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Authors: Saurette, Daniel D., Warren, C. James (Jim), and Heck, Richard J.

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Article

A proposed framework for assigning soil drainage classes to non-redoximorphic soils in the Canadian System of Soil Classification

Daniel D. Saurette[a,b], **C. James (Jim) Warren**[a,b], **and Richard J. Heck**[b]

[a]Ontario Ministry of Agriculture, Food and Rural Affairs, 1 Stone Road West, 3rd Floor SE, Guelph, ON N1G 4Y2, Canada; [b]School of Environmental Sciences, University of Guelph, 50 Stone Road East, Guelph, ON N1G 2W1, Canada

Corresponding author: **Daniel D. Saurette** (email: daniel.saurette@ontario.ca)

Abstract

Drainage refers to the frequency and duration of periods of saturation, and how quickly excess water is removed from the soil profile. It is one of the central concepts used to differentiate soil series within the Canadian System of Soil Classification (CSSC). Currently, seven drainage classes are recognized in the CSSC: very rapid, rapid, well, moderately well, imperfect, poor, and very poor. In redoximorphic soils (imperfect, poor, and very poor drainage classes), drainage is typically differentiated based on morphological features (i.e., the presence of gleying and mottles). Non-redoximorphic soils (very rapid, rapid, and well-drained classes) do not display such morphological features but are differentiated based on available water holding capacity (AWHC) as inferred from soil texture and particle size. Moderately well-drained soils are intermediate, in some cases defined by the presence of redoximorphic characteristics, but in other cases inferred based on texture. In effect, drainage in materials without redoximorphic features is estimated based on AWHC as related to texture class, which should include sand subfractions. Values for AWHC were calculated using a published pedotransfer function for combinations of sand, silt, and clay-sized particles, including various combinations of very fine to very coarse sand separates as input. Calculated values were compared with currently assigned drainage classes and several inconsistencies were identified. Revisions are proposed to textural assessment of soil drainage for non-redoximorphic soils.

Key words: soil water, sand separates, available water holding capacity, non-redoximorphic soils

Résumé

Le drainage exprime la fréquence et la durée des périodes de saturation d'eau, ainsi que la rapidité avec laquelle l'eau en excédent se retire du sol. Il s'agit d'un des principes fondamentaux employés pour différencier les séries de sols dans le Système canadien de classification des sols (SCCS). Pour l'instant, le SCCS répertorie sept classes de drainage : très rapide, rapide, bon, modérément bon, imparfait, pauvre et très pauvre. Chez les sols rédoximorphiques (drainage imparfait, pauvre ou très pauvre), on différencie habituellement le drainage d'après les paramètres morphologiques (p. ex., présence de gleyification et de marbrures). Comme ils ne présentent pas de caractères morphologiques de ce genre, on différencie les sols non rédoximorphiques (drainage très rapide, rapide ou bon) d'après leur capacité à retenir l'eau (CRE) disponible grâce à leur texture et à leur granulométrie. Les sols modérément bien drainés se situent entre les deux et sont définis parfois par l'existence de certains paramètres rédoximorphiques, parfois par leur texture. Le drainage des matériaux sans propriétés rédoximorphiques est estimé d'après la CRE et le type de texture, qui devrait inclure les sous-fractions sableuses. Les auteurs ont calculé la CRE de mélanges de sable, de limon et d'argile avec une fonction de pédotransfert publiée, notamment celle de fractions sableuses aux particules allant de très fines à très grossières. Ensuite, ils ont comparé les valeurs obtenues avec les valeurs actuelles des classes de drainage et relevé plusieurs incohérences. Ils proposent certaines modifications à l'évaluation du drainage des sols non rédoximorphiques en fonction de leur texture. [Traduction par la Rédaction]

Mots-clés : sol, eau, fractions sableuses, capacité de rétention de l'eau disponible, sols non rédoximorphiques

Introduction

One of the key attributes used to differentiate soils within the third edition of the Canadian System of Soil Classification (CSSC) is the determination of the natural soil drainage class. Soil drainage was originally defined in terms of (1) soil moisture content in excess of field moisture capacity and (2) the extent of the period during which excess water is present in the plant-root zone, while recognizing that permeability, level of groundwater, and seepage factors also affect soil moisture status (Matthews 1963). Soil drainage class is a subclass used to assess the soil water regime along with "aridity, hydraulic conductivity, impeding layer, depth of saturation zone and duration, and man-made modifiers" (Day 1983; SCWG 1998). A formal definition of soil drainage was never included in the CSSC (SCWG 1998), nor in its companion document, "The Canada Soil Information System Manual for Describing Soils in the Field" (Day 1983). Currently, seven drainage classes are recognized in the CSSC: very rapid (VR), rapid (R), well (W), moderately well (MW), imperfect (I), poor (P), and very poor (VP) as outlined in Day (1983).

There is a lack of consistency across Canada in the assessment of soil drainage in the field, despite the concepts of drainage put forward in a single national system (Day 1983). Since the dismantling of the Expert Committee on Soil Survey in the early 1990s, provinces have taken on the responsibility of refining field manuals and procedures; however, without oversight from a national committee or interprovincial collaboration, consistency and harmonization across jurisdictions are no longer apparent. For instance, British Columbia has adapted a soil drainage key from the Minnesota Division of Forestry Ecological Land Classification Program (British Columbia 2010). In Saskatchewan, the "Field Handbook for Saskatchewan Soils" (Pennock 2005) simply provides a slight modification to the definitions of the drainage classes as presented in Day (1983), as is the case in Manitoba (Manitoba Agriculture, Food and Rural Initiatives 2007). More recently, the "Field Handbook for the Soils of Western Canada" (Pennock et al. 2016), focusing on provinces and territories west of Ontario, omits soil drainage altogether. In Ontario, a key to soil drainage classes has been in use since the early 1980s (OCSRE 1993; Heck et al. 2017); however, it differs substantially from the key used in British Columbia. This clearly indicates a lack of coordination and standardization of one of the fundamental characteristics used to describe and classify soils in Canada.

In practice, drainage classes in redoximorphic soils (VP, P, I, and, in some cases, MW) are readily differentiated based on visual morphological expressions of gleying and mottling. By contrast, non-redoximorphic soils (i.e., VR, R, W, and, in some cases, MW), many of which are freely draining coarser textured materials, do not express any morphological features (i.e., absence of any gleying and mottling features). As such, drainage classes are differentiated, quantitatively, based on available water holding capacity (AWHC), which, in turn, is estimated on the basis of soil texture and particle size classes. For purposes here, "freely draining" means that there is no impediment to water movement in the soil aside from the restraints imposed by the texture of the material itself. Moderately well drained soils are at the interface between redoximorphic and non-redoximorphic drainage classes, in that they may be identified based on either the presence of mottles or the texture and its associated AWHC in the absence of mottles. For example, in Ontario, heavy clay (HC), silty clay (SiC), clay (C), and sandy clay (SC) textures are considered moderately well drained with the presence of distinct or faint mottles from 50 to 100 cm in the profile, or without the presence of any redoximorphic features in the profile (Heck et al. 2017).

Soil drainage classes for non-redoximorphic soils have been defined, in part, based on the AWHC within the control section of the soil profile (Table 1; Day 1983). These are in contrast to established classes and ranges for AWHC as related to soil texture documented elsewhere (e.g., McKeague et al. 1986; Haluschak et al. 2004; Kirkham 2014). For example, very rapidly drained soils are defined as having less than 2.5 cm of AWHC and being usually coarse textured; this is at odds with Haluschak et al. (2004) who reported 6 cm of AWHC for coarse sands in Manitoba soils. Soil drainage classes can be correlated to the AWHC classes from McKeague et al. (1986) as shown in Table 1. Although there is no direct link between the two classification systems, the terminology used in both systems provides a convenient and logical connection, as highlighted by bold font in Table 1. For example, very rapidly drained soils are characterized as having "very low available water holding capacity", which coincidentally shares the name of the class with the lowest AWHC from McKeague et al. (1986). As can be deduced from Table 1, drainage classes for non-redoximorphic soils can be quite easily aligned with the AWHC classes. It is important to note that soils with >20% AWHC would still be classified as moderately well drained when those soils lack redoximorphic features within the control section, despite exceeding the AWHC class that aligns with moderately well drained soils (Table 1). Our field observations, combined with these conflicting reports on the amount of AWHC in non-redoximorphic soils, seem to indicate inconsistencies in the literature and a need to re-evaluate the AWHC criteria as related to drainage class.

Clay-sized particles are <0.002 mm in diameter, silt-sized particles range from <0.05 to 0.002 mm in diameter, and sand-size particles range from 0.05 to 2 mm in diameter. Soils dominated by silt- and clay-sized particles have greater AWHC compared to soils dominated by sand; however, it should be recognized that AWHC varies greatly within sandy-textured materials depending on the distribution of grain sizes (sand separates) within the sand fraction itself. Haluschak et al. (2004) demonstrated that mean AWHC can vary from 6% in a coarse sand to 12% in a very fine sand in Manitoba soils. Size separates within the sand-size range, as determined in the laboratory, are recognized as very fine sand (0.05–0.1 mm diameter), fine sand (0.1–0.25 mm diameter), medium sand (0.25–0.5 mm diameter), coarse sand (0.5–1.0 mm diameter), and very coarse sand (1–2 mm diameter). Sand (S), loamy sand (LS), and sandy loam (SL) texture classes are further subdivided into very fine, fine, medium (inferred), and coarse texture classes (i.e., vfS, fS, S, cS, LvfS, LfS, LS, LcS, vfSL, fSL, SL, and cSL). Various percentages of the five sand-size separates are used to define the subdivisions within the base textural classes, and although there are five sand-size separates, only four subclasses are recognized within each of the base sand, loamy sand, and sandy loam textures (Day 1983). As an example, the breakdown of the loamy sand texture class is shown below (Day 1983):

Table 1. Correlation between drainage classes (Day 1983) and available water holding capacity (AWHC) classes (McKeague et al. 1986).

Soil drainage (adapted from Day 1983)		Available water holding capacity (McKeague et al. 1986)	
Class	Definition	Class	Definition
Very Rapid (VR)	Water is removed from the soil very rapidly in relation to supply. Soils have **very low available water storage capacity** (usually less than 2.5 cm) within the control section and are usually coarse textured or shallow, or both. Water source is precipitation.	**Very low** Soils have <5% AWHC.	1. Extremely gravelly or bouldery sandy loam to loam, or 2. Very gravelly loamy sand or sand containing little fine or very fine sand and less than 5% finer material, or 3. Medium to coarse sands with less than 5% finer material.
Rapid (R)	Water is removed from the soil rapidly in relation to supply. Soils have **low available water storage capacity** (2.5–4 cm) within the control section, and are usually coarse textured or shallow, or both. Water source is precipitation.	**Low** Soils have 5%–10% AWHC.	1. Medium to coarse sands with 5%–10% material finer than sand and loamy medium to coarse sands with ≤5% amorphous material, or 2. Very gravelly sandy loam.
Well (W)	Water is removed from the soil readily but not rapidly. Soils have **intermediate available water storage capacity** (4–5 cm) within the control section, and are generally intermediate in texture and depth. Water source is precipitation.	**Medium** Soils have >10%–15% AWHC.	1. Loamy medium to fine sands with bulk densities of 1.5 $Mg{\cdot}m^{-3}$ or more, or 2. Clays with bulk densities of 1.5–1.7 $Mg{\cdot}m^{-3}$.
Moderately well (MW)	Water is removed from the soil somewhat slowly in relation to supply. Soils have **intermediate to high water storage capacity** (5–6 cm) within the control section and are usually medium to fine textured. Precipitation is the dominant water source in medium to fine-textured soils; precipitation and significant additions by subsurface flow are necessary in coarse-textured soils.	**Moderately high** Soils have >15%–20% AWHC.	1. Fine sands with approximately 5%–10% silt + clay and ≤2% amorphous material, or 2. Sandy loams with bulk densities of 1.7 $Mg{\cdot}m^{-3}$ or more, or 3. Loams with bulk densities of 1.6 $Mg{\cdot}m^{-3}$ or more, or 4. Clays with bulk densities of approximately 1.4 $Mg{\cdot}m^{-3}$.

Loamy coarse sand (LcS): 25% or more very coarse and coarse sand, and less than 50% any other grade of sand.
Loamy sand (LS): 25% or more very coarse, coarse, and medium sand (but less than 25% very coarse and coarse sand), and less than 50% fine or very fine sand.
Loamy fine sand (LfS): 50% or more fine sand, or less than 50% very fine sand, and less than 25% very coarse, coarse, and medium sand.
Loamy very fine sand (LvfS): 50% or more very fine sand.

It can be seen from the ruleset above that the very coarse sand and coarse sand separates are always used together (summed) for classification purposes. It is worth noting that although sandy clay loam, fine sandy clay loam, and very fine sandy clay loam texture classes were originally recognized, these three subdivisions were not defined in terms of content of sand-size separates (Day 1983), likely due to higher clay content in this texture class.

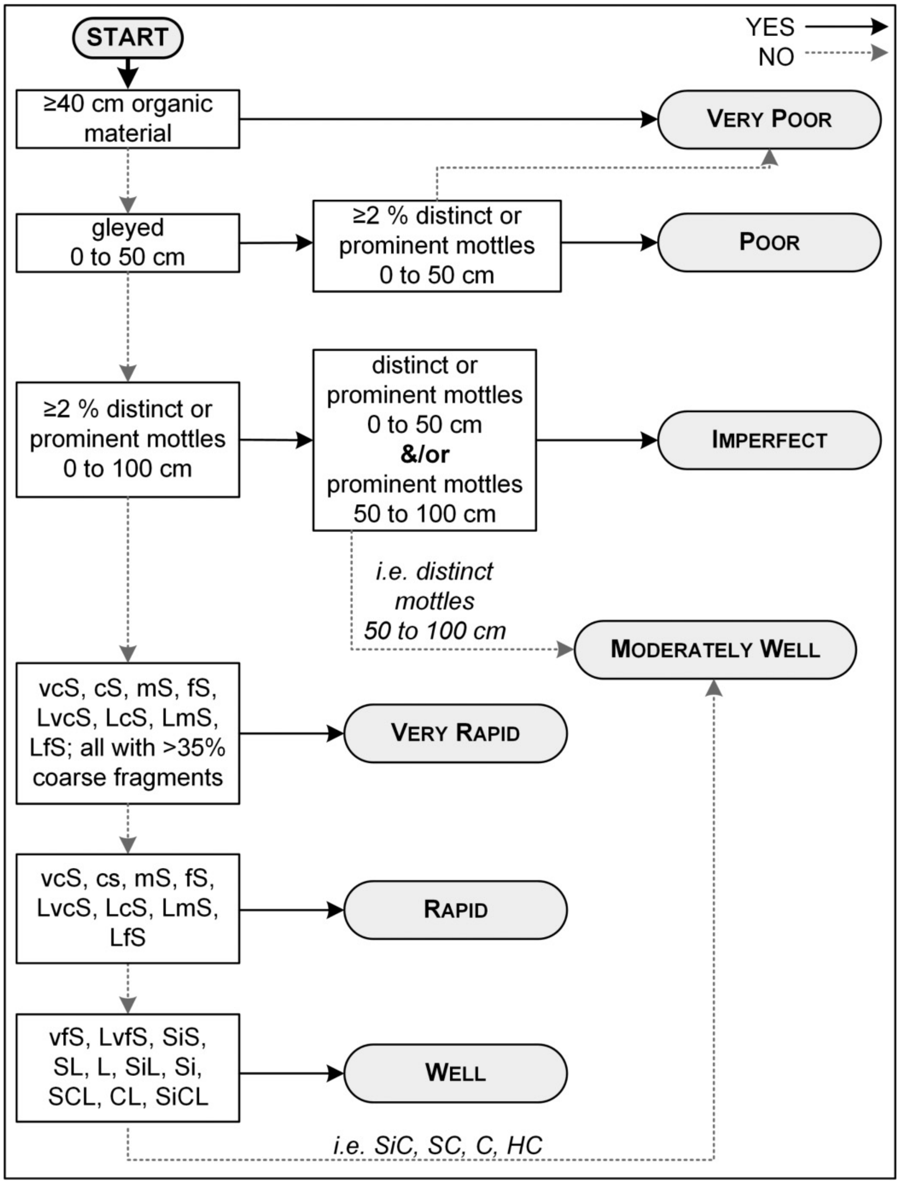
The purpose of this communication is to present evidence to suggest changes to the CSSC related to terminology for describing drainage classes in non-redoximorphic soils. This includes establishing new quantifiable criteria for estimating soil drainage class in the field for non-redoximorphic soils based on soil texture class, thus providing a standardized framework for use by pedologists in Canada to ensure consistency across jurisdictions.

Methods

Simulated soil texture data set

To estimate AWHC of various soil textures, we generated a simulated soil texture data set. Soil texture is compositional in that its components, sand, silt, and clay, sum to 100%. We generated all unique combinations of sand, silt, and clay that sum to 100% in increments of 1%. These combinations were then classified into one of 13 texture classes recognized in the CSSC using the *oss.texture* function in the *onsoilsurvey* package in R (R Core Team 2021; Saurette 2021). Sand separates are also compositional, either reported as a fraction of total sand (summing to total sand %) or as a percentage of total sand (summing to 100%). Treating the sand separates as a percentage, we generated all unique combinations of the five sand separates that sum to 100% in increments of 5%. These unique combinations of sand separates were then merged with the unique combinations of sand, silt, and clay to generate the

Fig. 1. Flowchart for the field estimation of soil drainage class. Adapted from Heck et al. (2017).



complete data set for analysis. Furthermore, the S, LS, and SL texture classes can each be subdivided, as described above, into four subclasses based on the distribution of the sand-size separates. Therefore, those records classified as S, LS, or SL were then classified into one of 12 texture subclasses (i.e., cS, S, fS, vfS, cLS, LS, LfS, LvfS, cSL, SL, fSL, or vfSL) based on the sand separate distribution using the rules provided in Day (1983). It may seem redundant to combine all "non-sandy" texture classes (e.g., clay) with all combinations of sand separates, given that the texture class is unaffected by sand separates; however, the calculation of AWHC relies on very fine sand and fine sand, regardless of texture class, as described below; thus, it was important to retain all combinations.

Estimating available water holding capacity

For each of the records in the simulated soil texture data set, the AWHC was estimated using the pedotransfer function (PTF) of Haluschak et al. (2004):

$$\text{(1)}\quad \text{AWHC} = 1.99 + 0.1599\,(\text{fS}) + 0.1555\,(\text{vfS}) + 0.2410\,(\text{Si}) + 0.1943\,(\text{C})$$

where AWHC is the available volumetric water holding capacity (%), fS denotes fine sand (% by mass), vfS denotes very fine sand (% by mass), Si denotes silt (% by mass), and C denotes clay (% by mass).

This PTF was selected because it accounts for the effect of sand-size separates on AWHC, whereas most other PTFs for estimating soil water characteristics do not (Saxton and Rawls 2006; Contreras and Bonilla 2018; Dobarco et al. 2019; Myeni et al. 2021). Based on this equation, very fine sand and fine sand separates have an influence on AWHC, while medium, coarse, and very coarse sand separates do not. Val-

Fig. 2. Texture triangle as per the Canadian System of Soil Classification (SCWG 1998) with 13 recognized soil textural classes.

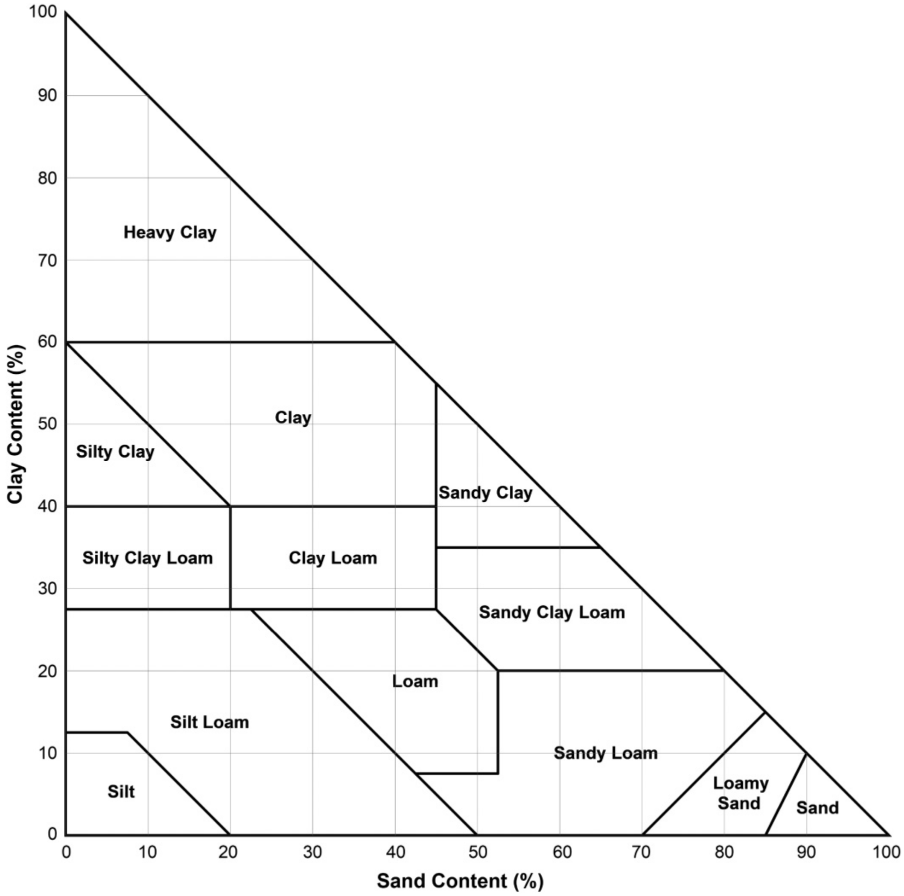
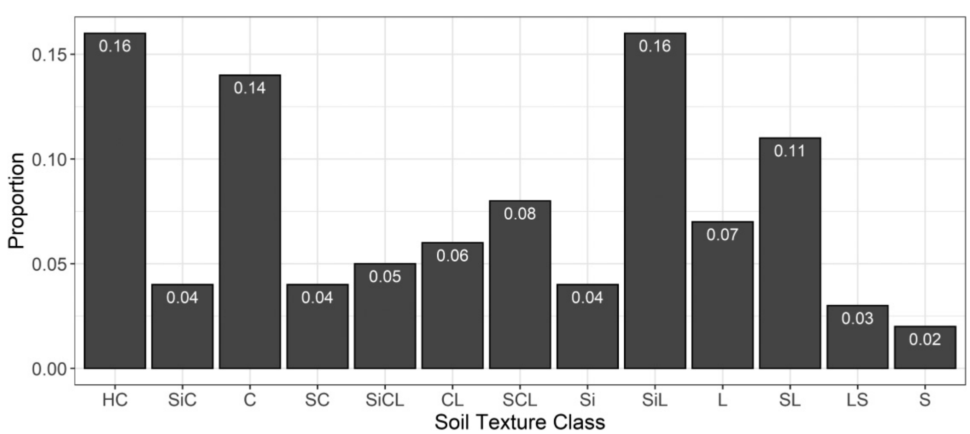


Fig. 3. Distribution of texture classes derived from all combinations of sand, silt, and clay in the texture triangle. HC, heavy clay; SiC, silty clay; C, clay; SC, sandy clay; SiCL, silty clay loam; CL, clay loam; SCL, sandy clay loam; Si, silt; SiL, silt loam; L, loam; SL, sandy loam; LS, loamy sand; S, sand.



ues for AWHC are heavily influenced by silt and clay contents for texture classes other than S, LS, and SL.

Assigning drainage classes

A drainage class was assigned to each record in the data set based on AWHC ranges as defined by Day (1983) and by McKeague et al. (1986). All records with AWHC > 6 cm in the case of Day (1983), and 20% in the case of McKeague et al. (1986), were assigned a drainage class of MW, since soils require redoximorphic features to be classified as I, P, or VP. The overall drainage class for each texture class was assigned based on the most frequent drainage class from all observations in the database for a given soil texture class using the drainage class interpretation criteria both from Day (1983) and from McKeague et al. (1986). In addition, it was neces-

Fig. 4. Distribution of texture subclasses for sands (*a*), loamy sands (*b*), and sandy loams (*c*), and associated drainage class when accounting for sand separate distribution. Bars represent the proportion of sand (*a*), loamy sand (*b*), and sandy loam (*c*) classified into the four subclasses within each texture class. Colours within stacked bars show the proportion of drainage class assignments based on available water holding capacity classes from McKeague et al. (1986). vfS, very fine sand; fS, fine sand; S, sand; cS, coarse sand; LvfS, loamy very fine sand; LfS, loamy fine sand; LS, loamy sand; LcS, loamy coarse sand; vfSL, very fine sandy loam; fSL, fine sandy loam; SL, sandy loam; cSL, coarse sandy loam; VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained. [Colour online.]

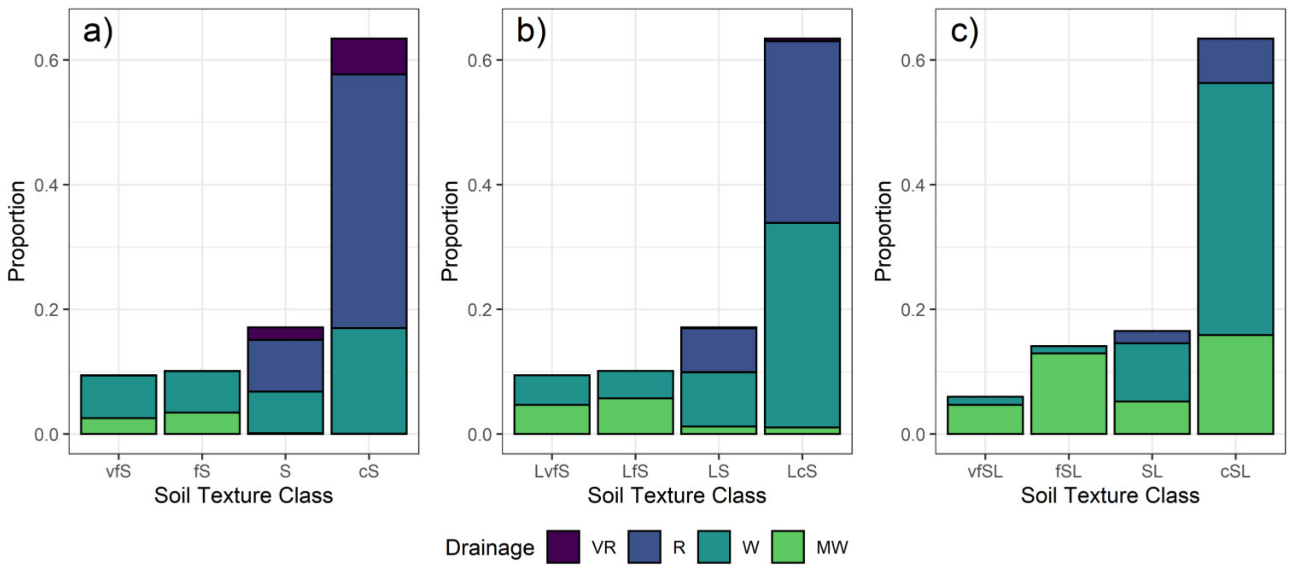


Table 2. Mean and standard deviation of available water holding capacity estimated for each texture class in the CSSC using the Haluschak et al. (2004) pedotransfer function.

		Available water holding capacity (%)				
Texture class	*n*	Minimum	Mean	Median	Maximum	SD
Coarse sand	572 730	2.0	8.4	8.4	15.6	2.5
Sand	154 360	2.0	8.9	9.0	15.6	3.1
Fine sand	91 120	10.0	14.1	14.1	19.1	1.8
Very fine sand	85 000	9.8	13.8	13.7	18.9	1.8
Sands	**903 210**	**2.0**	**9.6**	**9.4**	**19.1**	**3.3**
Loamy coarse sand	1 044 390	3.9	10.2	10.2	17.4	2.3
Loamy sand	281 480	3.9	10.7	10.7	17.4	2.9
Loamy fine sand	166 160	11.1	15.3	15.3	20.3	1.7
Loamy very fine sand	155 000	10.9	15.0	15.0	20.2	1.7
Loamy sands	**1 647 030**	**3.9**	**11.3**	**11.1**	**20.3**	**3.0**
Coarse sandy loam	3 806 970	4.9	13.2	13.3	20.3	2.5
Sandy loam	992 140	4.9	13.5	13.6	20.0	2.7
Fine sandy loam	845 805	11.7	17.5	17.6	22.2	1.7
Very fine sandy loam	358 775	11.5	16.4	16.4	22.0	1.7
Sandy loams	**6 003 690**	**4.9**	**14.0**	**14.1**	**22.2**	**2.9**
Loam	3 708 474	12.6	15.7	15.2	22.8	2.3
Silt loam	8 925 840	14.0	20.5	20.5	25.5	2.7
Silt	1 976 436	21.3	24.1	24.3	26.1	1.2
Sandy clay loam	4 165 392	5.9	11.0	10.6	21.1	3.2
Clay loam	3 453 450	13.4	17.0	16.9	23.1	2.2
Silty clay loam	2 900 898	19.4	22.3	22.4	24.8	1.5
Sandy clay	2 231 460	8.8	12.2	11.8	20.7	2.5
Clay	7 650 720	12.7	17.5	17.5	23.2	2.7
Silty clay	2 454 606	19.4	22.4	22.6	24.2	1.1
Heavy clay	8 713 320	13.8	19.7	20.1	23.2	2.1

Fig. 5. Distribution of texture subclasses for sands (*a*), loamy sands (*b*), and sandy loams (*c*), and associated drainage class when accounting for sand separate distribution. Bars represent the proportion of sand (*a*), loamy sand (*b*), and sandy loam (*c*) classified into the four subclasses within each texture class. Colours within stacked bars show the proportion of drainage class assignments based on available water holding capacity classes from Day (1983). vfS, very fine sand; fS, fine sand; S, sand; cS, coarse sand; LvfS, loamy very fine sand; LfS, loamy fine sand; LS, loamy sand; LcS, loamy coarse sand; vfSL, very fine sandy loam; fSL, fine sandy loam; SL, sandy loam; cSL, coarse sandy loam; VR, very rapidly drained; R, rapidly drained; W, well drained; and MW, moderately well drained. [Colour online.]

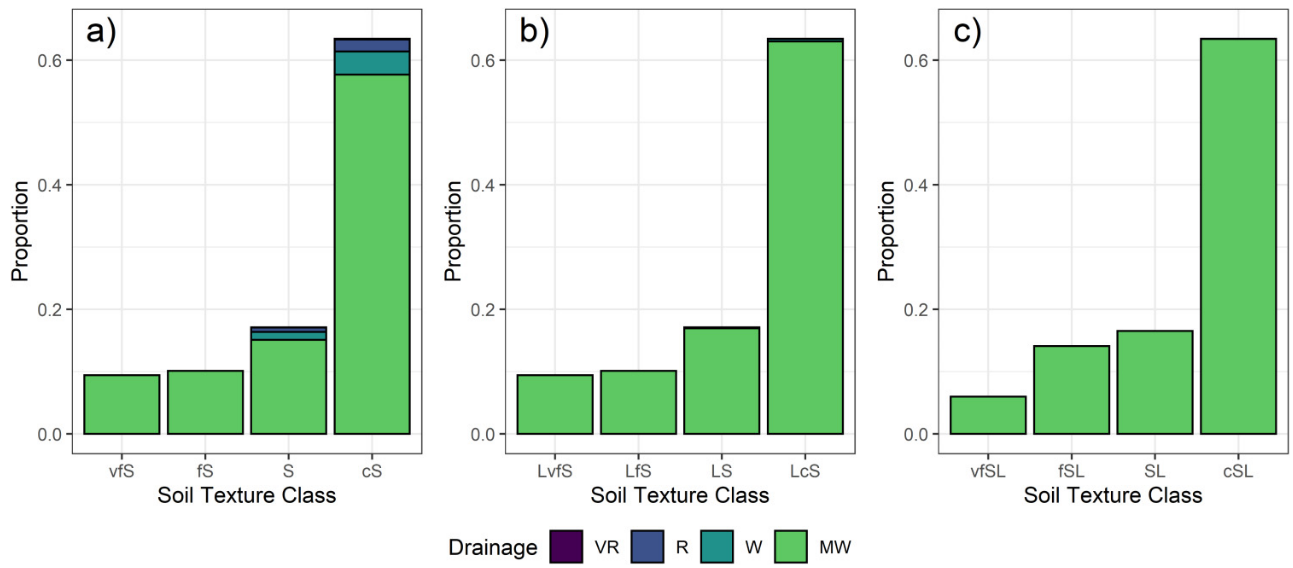


Table 3. Current criteria for assignment of soil drainage class for sand textures according to Heck et al. (2017) and interpreted soil drainage class according to Day (1983) and McKeague et al. (1986) based on calculated AWHC values adjusted for content of coarse fragments and/or depth to bedrock.

Texture class	Coarse fragments (% by volume)/depth to bedrock (cm)				
	0%/100 cm	15%/85 cm	35%/65 cm	60%/40 cm	90%/10 cm
Drainage classes based on Heck et al. (2017)					
vfS	W	W	W	W	W
fS	R	R	VR	VR	VR
S	R	R	VR	VR	VR
cS	R	R	VR	VR	VR
Drainage classes based on AWHC as defined by Day (1983)					
vfS	MW	MW	MW	MW	VR
fS	MW	MW	MW	MW	VR
S	MW	MW	MW	MW	VR
cS	MW	MW	MW	R	VR
Drainage classes based on AWHC as defined by McKeague et al. (1986)					
vfS	W	W	R	R	VR
fS	W	W	R	R	VR
S	R	R	R	VR	VR
cS	R	R	R	VR	VR

Note: vfS, very fine sand; fS, fine sand, S, (medium) sand; cS, coarse sand; VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained.

sary to account for the impact of coarse fragments (Baetens et al. 2009) and depth of the control section on AWHC, and hence drainage class. For the purpose of these calculations, it was assumed that coarse fragments proportionally reduce the volume of fine earth materials within a 1 m deep control section and proportionally decrease the AWHC. Similarly, the presence of a bedrock contact within 1 m of the surface limits the depth of the control section and proportionally replaces the volume of fine earth materials in the control section, but is assumed not to inhibit drainage (i.e., there is lateral

Table 4. Current criteria for assignment of soil drainage class for loamy sand textures according to Heck et al. (2017) and interpreted soil drainage class according to Day (1983) and McKeague et al. (1986) based on calculated AWHC values adjusted for content of coarse fragments and/or depth to bedrock.

Texture class	Coarse fragments (% by volume)/depth to bedrock (cm)				
	0%/100 cm	15%/85 cm	35%/65 cm	60%/40 cm	90%/10 cm
Drainage classes based on Heck et al. (2017)					
LvfS	W	W	W	W	W
LfS	R	R	VR	VR	VR
LS	R	R	VR	VR	VR
LcS	R	R	VR	VR	VR
Drainage classes based on AWHC as defined by Day (1983)					
LvfS	MW	MW	MW	MW	VR
LfS	MW	MW	MW	MW	VR
LS	MW	MW	MW	R	VR
LcS	MW	MW	MW	R	VR
Drainage classes based on AWHC as defined byMcKeague et al. (1986)					
LvfS	W	W	R	R	VR
LfS	MW	W	R	R	VR
LS	W	R	R	VR	VR
LcS	W	R	R	VR	VR

Note: LvfS, loamy very fine sand; LfS, loamy fine sand, LS, loamy (medium) sand; LcS, loamy coarse sand; VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained.

and/or fracture flow). In addition to the determination of soil drainage class using AWHC ranges, a drainage class was assigned to each soil texture class based on the flowchart from Heck et al. (2017), which considers the subclasses for S, LS, and SL texture classes accounting for differences in the sand separates (Fig. 1).

Results and discussion

The texture triangle contains 5151 unique combinations of sand, silt, and clay that sum to 100% in increments of 1%. These unique combinations were classified as one of the 13 texture classes in the CSSC (Fig. 2). The distribution of these unique combinations is a reflection of the overall size of the polygons of the texture classes (Fig. 3). The texture classes occupying the largest proportions of the texture triangle are the silt loam and heavy clay texture classes, each representing 16% of the triangle, followed by the clay (14%) and sandy loam (11%) classes. All remaining texture classes individually represent less than 8% of the texture triangle.

The SL, LS, and S texture classes represent 11%, 3%, and 2% of the area of the texture triangle, respectively (Fig. 3). In terms of the unique combinations of sand, silt, and clay, the SL, LS, and S texture classes represent 565, 155, and 85 observations, respectively, of the 5151 combinations that make up the texture triangle. These can be further subdivided into four subclasses each, based on the sand separate distribution. There were 10 626 unique combinations of sand separates that sum to 100% when using increments of 5%. After merging the SL, LS, and S data each with every sand fraction combination, this results in 6 003 690 unique combinations for the SL texture class, 1 647 030 unique combinations for the LS texture class, and 903 210 unique combinations for the S texture class (e.g., S: $85 \times 10\,626 = 903\,210$). These unique combinations were then classified, as per the CSSC, into the subclasses taking into consideration the sand separate distributions (Fig. 4). For all three texture classes (i.e., SL, LS, and S), the further refinement into subclasses yields a similar trend. The "coarse" class dominates the classification representing over 60% of the observations, whereas the remaining three subclasses within each texture class each represent less than 20%. This is a function of the ruleset described in Day (1983) that governs the placement of various combinations of sand separates into the four subclasses. Note that the rules for the S and LS texture classes are identical, and therefore the distributions into the subclasses are identical, but the ruleset for the SL texture class is slightly different, resulting in a small difference in the distribution. We can conclude from this assessment that, when considering all possible combinations of sand separates within the S, LS, and SL texture classes, the system is skewed toward the "coarse" subclasses. The reason for examining all possible permutations, for each of the subclasses of the S, LS, and SL texture classes, was to ensure that we captured the full range of AWHC, given that the PTF of Haluschak et al. (2004) uses very fine sand, fine sand, silt, and clay to estimate AWHC.

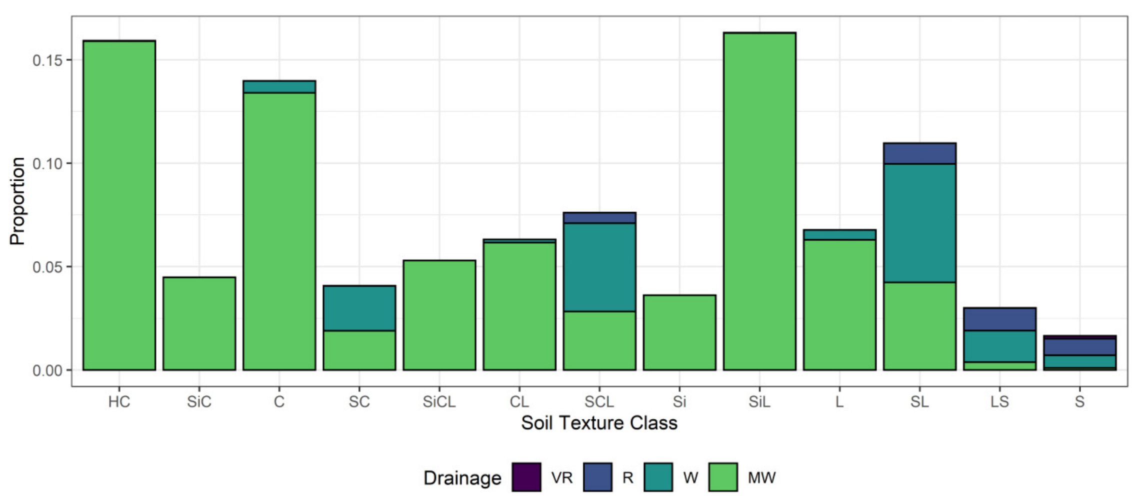
Estimated AWHC by texture class for all texture classes finer than SL is reported in Table 2. The number of observations reported by texture class represents the unique combinations of sand, silt, and clay that result in a particular texture class, merged with the 10 626 combinations of sand separates (e.g., HC: $820 \times 10\,626 = 8\,713\,320$). The ranges of AWHC by texture class are consistent with other reports (e.g., DeJong 1988; Tam et al. 2005; Saxton and Rawls 2006).

Table 5. Current criteria for assignment of soil drainage class for sand loam textures according to Heck et al. (2017) and interpreted soil drainage class according to Day (1983) and McKeague et al. (1986) based on calculated AWHC values adjusted for content of coarse fragments and/or depth to bedrock.

Texture class	Coarse fragments (% by volume)/depth to bedrock (cm)				
	0%/100 cm	15%/85 cm	35%/65 cm	60%/40 cm	90%/10 cm
Drainage classes based on Heck et al. (2017)					
vfSL	W	W	W	W	W
fSL	W	W	W	W	W
SL	W	W	W	W	W
cSL	W	W	W	W	W
Drainage classes based on AWHC as defined by Day (1983)					
vfSL	MW	MW	MW	MW	VR
fSL	MW	MW	MW	MW	VR
SL	MW	MW	MW	MW	VR
cSL	MW	MW	MW	MW	VR
Drainage classes based on AWHC as defined by McKeague et al. (1986)					
vfSL	MW	W	W	R	VR
fSL	MW	W	W	R	VR
SL	W	W	R	R	VR
cSL	W	W	R	R	VR

Note: vfSL, very fine sandy loam; fSL, fine sandy loam; SL, (medium) sandy loam; cSL, coarse sandy loam; VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained.

Fig. 6. Distribution of texture classes derived from all combinations of sand, silt, and clay in the texture triangle. Colours within stacked bars show the proportion of drainage class assignments based on available water holding capacity classes from McKeague et al. (1986) without consideration for sand separates in the SL, LS, and S texture classes. HC, heavy clay; SiC, silty clay; C, clay; SC, sandy clay; SiCL, silty clay loam; CL, clay loam; SCL, sandy clay loam; Si, silt; SiL, silt loam; L, loam; SL, sandy loam; LS, loamy sand; S, sand, VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained. [Colour online.]



It is worth noting a few interesting trends in the AWHC data. First, soils with high silt content (i.e., silt, silt loam, silty clay loam, and silty clay) have the highest AWHC, each with mean AWHC greater than 20%; however, the estimates of AWHC using the Haluschak et al. (2004) PTF are higher than those reported in Saxton and Rawls (2006). This is not surprising since the coefficient for the silt content (0.2410) in the PTF accounted for over 30% of the response. Second, subdividing the SL, LS, and S texture classes based on sand separates shows that the fine subclasses hold more water, on average, than the very fine subclass, which is counterintuitive. For example, the fine sand texture class has a mean AWHC of 14.1%, whereas the very fine sand texture class has a mean AWHC of 13.8%. This again is a function of the ruleset (Day 1983) for assigning the various combinations of sand separates to the four texture subclasses. It is not clear from accounts in the literature how the ruleset for assigning the SL, LS, and S classes to the subclasses based on sand separates was determined; however, this analysis shows that these rules affect the interpretation of derivative products and that the classes are not

Table 6. Current criteria for assignment of soil drainage class for other (non-sandy) textures according to Heck et al. (2017) and interpreted soil drainage class according to Day (1983) and McKeague et al. (1986) based on calculated AWHC values adjusted for content of coarse fragments and/or depth to bedrock.

Texture class	Coarse fragments (% by volume)/depth to bedrock (cm)				
	0%/100 cm	15%/85 cm	35%/65 cm	60%/40 cm	90%/10 cm
Drainage classes based on Heck et al. (2017)					
L	W	W	W	W	W
Si	W	W	W	W	W
SiL	W	W	W	W	W
SCL	W	W	W	W	W
CL	W	W	W	W	W
SiCL	W	W	W	W	W
SC	MW	MW	MW	MW	MW
C	MW	MW	MW	MW	MW
SiC	MW	MW	MW	MW	MW
HC	MW	MW	MW	MW	MW
Drainage classes based on AWHC as defined by Day (1983)					
L	MW	MW	MW	MW	VR
Si	MW	MW	MW	MW	R
SiL	MW	MW	MW	MW	VR
SCL	MW	MW	MW	R	VR
CL	MW	MW	MW	MW	VR
SiCL	MW	MW	MW	MW	VR
SC	MW	MW	MW	W	VR
C	MW	MW	MW	MW	VR
SiC	MW	MW	MW	MW	VR
HC	MW	MW	MW	MW	VR
Drainage classes based on AWHC as defined by McKeague et al. (1986)					
L	MW	W	R	R	VR
Si	MW	I	MW	R	VR
SiL	MW	MW	W	R	VR
SCL	W	R	R	VR	VR
CL	MW	W	W	R	VR
SiCL	MW	MW	W	R	VR
SC	W	R	R	VR	VR
C	MW	W	W	R	VR
SiC	MW	MW	W	R	VR
HC	MW	MW	W	R	VR

Note: HC, heavy clay; SiC, silty clay; C, clay; SC, sandy clay; SiCL, silty clay loam; CL, clay loam; SCL, sandy clay loam; Si, silt; SiL, silt loam; L, loam; VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained.

necessarily meaningful, as currently organized, when using them to interpret other soil properties such as soil water characteristics.

Drainage classes were assigned to each record in the simulated soil texture data set. The variability of drainage class assignment within each texture class for the SL, LS, and S subclasses is shown in Fig. 4 for the drainage assignments based on McKeague et al. (1986) criteria, and in Fig. 5 for assignments based on Day (1983) criteria. In most cases, a single drainage class is dominant within each texture subclass. For example, of all the unique combinations in the data set that classify as coarse sand texture class, the majority are determined to be rapidly drained (Fig. 4), with some smaller amounts of observations classifying as well and very rapidly drained, based on McKeague et al. (1986) criteria. In other cases, such as for the LS and LcS classes, the drainage class assignments were more evenly split between two drainage classes, in these cases between well and rapidly drained. This serves as a reminder that variability does exist in terms of AWHC, and thus drainage class assignment, within the individual soil texture classes, a concept that can be lost when converting continuous attributes (i.e., AWHC) to categorical attributes (i.e., drainage class) for ease of interpretation. Regardless, the dominant drainage class for each texture class was used as the representative drainage class. In contrast to the distribution of drainage class assignments across the texture classes based on McKeague et al. (1986) criteria (Fig. 4), the assignments based on Day (1983) are much less variable,

Table 7. Recommended drainage classes for freely draining soils without observable redoximorphic features for all textures in combination with coarse fragment content and/or depth to bedrock.

Texture class	Coarse fragments (% by volume)/depth to bedrock (cm)				
	0%/100 cm	15%/85 cm	35%/65 cm	60%/40 cm	90%/10 cm
cS	R	R	R	VR	VR
S	R	R	R	VR	VR
fS	W	W	R	R	VR
vfS	W	W	R	R	VR
LcS	W	R	R	VR	VR
LS	W	R	R	VR	VR
LfS	MW	W	R	R	VR
LvfS	MW	W	R	R	VR
cSL	W	W	R	R	VR
SL	W	W	R	R	VR
fSL	MW	W	W	R	VR
vfSL	MW	W	W	R	VR
L	MW	W	W	R	VR
Si	MW	MW	W	R	VR
SiL	MW	MW	W	R	VR
SCL	W	R	R	VR	VR
CL	MW	W	W	R	VR
SiCL	MW	MW	W	R	VR
SC	W	W	R	VR	VR
C	MW	W	W	R	VR
SiC	MW	MW	W	R	VR
HC	MW	MW	W	R	VR

Note: HC, heavy clay; SiC, silty clay; C, clay; SC, sandy clay; SiCL, silty clay loam; CL, clay loam; SCL, sandy clay loam; Si, silt; SiL, silt loam; L, loam; vfSL, very fine sandy loam; fSL, fine sandy loam; SL, sandy loam; cSL, coarse sandy loam; LvfS, loamy very fine sand; LfS, loamy fine sand; LS, loamy sand; LcS, loamy coarse sand; vfS, very fine sand; fS, fine sand; S, sand; cS, coarse sand; VR, very rapidly drained; R, rapidly drained; W, well drained; MW, moderately well drained.

and result almost exclusively in moderately well drained soils, clearly illustrating that assigning drainage classes for non-redoximorphic soils based on these criteria is ill-advised (Fig. 5).

Soil drainage classes assigned by interpretation of the AWHC limits from Day (1983) and from McKeague et al. (1986), as well as from interpretation of the flowchart from Heck et al. (2017), are summarized in Tables 3, 4, and 5 for the S, LS, and SL texture classes, respectively. This comparison reveals several inconsistencies. In the case of sand textures (Table 3), AWHC values translate to moderately well drainage classes as defined based on criteria from Day (1983) for all four texture subclasses (vfS, fS, S, and cS), except for soils containing ≥60% (extremely gravelly/cobbly/stony textures) and ≥90% (i.e., fragmental particle size) coarse fragments by volume. Soils dominated by extremely gravelly/cobbly/stony textures (≥60% coarse fragments by volume) ranged from moderately well to rapidly drained, while all fragmental soils (≥90% coarse fragments by volume) were predicted to be very rapidly drained. Similar inconsistencies were obtained for loamy sands (Table 4) and sandy loams (Table 5).

Drainage classes assigned based on AWHC criteria from McKeague et al. (1986) were more consistent with current drainage classes based on overall criteria outlined in Heck et al. (2017) and were more intuitive based on the range of textures and particle sizes. Very rapid drainage classes are predicted for all free-draining non-redoximorphic fragmental soils (≥90% coarse fragments), regardless of subfraction classes for S, LS, and SL (Tables 3, 4, and 5). All skeletal soils (consisting of ≥35% to <90% coarse fragments by volume) were predicted to be rapidly drained or very rapidly drained except for vfSL and fSL, which were well drained (Table 5). With the least amounts of coarse fragments (<35% by volume), vfS and fS were well drained, while S and cS textures were rapidly drained (Table 3). Loamy sands (Table 4) and sandy loams (Table 5) were either well or rapidly drained except for LfS, vfSL, and fSL textures that were predicted to be moderately well drained, based on AWHC values defined by McKeague et al. (1986).

Drainage classes from textural data other than SL, LS, and S based on calculated AWHC values are shown in Fig. 6 and summarized in Table 6. Comparison of drainage classes assigned based on Day (1983) with those of McKeague et al. (1986) shows a similar trend to the coarser textured soils, with most drainage classes predicted as MW except for fragmental and some extremely gravelly/cobbly/stony textures. Based on these observations, it is proposed that estimates for AWHC to determine drainage class be based on those provided by McKeague et al. (1986) rather than those provided by Day (1983). Recommended drainage classes for free-draining soils based on AWHC for all textures in combination with coarse fragment contents/depth to bedrock are summarized in Table 7. These revisions reflect drainage classes for free-draining soils in the absence of any redoximorphic features.

Implications for acceptance of the proposed revisions in the CSSC

The proposed changes described herein will mainly influence the section on soil water regime in Chapter 17 of the CSSC (SCWG 1998; p. 157) where reference is made to various sections of "the Manual" referring to Day (1983).

Conclusions and recommendations

Based on the above results, a summary of recommended drainage classes for non-redoximorphic soils based on calculated values for AWHC is provided in Table 7. These drainage classes, based on AWHC, should be adopted as part of the CSSC. The following conclusions were drawn based on the results presented here:

- Distinction between fine and very fine sand vs. medium, coarse, and very coarse sand is a key requirement for differentiation of drainage classes in coarse-textured non-redoximorphic soils.
- Documented AWHC ranges provided by McKeague et al. (1986) should be used to assign drainage classes for non-redoximorphic soils in favour of those provided by Day (1983).
- Coarse fragment content and depth to bedrock must be included as additional considerations for estimating soil drainage class.

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Author information

Author ORCIDs

Daniel D. Saurette https://orcid.org/0000-0002-1971-1238

Author notes

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References

Baetens, J.M., Verbist, K., Dornelis, W.M., Gabriels, D., and Soto, G. 2009. On the influence of coarse fragments on soil water retention. Water Resour. Res. **45**: W07408. doi:10.1029/2008WR007402.

British Columbia. 2010. Field manual for describing terrestrial ecosystems. 2nd ed. Land Management Handbook. Research Branch, British Columbia Ministry of Forests and Range and Resources Inventory Branch, British Columbia Ministry of Environment. Victoria, BC.

Contreras, C.P., and Bonilla, C.A. 2018. A comprehensive evaluation of pedotransfer functions for predicting soil water content in environmental modeling and ecosystem management. Sci. Total Environ. **644**: 1580–1590. doi:10.1016/j.scitotenv.2018.07.063. PMID: 30743870

Day, J. (*Editor*). 1983. The Canada Soil Information System (CanSIS). Manual for describing soils in the field, 1982 revised. Land Resource Research Institute Contribution No. 82–85. Research Branch, Agriculture Canada, Ottawa, ON.

de Jong, R., and Shields, J.A. 1988. Available water holding capacity maps of Alberta, Saskatchewan and Manitoba. Can. J. Soil Sci. **68**: 157–163.

Dobarco, M.R., Cousin, I., Bas, C.L., and Martin, M.P. 2019. Pedotransfer functions for predicting available water capacity in French soils, their applicability domain and associated uncertainty. Geoderma, **336**: 81–95. doi:10.1016/j.geoderma.2018.08.022.

Haluschak, P., Griffiths, J., and Shaykewich, C.F. 2004. Available water holding capacities of Manitoba soils. *In* Proceedings of the 47th Annual Manitoba Soil Science Society Meeting, 3–4 February 2004. pp. 224–232.

Heck, R.J., Kroetsch, D.J., Lee, H.T., Leadbeater, D.A., Wilson, E.A., and Winstone, B.C. 2017. Field manual for describing and classifying sites, soils and substrates in Ontario. School of Environmental Sciences, University of Guelph, Guelph, ON.

Kirkham, M.B. 2014. Field capacity, wilting point, available water, and the nonlimiting water range. *In* Principles of soil and plant water relations. 2nd ed. pp. 153–170. doi:10.1016/B978-0-12-420022-7.00010-0.

McKeague, A.J., Wang, C., and Coen, G.M. 1986. Describing and interpreting the macrostructure of mineral soils—a preliminary report. Land Resource Research Institute, LRRI Contribution No. 84-50. Agriculture Canada, Ottawa, ON. 47pp.

Manitoba Agriculture, Food and Rural Initiatives. 2007. Manual for describing soils in the field, revised 2007. Winnipeg, MN. Available from https://www.gov.mb.ca/agriculture/soil/soil-survey/pubs/manual_for_describing_soils_in_the_field.pdf.

Matthews, B.C. 1963. Report on soil moisture. *In* Report on the 5th Meeting of the National Soil Survey Committee of Canada, Winnipeg, MB, 4–8 March 1963. pp. 64–65.

Myeni, L., Mdlambuzi, T., Paterson, D.G., De Nysschen, G., and Moeletsi, M.E. 2021. Development and evaluation of pedotransfer functions to estimate soil moisture content at field capacity and permanent wilting point for South African soils. Water, **13**: 2639. doi:10.3390/w13192639.

Ontario Centre for Soil Resource Evaluation (OCSRE). 1993. Field manual for describing soils in Ontario. 4th ed. Publication 93-1, 2009 printing. Ontario Centre for Soil Resource Evaluation, Guelph Agricultural Centre, Guelph, ON. 62pp.

Pennock, D.J. 2005. Field handbook for Saskatchewan soils. Department of Soil Science, University of Saskatchewan, Saskatoon, SK.

Pennock, D.J., Watson, K., and Sanborn, P. 2016. Field guide to the soils of western Canada. Canadian Society of Soil Science. Available from https://soilsofcanada.ca/links.php.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Saurette, D.D. 2021. onsoilsurvey: making PDSM in Ontario better. R package version 0.0.0.9000.

Saxton, K.E., and Rawls, W.J. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. **70**: 1569–1578. doi:10.2136/sssaj2005.0117.

Soil Classification Working Group (SCWG). 1998. The Canadian System of Soil Classification. 3rd ed. Agriculture and Agri-Food Canada Publication No. 1646 (revised). 187pp.

Tam, S., Nyvall, T.J., and Brown, L. 2005. Plants, soil and water (Chapter 5). *In* BC Irrigation Management Guide. *Edited by* T.W. van der Gulik. Resource Management Branch, BC Ministry of Agriculture, Food and Fisheries.