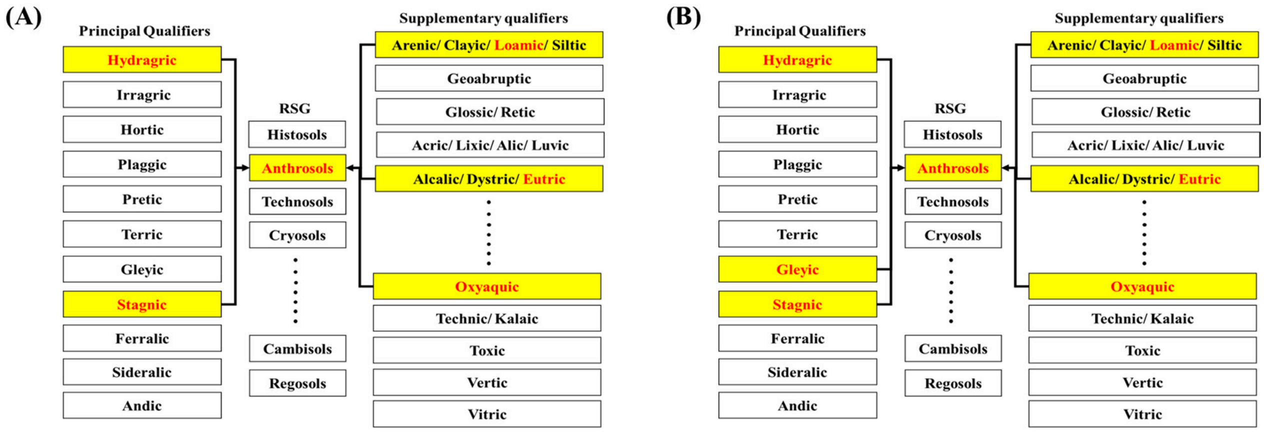

Figure 4. Soil classification for the two paddy soils, pedon 1 (**A**) and pedon 2 (**B**) with the WRB (2022).

Table 7. A draft of the classification criteria of paddy soils.

Main Color	Mottle		Drainage Class
	Color	Quantity	
Reductimorphic	Oximorphic	Few (<2%) Common (2–20%) Many (≥20%, <50%)	Very poorly drained Poorly drained Imperfectly drained
Oximorphic	Reductimorphic	<50%	Moderately well drained

4. Conclusions

In this study, paddy soils with different drainage grades were classified with two soil classification systems, the Soil Taxonomy and WRB systems, and based on the comparative results, a more suitable classification system for paddies was identified. Our results showed that the updated WRB system [9] better classified the two paddy soils, by precisely evaluating the state of water saturation by soil depths (i.e., topsoil and subsoil) than the ST system. However, the WRB classification criteria used in this study seem to make difficulties in precise classification work for paddies due to high variation in soil redox conditions affected by surface irrigation and the groundwater level by region. The degree of soil drainage is a crucial factor in rice growth and development because it regulates soil and water temperature and mediates the generation of harmful reduction products in paddies. Given this point, in the present study, a draft of the classification criteria was proposed that evaluates the drainage grade of paddy soils based on the redox state and the color and population of mottles in the main soil. This will provide farmers better information on how to effectively control soil drainage systems in agricultural land, thereby contributing to improving the soil quality and crop yield.

Author Contributions: Conceptualization, D.-B.L., Y.-K.S. and K.-H.K.; methodology, D.-B.L. and Y.-K.S.; validation, D.-B.L. and Y.-N.K.; formal analysis, D.-B.L. and Y.-K.S.; investigation, D.-B.L. and Y.-K.S.; writing—original draft preparation, D.-B.L. and Y.-K.S.; writing—review and editing,

Y.-N.K. and K.-H.K.; visualization, D.-B.L. and Y.-N.K.; supervision, K.-H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the 2022 sabbatical year research grant of the University of Seoul.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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