

# Classification of acid sulfate soils and soil materials in Finland and Sweden: Re-introduction of para-acid sulfate soils



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## Abstract

Established international soil classification systems have not properly accommodated acid sulfate soils (ASS) and soil materials in Finland and Sweden because: (1) in these soils some diagnostic ASS properties are too deep to meet the depth requirements, and (2) there is a lack of defined diagnostic soil classification criteria for acidic and potentially acidic soil materials that do not completely fulfill the diagnostic pH-criterion of  $\text{pH} < 4.0$ . In this paper, two new ASS materials are introduced with the prefix “para” for parasulfuric material (oxidized material) and parahypersulfidic material (reduced material). These materials have diagnostic pH-criteria of  $\text{pH} 4.0\text{--}4.5$  and  $3.0\text{--}3.5$  (field-pH for parasulfuric material and incubation-pH for parahypersulfidic material) for mineral and organic soil materials (here defined as  $> 20\%$  organic matter; peat and gytja), respectively. The term “para-acid sulfate soil (para-ASS) material” is introduced for soil materials which may have a considerable environmental impact due to mobilization of acidity and dissolved metals. Because organic acids may lower pH to values below the established pH-value of  $< 4.0$  for ASS materials, a pH of  $< 3.0$  is used in the Finnish-Swedish ASS classification for organic soil materials. These changes and new additions to existing diagnostic ASS materials have consequently also led to a slight modification of the required field-pH values of the existing terms “hypersulfidic material” and “sulfuric material”. The Finnish-Swedish ASS classification

further includes a systematic way for classification of the entire soil profile and no depth requirements for diagnostic ASS materials are present; what matters is the current or potential environmental impact that the soil has or may have. It is proposed that the Finnish-Swedish ASS classification may serve as a framework for establishing a unified ASS classification globally and that the new diagnostic ASS materials are included in relevant international soil classification systems.

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Keywords: Acid sulfate soil classification, para-acid sulfate soils, parahypersulfidic, parasulfuric, hypersulfidic

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## 1 Introduction

Acid sulfate soils (ASS) are globally defined as soils in which sulfuric acid is produced from oxidation of sulfidic material during soil formation processes in such quantities that the soil pH has dropped or may drop below 4 (e.g., Pons 1973). This soil type is therefore considered one of the worst soil types in the world (Dent & Pons 1995). The general definition of ASS has, in the past, encompassed potential acid sulfate soils (PASS), active (or actual) acid sulfate soils (AASS), and post-active acid sulfate soils (e.g., Fanning et al. 2017). Nevertheless, because these terms are not commonly defined or used in national or international soil classification systems, and to avoid potential confusion arising from these broad ASS types, the terms “sulfuric soils” and “hypersulfidic soils” have recently been introduced to be used instead of “active acid sulfate soils” and “potential acid sulfate soils”, respectively (e.g., Fitzpatrick 2013; Fitzpatrick et al. 2017a). In this paper, we adopt these refined terms.

Acid sulfate soil profiles in Finland and Sweden typically consists of: (1) a uniform brown-greyish topsoil plough layer (c. 30 cm) with circumneutral pH due to the application of agricultural lime, (2) a horizon with redoximorphic features comprising brownish (iron oxyhydroxides) and pale yellow (jarosite) redox concentrations and low pH (mostly < 3.8–4.0) due to sulfide oxidation, (3) greyish redox depletions in transition layer where the pH

ranges between c. 4 and 6, and (4) a uniform black or dark coloured, due to the presence of iron sulfide minerals, redox depletion layer (parent sediment) with predominantly neutral pH values (Fig. 1).

Mapping of ASS on the coastal plains of Finland and Sweden has been carried out by the Geological Survey of Finland (GTK) (Geological Survey of Finland 2023; Edén et al. 2023 this volume) and the Geological Survey of Sweden (SGU) (Geological Survey of Sweden 2023a). These ASS mapping surveys primarily focused on the coastal regions that were covered by the Baltic Sea during the Littorina Sea stage (e.g., Ojala et al. 2013), and are today elevated above sea level due to glacial isostasy (Fig. 2). The land area corresponding to the maximum extent of the Littorina Sea is about 5 010 000 ha in Finland, whereas the land area corresponding to the highest marine limit (including the maximum extent of the Littorina Sea) in Sweden is almost 10 000 000 ha (cf. Pässe & Daniels 2015). The potential area for ASS occurrences on the west coast of Sweden is not solely defined by the maximum extent of the Littorina Sea. In Finland, the mapping programme took place 2009–2021 and has resulted in an occurrence map showing the probability (four classes) to encounter ASS (Edén et al. 2023 this volume). In Sweden, systematic ASS mapping has been done since 2012 and today there are ASS occurrence maps for several catchments. The total extent of ASS occurrences in Finland has recently been estimated to around 1 000 000 ha (Edén et al. 2023 this volume).

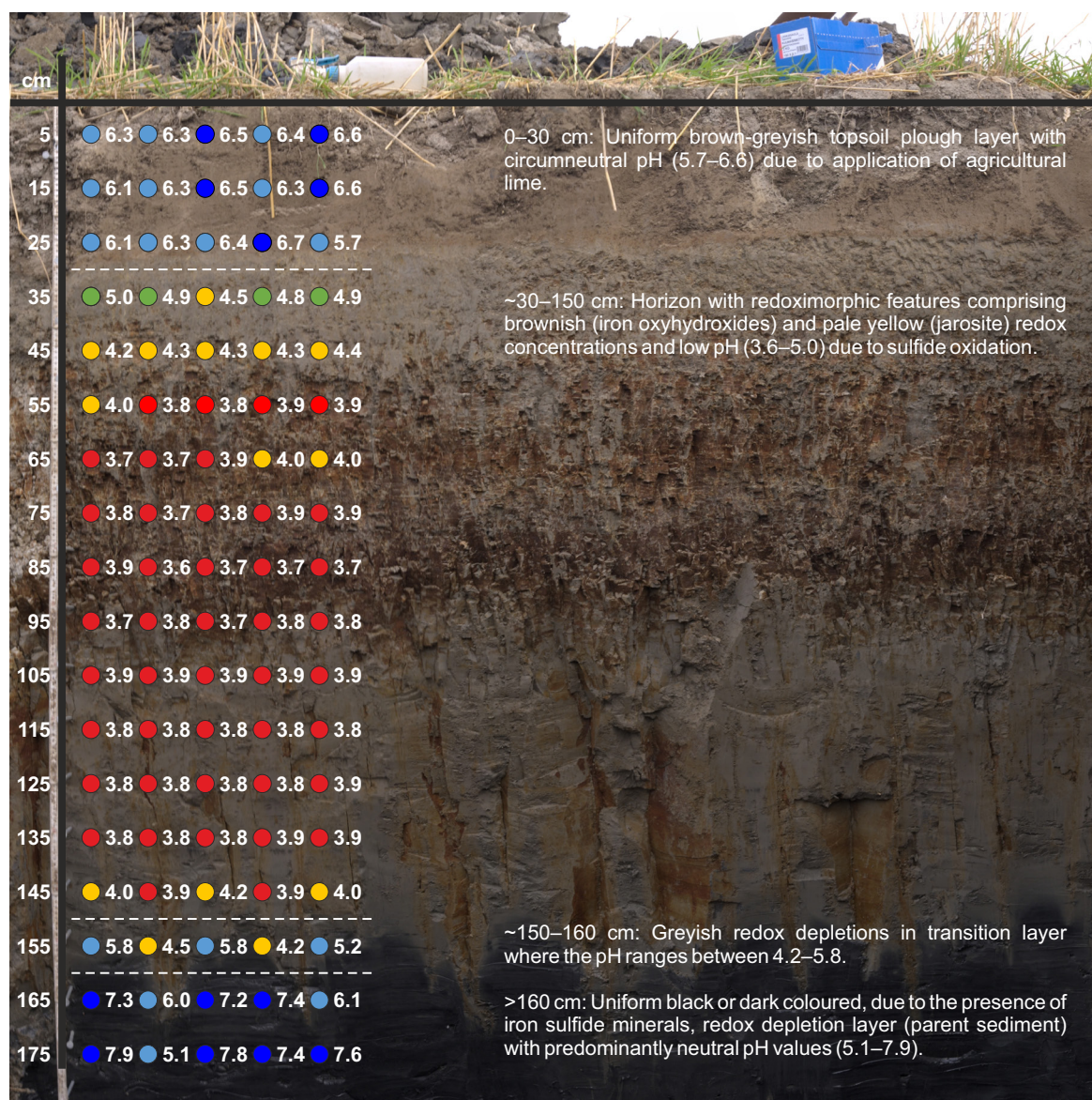


Figure 1. A typical acid sulfate soil (ASS) profile from Söderfjärden in western Finland consisting of mainly fine-grained (clay and silt) and gyttja-containing (2–20% organic matter) soil materials. Note that the range of pH varies considerably (pH 3.6–7.9) vertically, and that pH also displays a slight horizontal variation, especially where soil cracks result in a wavy boundary between the horizons, like the one between the brown and black horizon around 160 cm.

The definitions, diagnostic criteria and terminology for ASS materials set by the International Acid Sulfate Soils Working Group in 2008 (Sullivan et al. 2010) have largely been adopted in Finland and Sweden. However, the ASS mapping surveys raised the necessity to identify soil properties that are important to consider in the

classification and risk assessment of these potentially harmful soils. Thus, some modifications have been proposed and implemented in the Finnish-Swedish ASS classification. Previously, Finnish and Swedish ASS have not been adequately characterized and classified according to international soil taxonomy systems, such as previous versions (prior to 2015)



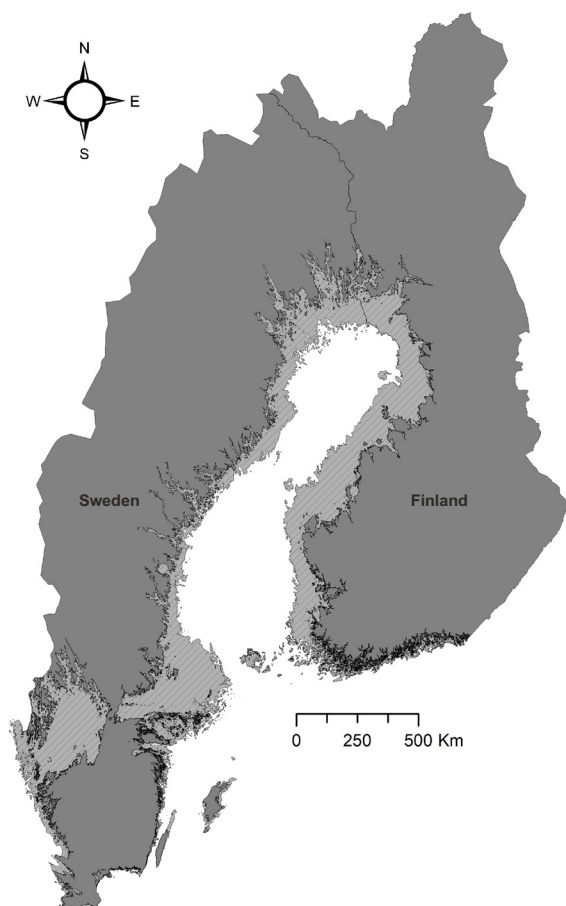


Figure 2. The potential area (light grey colour) in Finland and Sweden where acid sulfate soils (ASS) are frequently occurring. This land area corresponds to the maximum extent of the Littorina Sea in Finland and the highest marine limit (including the maximum extent of the Littorina Sea) in Sweden.

of the “World reference base for soil resources” (hereafter WRB) and both past and current versions of “Keys to Soil Taxonomy” (hereafter KST) (e.g., Soil Survey Staff 2022). This is because the typical ASS properties and diagnostic materials are commonly located too deep to fulfill the depth criteria present in these international soil classification systems (e.g., Yli-Halla et al. 1999). Typically, only the uppermost 1–1.5 m of the soil profile, depending on classification system, have been considered. The depth criteria have been waived from the updated WRB (IUSS Working Group WRB 2015, 2022) and since 2015 they

have no longer been an issue. However, some problematic issues remain regarding the pH criteria. In WRB, sulfuric material must have a field-pH < 4.0 and hypersulfidic material should have an incubation-pH < 4.0. Many soils in Finland and Sweden contain acidic soil materials in the oxidized horizon, with a pH slightly above 4.0 (i.e., not fulfilling diagnostic criteria for sulfuric or thionic horizons). Such materials may still have a considerable acidifying impact on the environment although they are not currently considered ASS materials according to the criteria of the established international classification systems. There are indications of mobilization of acidity and potentially harmful elements, particularly Al, into watercourses from these soil materials. Typically, these soils have hypersulfidic material in reduced parts of the soil, but there is no good way to indicate the acidic properties in the oxidized horizon using the nomenclature of the available international classification systems.

Using the current criteria of the international classification systems, there are also limitations for classification of organic soil materials (here defined as > 20% organic matter; peat and gyttja), which are very common in boreal and arctic regions (e.g., peatlands). In these soil materials, the pH may be low due to organic acids (often < pH 4.0) and not because of sulfide oxidation. These two new discoveries have led to a need to include new diagnostic ASS materials and to make minor changes to the existing definitions and diagnostic ASS criteria in the Finnish-Swedish ASS classification.

Here we present a unified classification system for ASS materials, including ASS profiles, that can be used in Finland and Sweden by environmental authorities and research organisations working with ASS related issues. This ASS classification system is the outcome of the extensive characterization of ASS properties, such as pH, acidity, sulfur, and organic matter, obtained during ASS surveys.

## 2 Origin of acid sulfate soil materials in Finland and Sweden

The parent sediment from which ASS are formed is typically organic-rich (gyttja-containing) fine-grained sediment (sapropel) but may comprise also coarse-grained parent soil materials such as littoral and delta sediments, as well as glacial till. In the present context, and in accordance with the internationally widely used ASS terminology, the term “soil material” also includes the parent sediment, which may or may not have been subjected to soil forming processes. Soil material is here further categorized by composition into “mineral soil material” and “organic soil material” (loss on ignition, LOI > 20%). The main types of soil material described in this publication are: (1) non-ASS material, (2) ASS material, and, according to our proposal, (3) para-ASS material. These are defined in detail in Section 4 and its subsections.

### 2.1 Postglacial sediments

In Finland and Sweden, the mineral soil materials (siliciclastic sediments) that form ASS are typically layered sediments of varying grain sizes (e.g., clay, silt, sand fractions). The siliciclastic sediments contain variable amounts of organic material (mineral soil material with LOI < 20%) and are interbedded with organic soil material. In ASS surveys, the mineral soil materials are divided into fine-grained (< 63 µm, clay-silt) and coarse-grained (≥ 63 µm, e.g., sand and gravel) material (see Figs. 3 and 4), and the fine-grained ASS material is usually regarded as environmentally the most unfavourable one (Mattbäck et al. 2017, 2022).

The postglacial sediments were deposited in the preceding Littorina Sea and uplifted due to the isostatic rebound, taking place after the melting of the Weichselian ice sheet. Sorted coarse-grained soil materials associated with ASS are commonly river delta deposits or beach/littoral sediments composed of reworked glaciofluvial materials. Sorted fine-grained mineral soil materials represent several

basin stages of the current Baltic Sea. Reducing conditions, favourable for sulfide formation in sediments, were not common in the coastal areas of the basin, before brackish-water conditions were established in the Littorina Sea stage (cf. Winterhalter 1992). Accordingly, the sediments formed in earlier Baltic Sea phases are mostly not developed into sulfuric soils. During the past 8 000 years, reducing conditions and an abundance of organic matter, sulfate and iron allowed the build-up of gyttja-containing sedimentary units. In this paper, the term “gyttja-containing” refers to mineral soil materials with 2–20% organic matter (as LOI), whereas “gyttja” refers to organic soil material (LOI > 20%; cf. Haavisto-Hyvärinen & Kutvonen 2007). Gyttja started to form after the melting of the continental ice sheet (Haavisto-Hyvärinen & Kutvonen 2007), and still today, organic-rich, sulfidic sediments are continuously formed in shallow coastal areas in Finland and Sweden (e.g., Mokma et al. 2000; Boman et al. 2010).

The sapropelic sediments show a characteristic dark grey or black colour caused by the presence of iron sulfides. Black sediment colour is an indicator for the presence of metastable iron sulfides, such as mackinawite and greigite (Boman et al. 2008), whereas abundance of the more stable pyrite usually results in more greyish colours and makes the identification of these horizons more difficult by visual observation.

### 2.2 Peat

Peat (here defined according to the national Finnish criteria as soil material having an organic matter content of > 40%, LOI) occurs both covering and interlayering glacial till and the postglacial sedimentary successions (Haavisto-Hyvärinen & Kutvonen 2007) and is commonly the most important component of organic soil materials. Most typically, a peat layer forms over the glacial and postglacial sediments, and many presently sulfuric soils in Finland and Sweden were therefore once covered with peat. If the peat cover is not removed, it may serve as a protective layer and prevent extensive oxidation of hypersulfidic materials underneath

(cf. Nystrand et al. 2021). However, due to land use, for instance agriculture or peat extraction, this peat layer has in many areas been decomposed or removed and a sulfuric soil has formed (Yli-Halla et al. 2017).

Peat (and gyttja) may be naturally acidic (pH < 4.0 not uncommon) due to the presence of organic acids (e.g., Shotyk 1988; Haavisto-Hyvärinen & Kutvonen 2007). In an extensive peat survey done by GTK, the average pH in Finnish peat was 4.4 with a range of 2.2–6.9 (Herranen 2009). A low pH in this type of material should therefore not automatically be regarded as a consequence of sulfide oxidation. However, although peat typically comprises mainly organic forms of sulfur, several studies have indicated that inorganic forms of sulfur may be abundant (e.g., Papunen 1966; Hadzic et al. 2014; Dalhem et al. 2021; Visuri et al. 2021), acidifying the environment when oxidized. Thus, peat may serve as a protective layer against the oxidation of underlying sulfidic material. At the same time, it can act as a source of acidity through the oxidation of inherent sulfidic material, leading to formation of sulfuric material. The presence of ASS materials in peat landscapes have been documented, among others, in Denmark (e.g., Madsen et al. 1985), northern Germany (Gröger 2013), and Australia (e.g., Dear et al. 2023), and their presence in Finland has also been reported earlier (e.g., Erviö 1975; Yli-Halla et al. 1999; Auri et al. 2012; Edén et al. 2014; Hannukkala et al. 2015). Extensive peatlands exist in Finland (ca. 10 000 000 ha) and Sweden (ca. 6 000 000 ha), which may serve as an important, but largely unknown, source of ASS that should be investigated more thoroughly in the future. In a recent report by Visuri et al. (2021), it was indicated that peat materials having a total sulfur concentration of > 1% (most as inorganic sulfur) often transforms into sulfuric soils if they are oxidized.

### 2.3 Glacial till

Some sulfidic materials are related to glacial till containing black shale material eroded from the

bedrock by the continental ice. Glacial till having pH values < 4.0 in their oxidized parts as well as after incubation has been encountered occasionally during the ASS mapping in Finland (Edén et al. 2023 this volume). Such soil materials are here referred to as unsorted ASS materials. Sulfidic black shales are found in various places in the bedrock of Finland and Sweden (Geological Survey of Sweden 2023b; Loukola-Ruskeeniemi, 2023). It has been shown that such glacial till occasionally contain high sulfide concentrations which may upon oxidation acidify the environment (cf. Loukola-Ruskeeniemi et al. 1998; Mäkilä et al. 2012). Some studies, not related to ASS mapping, indicate that unsorted ASS generally occur in bedrock regions with black shales or sulfide mineralisations (cf. Herranen 2009; Hadzic et al. 2014).

## 3 The need for introducing para-acid sulfate soil materials

An important issue in the classification of ASS is how to handle soil materials, where the pH, due to sulfide oxidation, drops considerably during incubation in the laboratory or, field conditions, reaching values close to but not triggering the diagnostic criteria for sulfuric and hypersulfidic material. According to the present WRB (IUSS Working Group 2022) and the Australian soil classification (Isbell & NCST 2021), such soil materials are classified as hyposulfidic materials. It is recognized that hyposulfidic material does not form ASS upon oxidation (IUSS Working Group 2022), and the classification further implies an intermediate to weak degree of acidification (Isbell & NCST 2021). However, the criteria for defining hyposulfidic material are very broad, encompassing pH values ranging from 4 to ~9. Within this extensive pH-range, hyposulfidic material can have a field-pH of  $\geq 4$ , which, after incubation may drop by at least 0.5 pH-units but not fall below 4. Recent studies in Finland have shown that there are sulfidic materials (reduced), which upon incubation, experience a substantial pH-drop from near-neutral

values to close to, but not below, 4 (below pH 3 in organic soil materials). Nevertheless, these soil materials may have a significant environmental impact due to release of acid and metals (especially Al) (e.g., Mattbäck et al. 2017, 2022). Mapping of ASS in Finland and Sweden has drawn attention to areas covered by such soil materials (i.e., reduced sulfidic material) and oxidized soil materials with a field-pH of 4–4.5 (pH 3–3.5 for organic soil materials), which is acidic but not triggering the criteria for sulfuric material. The current definition of hyposulfidic material does not adequately indicate the degree of acidification, which may be quite substantial for this type of acidic soil material. Therefore, this soil material, including both acidic and potentially acidic soil materials, needs to be identified and clearly classified as a separate diagnostic ASS material.

In the literature, acidic soils that are close to fulfilling the pH-criterion for ASS due to sulfide oxidation, have previously been considered pseudo- or para-acid sulfate soils (from Greek *pseudos*, lie, fake and Greek *para*, alongside) (e.g., Pons 1973; Brinkman and Pons 1973; Boer 1979). In previous reports and conference abstracts by Finnish and Swedish researchers (e.g., Visuri et al. 2021; Auri et al. 2022; Autiola et al. 2022; Boman et al. 2023), the prefix “pseudo” has been used instead of the prefix “para”. However, due to the pejorative meaning of the prefix “pseudo” and the common conception that this prefix should be avoided in scientific context, we prefer the prefix “para” and suggest that it is hereafter used for defining soils and soil materials that are close to fulfilling ASS diagnostic criteria. Since the introduction in the 1960s, the term “para-acid sulfate soil” has been used rather sparingly by the ASS community, even though exceptions do exist (e.g., van Breemen 1976). Now this term is re-introduced in the Finnish-Swedish ASS classification. The definition of para-acid sulfate soil materials is further extended to include two completely new ASS materials, not found in any current international soil taxonomy systems, for describing soil materials which are close to fulfilling the diagnostic criteria of hypersulfidic

and sulfuric material, i.e., parahypersulfidic and parasulfuric material. These new diagnostic ASS materials are defined and discussed in detail below.

The term “para-acid sulfate soil” (“pseudo cat clay” in the original publication) was already applied by Leen Pons in the early 1960s to describe acid soils in Surinam having a pH between 4–5 formed by oxidation of sulfidic sediments with “low” (< 0.64%) pyrite concentrations and with no presence of carbonates (Pons 1965). During the first International Acid Sulfate Soils Conference in Wageningen 1972, “pseudo acid sulfate soils” were defined by Brinkman & Pons (1973) as soils containing one or more horizons with the characteristic yellow mottling (i.e., jarosite) commonly associated with acid sulfate conditions, but which do not have a pH below 4 and do not contain free acids or have more than about 60% of cation exchange sites occupied by Al. In the Soil Classification for Surinam (Boer 1979), the term pseudo acid sulfate soil was used for describing acid soils having a pH-KCl of > 3 and < 3.5 (pH ≤ 3 is considered ASS in that classification) and which did not have toxic Al-concentrations. The extent of para-acid sulfate soils has previously been mapped in Thailand (van Breemen 1976). The definition of para-acid sulfate soils (here abbreviated as para-ASS) differs somewhat among the above-mentioned sources, including differences in pH thresholds. However, common denominators for para-ASS include being: (1) low in sulfidic compounds, (2) poor in carbonates, (3) acidic but not fulfilling the diagnostic pH-criteria for sulfuric and hypersulfidic materials, and (4) lacking toxic Al-concentrations. In this sense, the definition of Finnish-Swedish para-ASS materials (see below), where also Al leaching may be of concern, differs slightly from the previous definitions.

It has been shown that para-ASS materials may sometimes contain higher total sulfur concentrations and higher titratable incubation acidities (TIA) compared with some types of ASS materials (Visuri et al. 2021; Figs. 3 and 4). This is often the case if the para-ASS material consists of fine-grained materials (clay and silt) and the ASS

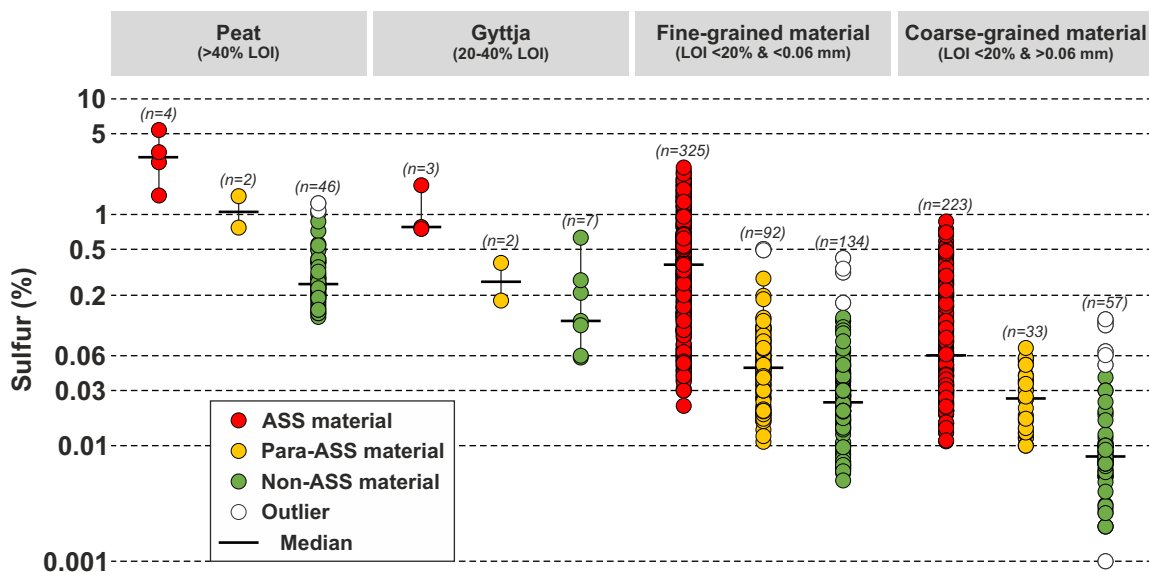


Figure 3. Distribution of total sulfur in reduced acid sulfate soil (ASS) materials (hypersulfidic material), para-acid sulfate soil (para-ASS) materials (parahypersulfidic material), and non-ASS materials based on grain size and organic matter content (loss on ignition, LOI). The classification of soil materials follows the current Finnish-Swedish ASS classification. Both fine- (clay and silt) and coarse-grained (e.g., sand and gravel) materials include gyttja-containing materials (2–20% LOI). Total sulfur concentrations were determined by dissolution with *aqua regia* followed by IPC-OES for quantification. Slightly modified after Visuri et al. (2021).

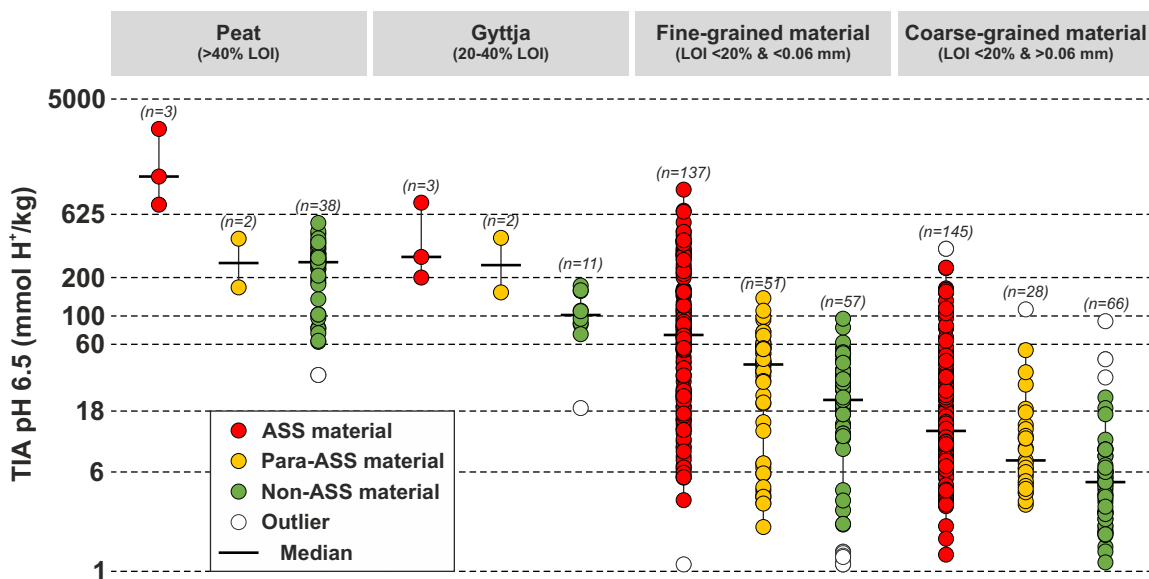


Figure 4. Distribution of titratable incubation acidity (TIA) in acid sulfate soil (ASS) materials (hypersulfidic material), para-acid sulfate soil (para-ASS) materials (parahypersulfidic material), and non-ASS materials based on grain size and organic matter content (loss on ignition, LOI). The classification of soil materials follows the current Finnish-Swedish ASS classification. Both fine- (clay and silt) and coarse-grained (e.g., sand and gravel) materials include gyttja-containing materials (2–20% LOI). TIA was determined on incubated (at least 19 weeks) soil samples using procedures based on KCl extraction followed by titration with NaOH, as described in Österholm & Nystrand (2016) and Mattbäck et al. (2017). Slightly modified after Visuri et al. (2021).



consists of coarse-grained materials (e.g., sand and gravel) (Figs. 3 and 4). By including diagnostic para-ASS materials, the risk of leaving out potentially harmful soils is minimised.

Another important reason for including para-ASS materials (i.e., parasulfuric and parahypersulfidic material) in the Finnish-Swedish ASS classification, emphasizing the environmental risk, is to encompass soil materials where, in addition to acidity leaching, the mobilization of bioavailable Al can be an environmental hazard but where the acidity formed is not sufficient to trigger the diagnostic pH-criterion for sulfuric material. At pH values of 4 to 5, trivalent Al is present in soils (dissolved in pore water or as an exchangeable cation) unless they contain high concentrations of organic matter (Thomas 2006). In the study by Peltola & Åström (2002), it was indicated that above a soil pH of ca. 4.5, Al is mainly immobile in various oxide and silicate minerals. However, as the pH decreases, Al becomes increasingly soluble and is leached from the soil. This often results in severe problems for organisms living in water and fish kills are frequent unwanted phenomena in ASS landscapes in Finland and Sweden as well as in other similar places globally. Nystrand & Österholm (2013) showed that the runoff from ASS (low pH and organic C) contained more bioavailable Al compared with the runoff from forested areas (higher pH and organic C) where Al was primarily complexed with colloidal organic C. Similar results have been reported by Helmer et al. (1990) who showed that in acidic (low pH) peatland waters rich in organic matter Al is generally complexed (up to 90%) with dissolved organic matter (i.e., not bioavailable), whereas in waters with a low dissolved organic matter content Al exist to a large part in the most toxic form,  $\text{Al}^{3+}$ . It has also been shown in two artificial soils (sand and montmorillonite) mixed with 10% organic matter that the amount of exchangeable Al was much higher in the soils where no organic matter was added (Thomas 2006). Consequently, in organic soils (e.g., peatland areas), high acidity (resulting from both sulfide oxidation and occurrence of organic acids) is therefore most

likely a larger issue than problems associated with leaching of bioavailable Al.

## 4 Unified classification for acid sulfate soil materials in Finland and Sweden

Diagnostic ASS materials significantly influence pedogenetic processes in ASS and para-ASS or are indicative of them and include all soil materials (and parent sediment) containing sulfidic and sulfuric material as well as their para-variants (i.e., parasulfuric and parahypersulfidic material). To fulfill classification as an ASS material, the diagnostic criteria (i.e., certain numerical values such as pH and sulfide concentration) need to be within the given threshold values. An overview of diagnostic ASS materials and their diagnostic criteria (sulfur and pH) is presented in Table 1 and described in more detail below (see 4.1 and 4.2). Some examples of ASS materials are presented in Fig. 5.

The most common approach to identify ASS materials is to use pH-measurements obtained directly from the field and/or during soil incubation (for reduced or partly oxidized soil material). Soil incubation is often considered the best approach to study soil acidifying processes as it lets the soil “speak for itself” (Dent 1986). Soil pH depends not only on the occurrence of sulfidic materials but also on many other factors such as the presence of organic matter, carbonates (inorganic or organic forms), clay minerals and aluminium and iron oxides, which either may produce acidity or neutralize the acidity in the soil (Thomas 2006). When interpreting incubation-pH for soil materials rich in organic matter, such as peat, some caution is needed, whereas for mineral soil materials, pH values below 4 is usually a very good indication of sulfide oxidation. For instance, organic acids may lower pH to < 4.0 in peat (e.g., Shotyck 1988), whereas soil pH values of 2–3 usually indicate the presence of sulfuric acid ( $\text{H}_2\text{SO}_4$ ), which generally is due to the oxidation of iron sulfides (Thomas 2006). For these reasons, a lower pH limit of < 3.0

Table 1. Overview of diagnostic acid sulfate soil (ASS) materials and their classification criteria. The limits for sulfidic-S, AVS-S, and  $\text{SO}_4$  are presented as mass fraction (%) of total dry weight. Note that for sulfuric and parasulfuric material,  $\geq 0.05\%$  water-soluble sulfate do not need to be fulfilled if there are other signs of sulfide oxidation (see Section 4.2).

Diagnostic ASS material	Diagnostic criteria								Comment
	Sulfur (%)			pH					
	Sulfidic-S	AVS-S <sup>a)</sup>	SO <sub>4</sub>	Field		Incubation			
Mineral				Organic	Mineral	Organic	Drop		
Sulfidic	≥0.01	-	-	-	-	-	-	-	Same criteria as in <sup>b), c), d)</sup>
Hypersulfidic	≥0.01	-	-	≥4.0	≥3.0	<4.0	<3.0	≥0.5	Modified criteria compared to <sup>b), c), d)</sup>
Parahypersulfidic	≥0.01	-	-	>4.5	>3.5	4.0-4.5	3.0-3.5	≥0.5	New term
Hyposulfidic	≥0.01	-	-	≥4.0	≥3.0	>4.5	>3.5	-	Modified criteria compared to <sup>b), c), d)</sup>
Monosulfidic	-	≥0.01	-	-	-	-	-	-	Same criteria as in <sup>b), c)</sup>
Hypermonosulfidic	-	≥0.01	-	≥4.0	≥3.0	<4.0	<3.0	≥0.5	Modified criteria compared to <sup>b)</sup>
Parahypermonosulfidic	-	≥0.01	-	>4.5	>3.5	4.0-4.5	3.0-3.5	≥0.5	New term
Sulfuric	-	-	≥0.05	<4.0	<3.0	-	-	-	Modified criteria compared to <sup>b), c)</sup>
Parasulfuric	-	-	≥0.05	4.0-4.5	3.0-3.5	-	-	-	New term

<sup>a)</sup>AVS = Acid volatile sulfide

<sup>b)</sup>Sullivan et al. (2010)

<sup>c)</sup>Isbell & NCST (2021)

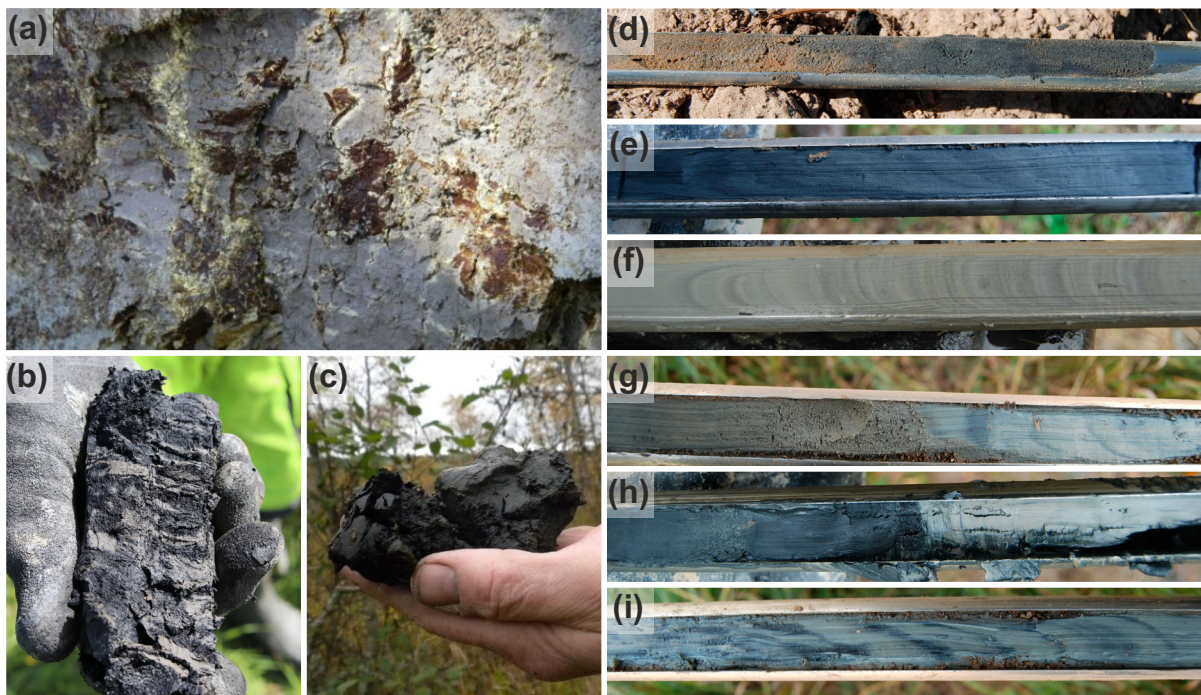


Figure 5. Examples of various types of acid sulfate soil (ASS) materials commonly found in Finnish and Swedish ASS. (a) Sulfuric material containing jarosite (yellow mottles) and iron hydroxides in gyttja-containing silt (oxidized). (b) Clayey hypersulfidic material with monosulfidic bands. (c) Black coloured hypermonosulfidic material (similar to the material in Fig. e). (d) Hypermonosulfidic black sand, upper part (left) oxidized. (e) Weakly stratified gyttja-containing hypermonosulfidic silt. (f) Stratified gyttja-containing hypersulfidic silt. (g) Gyttja-containing hypersulfidic silt on top (left) of bluish-gray clay with black monosulfidic bands (deposited in the Ancylus Lake; often classified as hyposulfidic or parahypersulfidic material) with an erosional contact (thin sandy layer) in-between. (h) Sharp erosional contact between gyttja-containing black hypersulfidic silt (left) and underlying grey massive hyposulfidic clay (right). (i) Massive bluish-gray clay with black monosulfidic bands (similar to the material in the lower part in Fig. g).

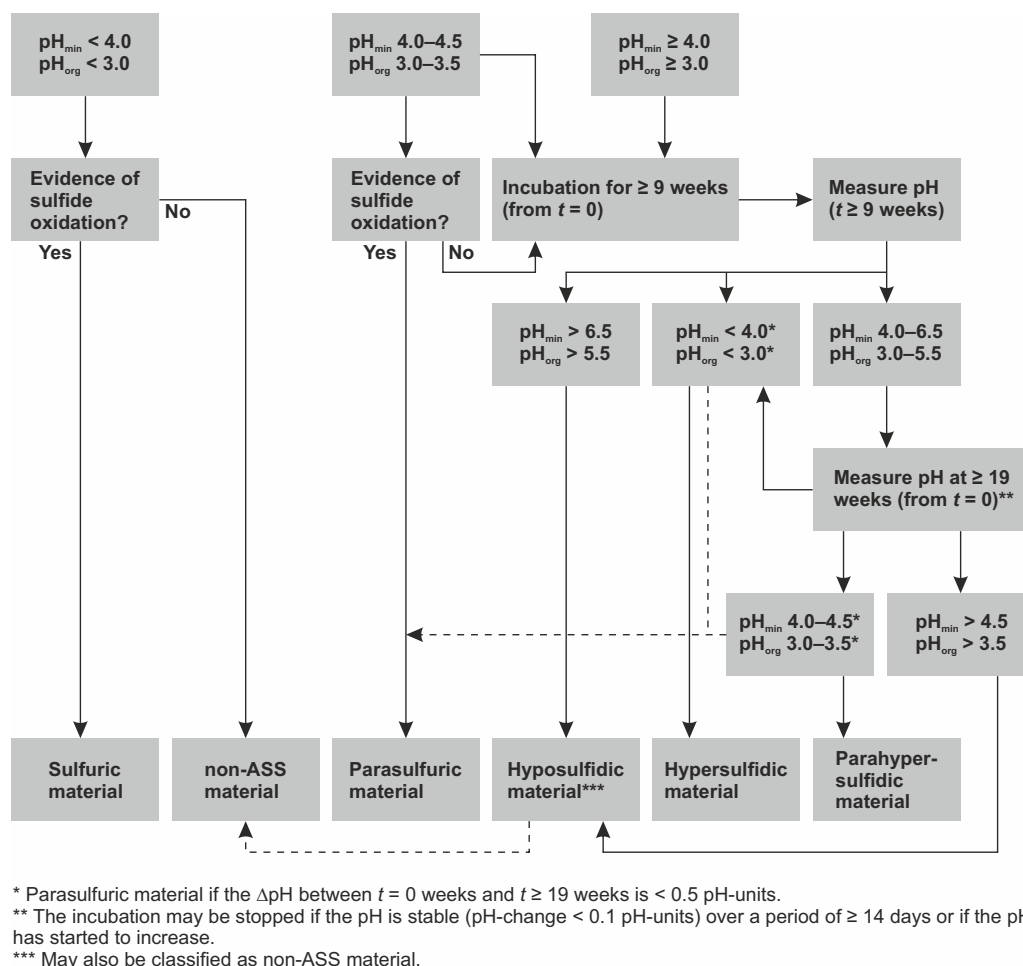


Figure 6. A flow chart showing the procedure for classification of acid sulfate soil (ASS) materials based on field- and incubation-pH. Note that hypersulfidic, parahypersulfidic, and hyposulfidic may be monosulfidic.

for classification of organic soil materials is used in the Finnish-Swedish ASS classification.

During soil incubation, acid-generating oxidation reactions will occur and if the amount of acidity produced during soil oxidation exceeds its acid-neutralizing capacity, the soil will acidify, which can be seen as a drop in pH. The soil incubation approach used in Finland and Sweden follows, with some minor adjustments (modified pH thresholds for mineral and organic soil materials), the procedures described in Creeper et al. (2012). In this method, the soil is incubated under moist conditions (maintained by regular addition

of deionised water) in room temperature for at least 9 weeks and up to 19 weeks. The procedure for classification of ASS materials using pH and the soil incubation method is illustrated in Fig. 6.

The soil incubation proceeds until: (1) at  $\geq 9$  weeks, the soil pH has changed by  $\geq 0.5$  pH units and reached values  $< 4.0$  and  $< 3.0$  for mineral and organic soil materials, respectively (i.e., classified as hypersulfidic), (2) at  $\geq 9$  weeks, the pH has remained stable (pH change  $< 0.1$  pH-units over a period of  $\geq 14$  days) or has started to increase, (3) at  $\geq 9$  weeks, the pH is  $\geq 6.5$  and  $\geq 5.5$  for mineral and organic soil materials, respectively; a lower pH-

limit is used for peat as it is naturally more acidic than mineral soil materials, or (4) at  $\geq 19$  weeks and none of the above criteria is fulfilled. It is important to know the accuracy of the pH-measurement used for ASS classification as this may have a huge impact on how the soil material is finally classified (i.e., ASS material or not). For instance, in internationally established soil taxonomy systems, there is a distinct pH-limit separating ASS materials (e.g., hypersulfidic and sulfuric/thionic material) from non-ASS materials (e.g., hyposulfidic material) meaning that if there is a large uncertainty in the pH-measurements, a material classified as non-ASS material may in fact be ASS material. This problem is somewhat addressed in the Finnish-Swedish ASS classification by adding parasulfuric and parahypersulfidic material. During GTK's classification, it was observed that the soil pH may vary around 0.1–0.2 pH-units when using a Hamilton Flatrode electrode and a WTW 3320 multi meter. This need to be taken into consideration when the incubation-pH results are interpreted. Also, due to the spatial variability of soil, small vertical and horizontal pH-variations typically occur in the soil (see Fig. 1) even at small distances.

## 4.1 Sulfidic materials

Sulfidic materials refer to soil materials (mineral and organic) containing  $\geq 0.01\%$  (dry weight) sulfidic sulfur. The diagnostic criteria for sulfidic materials in the Finnish-Swedish ASS classification are the same as in Sullivan et al. (2010), the WRB version from 2015 (IUSS Working Group 2015), and in the Australian soil classification (hereafter ASC) (Isbell & NCST 2021). The term “sulfidic materials” has been excluded from the current version of WRB (IUSS Working Group 2022). In the most recent version of the ASC, the thickness of sulfidic materials has been set at 30 mm.

The total sulfide concentration can be determined using the chromium reducible sulfur (CRS) method described in Backlund et al. (2005), Boman (2008), Burton et al. (2008), and Dalhem et al. (2021). For fine-grained ( $< 63 \mu\text{m}$ , i.e., clay and

silt fractions) mineral soil materials, the analysis of total sulfur (e.g., aqua regia dissolution followed by ICP-OES/MS) can be sufficient, because previous studies have shown that most of the sulfur in such materials is usually in sulfidic form (e.g., Boman 2008). For organic soil materials, such as peat, it is not advisable to use this approach as a significant proportion of the sulfur may be bound into the molecular structures of organic matter (e.g., Boman et al. 2010; Visuri et al. 2021).

Depending on how the soil pH changes during the incubation of sulfidic materials, several subgroups are identified and include: hypersulfidic, parahypersulfidic, and hyposulfidic material, which are characterized in detail and presented below.

### 4.1.1 Hypersulfidic material

Hypersulfidic material (see Fig. 5 for some examples) is defined as sulfidic material ( $\geq 0.01\%$  sulfidic sulfur) capable of very strong acidification as a result of oxidation of contained sulfides. It should be noted that hypersulfidic material is also commonly referred to as “potential ASS material”. The Finnish-Swedish ASS classification uses the same diagnostic criteria for hypersulfidic material in mineral soil materials as in Sullivan et al. (2010) and in the current WRB soil classification (IUSS Working Group, 2022) and in the ASC (Isbell & NCST 2021) but with a criterion of  $\text{pH} < 3.0$  for organic soil materials where the contribution to the acidity may be significant also from organic acids.

Hypersulfidic material is in a reduced state, but also partially oxidized soil materials, e.g., in the transition zone of an ASS, may contain enough sulfidic materials to lower the pH during incubation below the diagnostic criteria.

Hypersulfidic material in the Finnish-Swedish ASS classification has the following diagnostic criteria:

- (1)  $\geq 0.01\%$  sulfidic sulfur (dry mass); *and*
- (2) A field-pH of  $\geq 4.0$  for mineral soil materials and  $\geq 3.0$  for organic soil materials ( $> 20\%$  organic matter, e.g., peat and gytja), that undergoes a drop in pH to  $< 4.0$  and  $< 3.0$ ,



respectively, when a 2–10 mm thick layer of material is incubated (oxidized) under moist conditions for 9–19 weeks following the incubation procedure described above (Section 4).

According to Thomas (2006), soil pH values of 2–3 indicate the presence of sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and for this reason a pH-drop to  $< 3.0$  during incubation has been added to the Finnish-Swedish ASS classification for recognition of hypersulfidic material in organic soil materials. In Hadzic et al. (2014), it was suggested that for peat, a field and/or incubation-pH of  $< 3.0$  (pH-drop  $\geq 0.5$  units) or incubation-pH  $< 3.5$  if the pH-drop has been  $> 1$  pH-unit, should be used for indicating acidification due to sulfide oxidation. If it can be proven that the pH-drop in organic soil materials (e.g., peat) is mainly due to sulfide oxidation, the pH-criterion for mineral soil materials may be used instead. The source(s) of acidity can for instance be studied by using a suite of analytical methods such as the CRS-methods (e.g., Backlund et al. 2005; Boman 2008; Burton et al. 2008; Dalhem et al. 2021), which gives the total sulfide concentration, together with titratable incubation acidity (TIA; Österholm & Nystrand 2016; Mattbäck et al. 2017), giving an estimate of the amount of acidity (expressed as  $\text{mmol H}^+ / \text{kg}$ ) formed during oxidation. In peat, TIA is generally very high due to the influence of organic acids. By comparing the potential acidity calculated from CRS, obtained by multiplying with 623.7 (Sullivan et al. 2018), with the TIA results, it is possible to give a crude estimate of the contribution from sulfide oxidation and other sources, such as organic acids. Obviously, several buffering agents will most likely occur in the soil, such as clay minerals, organic matter, and carbonates, which will influence the amount of acidity produced, and the interpretations should be used carefully.

In the current “Keys to Soil Taxonomy” (KST) published by the United States Department of Agriculture and the Natural Resources Conservation Service (Soil Survey Staff 2022),

the concept of sulfidic materials aligns with the concept of hypersulfidic materials used in the WRB and ASC. The diagnostic characteristics of sulfidic materials in KST are quite similar (drop to pH 4.0 or less when incubated) to those described here and in the WRB from 2015 (IUSS Working Group WRB 2015) and the ASC (Isbell & NCST 2021). However, KST includes soil materials with a pH value of  $> 3.5$  (regardless of pH-drop during incubation) and containing  $> 0.75\%$  sulfur (dry mass and mainly in sulfidic form), and less than three times as much calcium carbonate equivalent as sulfur.

#### 4.1.2 Parahypersulfidic material

Parahypersulfidic material is a new term and corresponds to sulfidic material ( $\geq 0.01\%$  sulfidic sulfur) that is capable of moderate to strong acidification because of the oxidation of contained sulfides but where the resulting pH-drop is not sufficient to trigger the pH threshold for being classified as hypersulfidic material (see Fig. 5 for some examples). Parahypersulfidic material in mineral soils can be a potential environment hazard due to the risk of leaching of acidity, as well as leaching of bioavailable Al, into watercourses. In organic soil materials, acidification is most likely a larger problem than leaching of bioavailable Al. In Fitzpatrick et al. (2008), a similar term, “pseudo sulfidic”, was used for describing sulfidic material with an incubation-pH value between 4 and 5.

Parahypersulfidic material in the Finnish-Swedish ASS classification has the following diagnostic criteria:

- (1)  $\geq 0.01\%$  sulfidic sulfur (dry mass); *and*
- (2) A field-pH of  $> 4.5$  for mineral soil materials and  $> 3.5$  for organic soil materials ( $> 20\%$  organic matter), that undergoes a drop in pH to 4.0–4.5 and 3.0–3.5, respectively, when a 2–10 mm thick layer of material is incubated (oxidized) under moist conditions for at least 19 weeks following the incubation procedure described above (Section 4).

### 4.1.3 Hyposulfidic material

Hyposulfidic material is not capable of very strong acidification because of the oxidation of contained sulfides (see Fig. 5 for some examples). The Finnish-Swedish definition for hyposulfidic material is conceptually the same as the definitions presented in Sullivan et al. (2010), WRB (IUSS Working Group WRB 2015, 2022), KST (Soil Survey Staff 2022), and the ASC (Isbell & NCST 2021), but has slightly modified diagnostic criteria for field- and incubation-pH (Table 1) because of the introduction of parahypersulfidic material and a lower pH-criterion for organic soil materials. Thus, during incubation none of the diagnostic criteria for hypersulfidic or parahypersulfidic material are fulfilled. It should be pointed out that hyposulfidic material may contain high sulfide concentrations, but due to presence of inherent neutralizing agents (e.g., shell material), and/or high buffering capacity, the produced acid is partially neutralized.

In the transition zone between oxidized and reduced soil materials, circumstances may arise where sulfidic material is partially oxidized, the starting pH during incubation exceeds the field-pH criteria (Table 1), and the final incubation-pH falls below the diagnostic criteria for parahypersulfidic and hypersulfidic material. However, if the criterion for the pH-drop ( $\geq 0.5$  pH-units) is not met, the material is thus classified as hyposulfidic material, even though the pH-drop is likely attributed to the oxidation of sulfidic material. One such example could be a mineral soil material where the field-pH is 4.8 and the final incubation-pH is 4.4, which means that the diagnostic criteria for parahypersulfidic material (or hypersulfidic material) is not fulfilled as the pH-drop is only 0.4 pH-units. In cases where the soil is partially oxidized and the starting pH is for instance 4.4 and the pH-drop is 0.4 pH-units to 4.0, the soil material can be classified as parasulfuric material based on the field-pH (Fig. 6). If the pH-drop in the example above had been 0.5 pH-units, resulting in a pH of 3.9, the material would be classified as hypersulfidic material. The potential error margin during soil pH-

measurements alone may be sufficient for incorrect classification of soil materials. These examples emphasize the need for careful interpretations of pH changes during incubation and ASS classification.

### 4.1.4 Monosulfidic materials

The definition of monosulfidic material (see Fig. 5 for examples) in the Finnish-Swedish ASS classification is the same as in Sullivan et al. (2010) and in the ASC (Isbell & NCST 2021). Monosulfidic material refers to sulfidic material that contains  $\geq 0.01\%$  (dry weight) acid volatile sulfides (AVS). The AVS fraction is generally considered to comprise metastable iron sulfides such as mackinawite (FeS) and greigite (Fe<sub>3</sub>S<sub>4</sub>) (Boman et al. 2008) and is usually the reason for the dark or black colour (see Fig. 5 for examples) of sulfidic materials in postglacial sediments in Finland and Sweden. These metastable iron sulfides usually oxidize rapidly (into elemental sulfur), within hours, upon exposure to oxygen which results in the sediment colour turning from dark grey/black to light grey.

Monosulfidic material is further classified in the same way as sulfidic material and the corresponding subgroups are therefore also possible for monosulfidic material:

- Hypermonosulfidic material consists of both monosulfidic and hypersulfidic material.
- Parahypermonosulfidic material is a new term for describing a material consisting of both monosulfidic and parahypersulfidic material.
- Hypomonosulfidic material consists of both monosulfidic and hyposulfidic material.

It is, however, suggested that the term monosulfidic should be used only when the soil material exhibits a very dark colour (e.g., black or dark grey) characterized for example by the Munsell colour chart and the presence of “monosulfides” (i.e., AVS) have been demonstrated using reliable methods. In the surveys done by GTK, monosulfide-rich soil materials commonly have a hue darker than GLEY 2 5/10PB in the Munsell chart (see Fig. 5). In the laboratory, the AVS concentration can be determined using the methods described in among

others, Backlund et al. (2005), Boman (2008), and Dalhem et al. (2021). In the field, monosulfidic material can for instance be identified using the so-called whiff test (e.g., Darmody et al. 1977) where HCl is added to the sample and the smell of rotten egg ( $\text{H}_2\text{S}$ ) indicates the presence of AVS. Presence of AVS can be semi-quantitatively determined by placing a filter paper soaked in lead acetate within a closed chamber. In this setup, the reaction between monosulfides and subsequently added HCl forms  $\text{H}_2\text{S}$ , which precipitates as black PbS on the filter paper (Pellegrini et al. 2018). Furthermore, the relatively quick (hours) colour change from dark (often black) to lighter colours (greyish) during oxidation of reduced soil materials is a good indication of presence of monosulfidic material.

## 4.2 Sulfuric material and sulfuric horizon

The definition for sulfuric material in the Finnish-Swedish ASS classification is conceptually the same as in Sullivan et al. (2010) and the ASC (Isbell & NCST 2021) but with slightly modified diagnostic criteria for organic soil materials (peat and gyttja). Because a pH of  $< 3.0$  in soils is indicative of oxidation of sulfidic material (Thomas 2006), a lower pH-limit (pH  $< 3.0$ ) for organic soil materials is used for distinguishing a low pH due to sulfide oxidation from a low pH originating from organic acids.

Sulfuric material in the Finnish-Swedish ASS classification has the following diagnostic criteria:

- (1) A field-pH of  $< 4.0$  and  $< 3.0$  for mineral and organic soil materials, respectively, when measured during field conditions as a result of the oxidation of sulfidic materials. Evidence for sulfide oxidation, besides the low pH, is adopted from the descriptions in Sullivan et al. (2010) and includes one or more of the following:
  - (a) Mottles and coatings with accumulations of jarosite  $[\text{KFe}_3(\text{OH})_6(\text{SO}_4)_2]$  or other iron and aluminium sulfate or hydroxysulfate minerals such as natrojarosite  $[\text{NaFe}_3(\text{SO}_4)_2(\text{OH})_6]$ , schwertmannite

$[\text{Fe}_{16}(\text{OH}, \text{SO}_4)_{12-13} \text{O}_{16} \times 10-12\text{H}_2\text{O}]$ , sideronatriite  $[\text{Na}_2\text{Fe}(\text{SO}_4)_2(\text{OH}) \times 3\text{H}_2\text{O}]$ , tamarugite  $[\text{NaAl}(\text{SO}_4)_2 \times 6\text{H}_2\text{O}]$  etc. Jarosite is a common mineral in Finnish and Swedish ASS materials, and natrojarosite has been identified (e.g., Öborn & Berggren 1995). The presence of schwertmannite, sideronatriite, and tamarugite is not well documented for ASS materials in Finland (schwertmannite has recently been identified by Yli-Halla et al. 2017 and Changxun et al. 2023) and Sweden but is commonly identified by XRD in Australian ASS (e.g., see references in Sullivan et al. 2010; Fitzpatrick et al. 2017b).

- (b)  $\geq 0.05\%$  (mass fraction of total dry weight) water-soluble sulfate. This criterion is included because it indicates the presence of soluble Al-Fe hydroxysulfates (Sullivan et al. 2010).
- (c) Underlying hypersulfidic (or monohypersulfidic) material.

If the sulfuric material has a thickness of  $\geq 15$  cm, it may be termed a “sulfuric horizon”, which is conceptually the same as the definition of a thionic horizon (pH  $< 4.0$ ) in the current WRB (IUSS Working Group WRB 2022) and in the KST (sulfuric horizon; pH  $\leq 3.5$  or pH  $< 4.0$  if evidence of sulfide oxidation is present; Soil Survey Staff 2022), but with the addition of a lower diagnostic pH-criterion (i.e., pH  $< 3.0$ ) for organic soil material. If the water-soluble sulfate concentration is  $\geq 0.05\%$  (i.e., criterion 1b), the sulfuric material is considered “active ASS material” and thus currently producing acidity.

### 4.2.1 Parasulfuric material

Parasulfuric material is a new term and includes soil material showing signs of oxidation of sulfidic material but where the field-pH is not low enough for triggering the diagnostic pH-criterion for

classification as sulfuric material. Quite often ASS, and especially fine-grained types, in Finland and Sweden contain soil materials that have a field-pH between 4.0 and 4.5 in the oxidized horizon. This means that they do not fulfill any diagnostic ASS criteria of the major international soil taxonomy systems (e.g., Isbell & NCTS 2021; IUSS Working Group WRB 2022; Soil Survey Staff 2022). In fact, these soils are generally considered to be among the most harmful soils in Finland and Sweden in terms of environmental impact. Without the recognition of parasulfuric material as a diagnostic ASS material, these soils would be classified as either non-ASS or hypersulfidic soils (if they have underlying hypersulfidic material), even though they are indeed often very active and releasing acidity and Al, along with other potentially harmful elements into watercourses.

Parasulfuric material in the Finnish-Swedish ASS classification has the following diagnostic criteria: a field-pH between 4.0–4.5 for mineral soil materials and between 3.0–3.5 for organic soil materials, when measured during field conditions and due to oxidation of sulfidic material (Table 1). Evidence for sulfide oxidation is the same as described for sulfuric material, but it may not be as evident for criterion 1a for sulfuric material (see Section 4.2) as many typical  $\text{Fe-SO}_4$  minerals precipitate at pH values below 4. Similar to sulfuric material, parasulfuric material is considered “active ASS material” if the water-soluble sulfate concentration is  $\geq 0.05\%$  (mass fraction of total dry weight).

## 5 Unified classification system for acid sulfate soil profiles in Finland and Sweden

The umbrella terms acid sulfate soil (ASS) and para-acid sulfate soil (para-ASS) are broad and encompass soils where sulfuric material, hypersulfidic material, and/or hypermonosulfidic

material, including their para-variants (parasulfuric and parahypersulfidic material), occur in the soil profile. In many international soil taxonomy systems, typical ASS properties in Finnish and Swedish ASS are commonly located too deep to fulfill the depth criteria set for various soil types. This was also the case in the older versions of WRB but has been updated in previous editions (IUSS Working Group 2015, 2022) to allow soil properties present deep down in the profile. This means that the depth requirement is no longer an issue in the current WRB, where the prefix “bathy” (derived from the Greek word “bathus”, which means “deep”) can be used to attribute ASS properties (e.g., bathyhypersulfidic) also several meters below the soil surface. In “Keys to soil taxonomy” (Soil Survey Staff 2022), there is still a depth criterion for ASS properties (e.g., sulfuric and sulfidic materials within 50–150 cm of the soil surface depending on soil type), which are often not met in many Finnish and Swedish ASS. Therefore, many environmentally relevant ASS escape appropriate classification when the KST system is applied. Consequently, the use of KST cannot be recommended for ASS of Finland and Sweden.

Even though the depth criteria are no longer an issue in WRB (IUSS Working Group 2015, 2022), there are still issues to take into account with such soil materials (i.e., parasulfuric material) where the acidification and release of Al and other potentially harmful elements can be quite severe but do not fulfill the pH-criterion ( $\text{pH} < 4$ ) of a given ASS property (e.g., hypersulfidic and sulfuric/thionic). The abundance of organic soils (e.g., peat) in Finland and Sweden having naturally low pH values due to humic acids (cf. Herranen 2009), and which often also contain sulfidic materials, indicates the need for a modified (lowered) pH-criterion for this type of soil material. Due to these reasons, there is a need for a modified ASS classification in Finland and Sweden, and in other environments with similar conditions. In the Finnish-Swedish ASS classification, there are no depth requirements for presence of diagnostic ASS materials; what matters is the actual or potential harmful impact the soil



Table 2. Acid sulfate soils (ASS) and para-acid sulfate soils (para-ASS) are divided into two main soil types (in plain bold) with a further subdivision into four soil subtypes (in bold italics). The ASS and para-ASS subtypes can, in turn, be subdivided into soil subtypes (in plain italics), where the diagnostic ASS/para-ASS properties are indicated. Included in sulfuric soils are also soils lacking sulfuric material but having both parasulfuric and hypersulfidic material. Detailed definitions of the soil types and soil subtypes are found in the text.

<b>Acid sulfate soils (ASS)</b>		
<b>Sulfuric soils</b>		<b>Hypersulfidic soils</b>
<i>Sulfuric organic soil</i>	<b>&lt; Organic ASS &gt;</b>	<i>Hypersulfidic organic soil</i>
<i>Sulfuric fine-grained soil</i>	<b>&lt; Fine-grained ASS &gt;</b>	<i>Hypersulfidic fine-grained soil</i>
<i>Sulfuric coarse-grained soil</i>	<b>&lt; Coarse-grained ASS &gt;</b>	<i>Hypersulfidic coarse-grained soil</i>
<i>Sulfuric unsorted soil</i>	<b>&lt; Unsorted ASS &gt;</b>	<i>Hypersulfidic unsorted soil</i>
<b>Para-acid sulfate soils (para-ASS)</b>		
<b>Parasulfuric soils</b>		<b>Parahypersulfidic soils</b>
<i>Parasulfuric organic soil</i>	<b>&lt; Organic para-ASS &gt;</b>	<i>Parahypersulfidic organic soil</i>
<i>Parasulfuric fine-grained soil</i>	<b>&lt; Fine-grained para-ASS &gt;</b>	<i>Parahypersulfidic fine-grained soil</i>
<i>Parasulfuric coarse-grained soil</i>	<b>&lt; Coarse-grained para-ASS &gt;</b>	<i>Parahypersulfidic coarse-grained soil</i>
<i>Parasulfuric unsorted soil</i>	<b>&lt; Unsorted para-ASS &gt;</b>	<i>Parahypersulfidic unsorted soil</i>

may have on the environment regardless of which depth the ASS material is located.

## 5.1 Acid sulfate soil and para-acid sulfate soil types

To classify as an ASS, the soil must have a direct (active) or indirect (potential) acidifying impact on soil and/or water due to the influence of diagnostic ASS materials and contain at least one of the following:

- (1) Sulfuric material with a combined thickness of  $\geq 15$  cm; *and/or*
- (2) Parasulfuric material with a combined thickness of  $\geq 15$  cm *and* hypersulfidic (incl. monosulfidic) material with a combined thickness of  $\geq 15$  cm within 1 m of the oxidation depth, and/or the lowermost part of organic soil materials such as peat and gyttja; *and/or*
- (3) Hypersulfidic (incl. monosulfidic) material with a combined thickness of  $\geq 15$  cm within 1 m of the oxidation depth, and/or the lowermost part of organic soil materials such as peat and gyttja.

Acid sulfate soils are further divided into sulfuric soils (acid producing; synonym “active or actual ASS”) and hypersulfidic soils (potentially acid

producing; synonym “potential ASS”) depending on whether they have started to produce and leach acidity or if they contain sulfidic material that may start producing acidity if exposed to oxygen (Table 2).

Sulfuric soils contain either sulfuric material and/or parasulfuric material together with hypersulfidic material, as defined above, whereas hypersulfidic soils contain only hypersulfidic material. After the sulfidic material has been exposed to oxidation and leaching for a sufficient time, much of the acidity and sulfate generated from the immediate oxidation of sulfidic compounds has been removed from the soil profile. Acid sulfate soils that have been leached (e.g., sulfate) to such an extent that they no longer meet the criteria for a sulfuric soil are also sometimes referred to as “post-active ASS” (Fanning 2002). However, the pH of the remaining soil material in this type usually stabilizes at 4.0–4.5 (i.e., classified as parasulfuric material), and metals, Al in the first place, are dissolved from the soil matrix in abundant amounts (e.g., Sundström et al. 2002). Despite the exhaustion of acidity associated with sulfide oxidation, residual acidity contained in jarosite and schwertmannite (e.g., Vithana et al. 2013) can result in a substantial environmental load for a long time. Therefore, also “post-active” ASS (i.e., containing parasulfuric material) in Finland and Sweden can be substantial sources of environmental

loading, justifying the classification of this type of soil material separately from the non-ASS materials. Moreover, the cryic temperature regime (Yli-Halla & Mokma 1998) and commonly aquic moisture regime in Finland and Sweden may contribute to slower oxidation of sulfidic materials, especially in very fine-grained soils (clay and silt), resulting in less drastic pH values in soil. In coarse-grained ASS (e.g., sand extraction areas), the active phase of the ASS may be quite short as the poor buffering capacity and high permeability for sandy soil materials quickly discards acidifying products, which lead to a pH-rise and often with no signs of sulfide oxidation (i.e., post-active ASS properties are not recognised in the field). Under these circumstances, the ASS could quite quickly transition from a sulfuric soil into a hypersulfidic soil (if there are hypersulfidic materials at depth). If the groundwater table in such areas is further lowered and hypersulfidic material at depth is oxidized, the hypersulfidic soil would become active again.

To be classified as a para-ASS, the soil must contain at least one of the following materials:

- (1) Parasulfuric material with a combined thickness of  $\geq 15$  cm; *and/or*
- (2) Parahypersulfidic material with a combined thickness of  $\geq 15$  cm within 1 m of the oxidation depth, and/or the lowermost part of organic soil materials such as peat and gyttja.

Para-acid sulfate soils thus do not contain either sulfuric or hypersulfidic material and can further be divided into parasulfuric soils (moderately acid producing) and parahypersulfidic soils (potentially moderately acid producing, containing only parahypersulfidic material), depending on whether they are active or not (Table 2). If none of the diagnostic criteria for ASS or para-ASS are fulfilled, the soil is classified as a non-ASS.

### 5.1.1 Acid sulfate soil and para-acid sulfate soil subtypes

The ASS and para-ASS types are further divided into four broad soil subtypes based on their organic matter content and the presence of certain mineral soil materials: 1) organic ASS/para-ASS, 2) fine-grained ASS/para-ASS, 3) coarse-grained ASS/para-ASS, and 4) unsorted ASS/para-ASS (i.e., hypersulfidic/parahypersulfidic material is contained in the glacial till) (Table 2). The ASS and para-ASS subtypes can, in turn, be further subdivided into specific soil subtypes indicating diagnostic ASS/para-ASS properties, such as sulfuric organic soil, hypersulfidic fine-grained soil, parasulfuric organic soil, and parahypersulfidic fine-grained soil (Table 2). Selections of ASS and para-ASS subtypes are illustrated in Figs. 7–11.

The naming of the soil type is based on the first (uppermost) encountered soil material (mineral or organic soil material) that contains a diagnostic ASS material, following a certain thickness requirement that is explained below. Hypersulfidic and sulfuric material are prioritised before any para-ASS material if both are present in the soil profile. For example, if the first encountered diagnostic ASS material is fine-grained para-ASS material, which is overlying coarse-grained ASS material, then the profile will be classified as a “coarse-grained ASS”. If there are only para-ASS materials present, the profile is classified as a para-ASS.

For organic ASS, the combined thickness of the diagnostic ASS materials consisting of organic soil material must be  $\geq 40$  cm, or if there are no underlying diagnostic mineral ASS materials, a combined thickness of  $\geq 15$  cm organic ASS materials is sufficient. Organic para-ASS are classified using the same thickness and depth requirements for organic ASS materials.

For fine-grained ( $< 63 \mu\text{m}$ ), coarse-grained ( $\geq 63 \mu\text{m}$ ), and unsorted ASS (i.e., containing glacial till), including the para-ASS variants of these, the combined thickness of the diagnostic ASS material must be  $\geq 15$  cm to name the profile. For instance, if the first encountered diagnostic

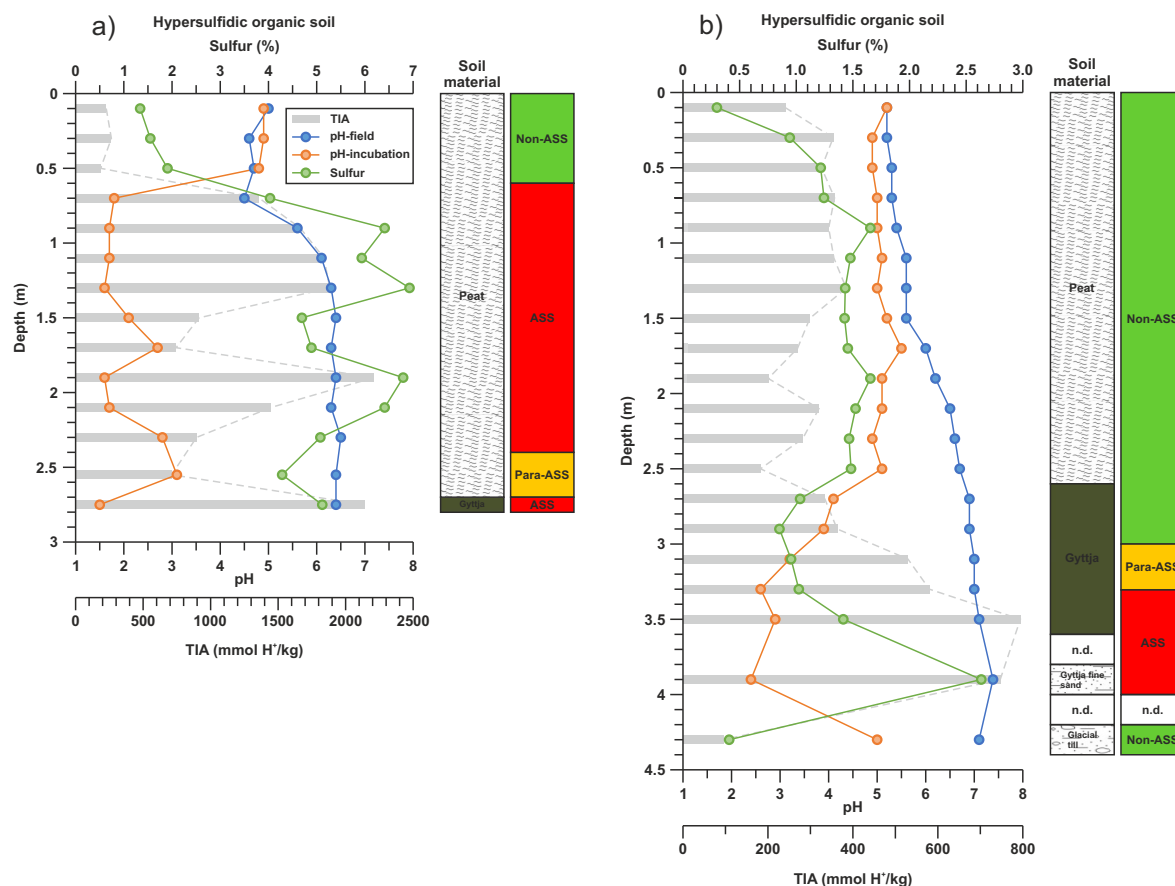


Figure 7. Two examples of hypersulfidic organic soil subtypes, where the acid sulfate soil (ASS) properties (hypersulfidic material) are present in the peat (profile a), gytja (both profiles), and in the gytja-containing fine sand (profile b). Para-acid sulfate soil (para-ASS) properties (parahypersulfidic material) are present in the peat (profile a) and gytja (profile b). TIA = titratable incubation acidity.

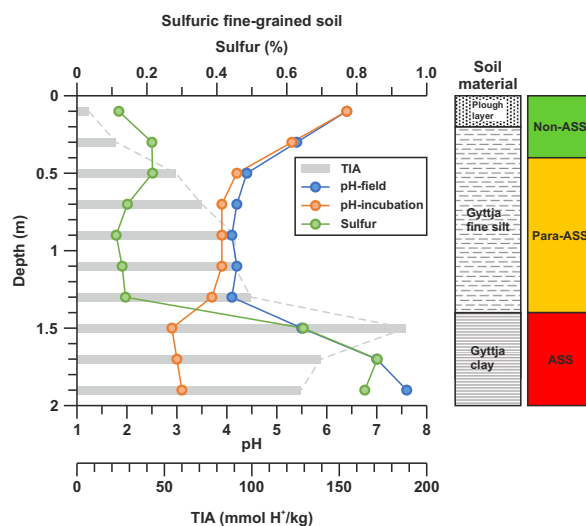


Figure 8. An example of a sulfuric fine-grained soil subtype, where the acid sulfate soil (ASS) properties (hypersulfidic material) are present in the gytja-containing clay. Para-acid sulfate soil (para-ASS) properties (parasulfuric material) are present in the gytja-containing fine silt. Note that the coexistence of parasulfuric and hypersulfidic material designates the profile as "sulfuric". Note the leaching of acidity, which is noticed in the low pH, the loss of sulfur, and decreasing titratable incubation acidity (TIA) towards the surface of the soil. The elevated pH in the plough layer is due to liming.

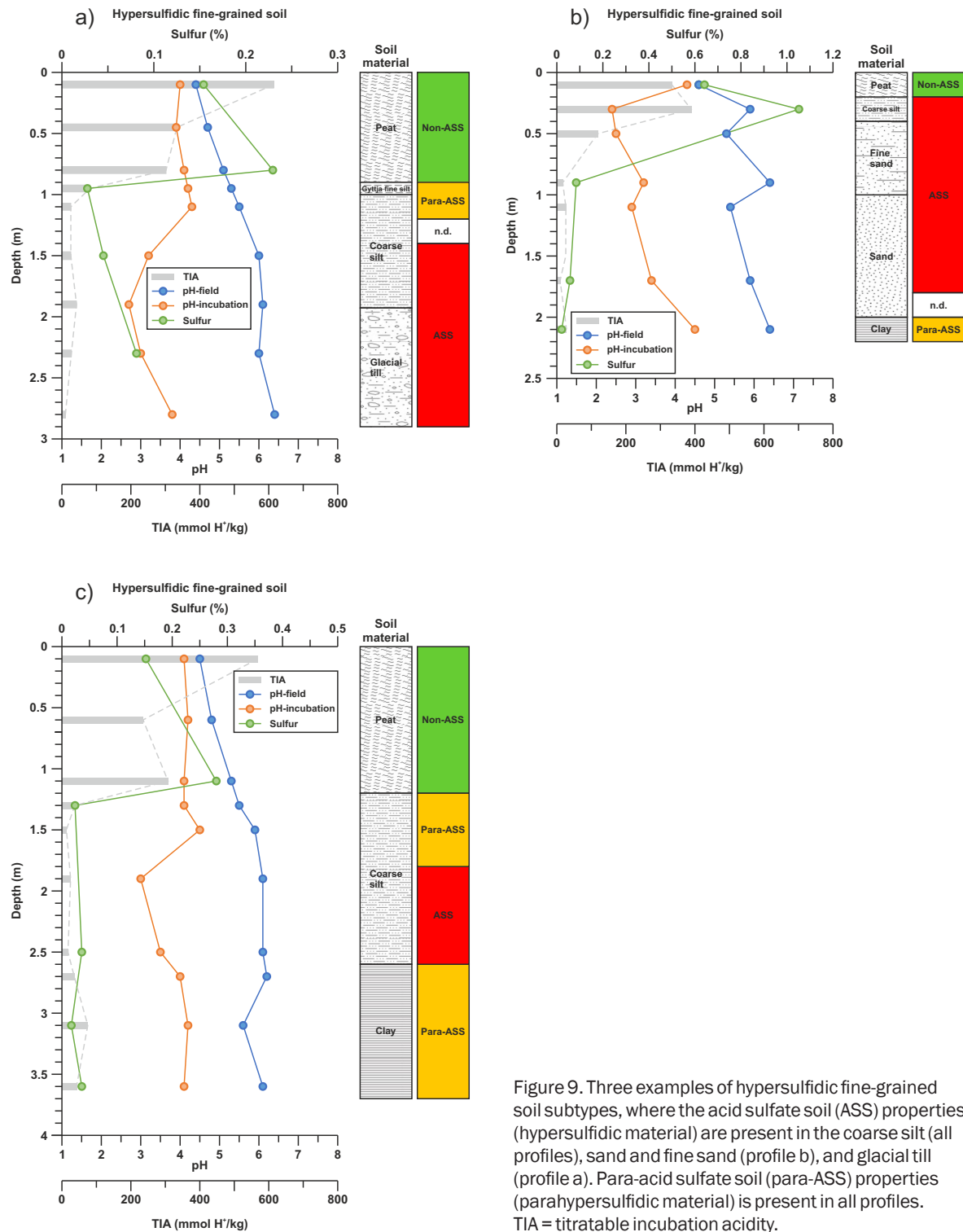


Figure 9. Three examples of hypersulfidic fine-grained soil subtypes, where the acid sulfate soil (ASS) properties (hypersulfidic material) are present in the coarse silt (all profiles), sand and fine sand (profile b), and glacial till (profile a). Para-acid sulfate soil (para-ASS) properties (parahypersulfidic material) is present in all profiles. TIA = titratable incubation acidity.



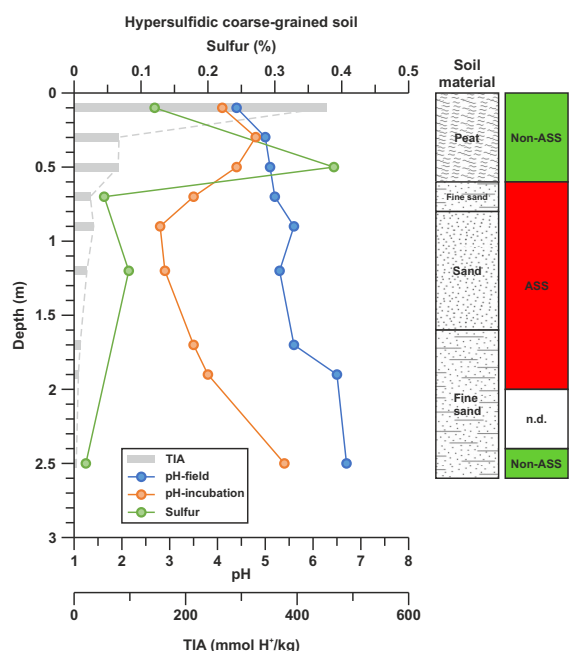


Figure 10. An example of a hypersulfidic coarse-grained soil subtype, where the acid sulfate soil (ASS) properties (hypersulfidic material) are present in both the fine sand and sand. TIA = titratable incubation acidity.

ASS material (and  $\geq 15$  cm in thickness) is present in fine-grained soil material, the profile is named “fine-grained ASS”. It should be noted that in many cases, an ASS profile contains several types of ASS materials and has layers of varying soil materials (e.g., clay/silt with interbedded sand layers) and organic matter contents as shown in Figs. 7–11. Fine-grained ASS are commonly the most environmentally harmful ASS type in Finland and it has been shown that such soils are responsible for a higher metal load to watercourses in Finland compared with that coming from the entire Finnish industry (Sundström et al. 2002). The most important coarse-grained soil materials are typically ranging between 63 and 2000  $\mu\text{m}$  (very fine sand to very coarse sand) but coarser soil materials have also been seen to develop low pH values during incubation and may be classified as ASS materials. In sand extraction areas, this ASS subtype may be of importance (Mattbäck et al. 2017, 2022).

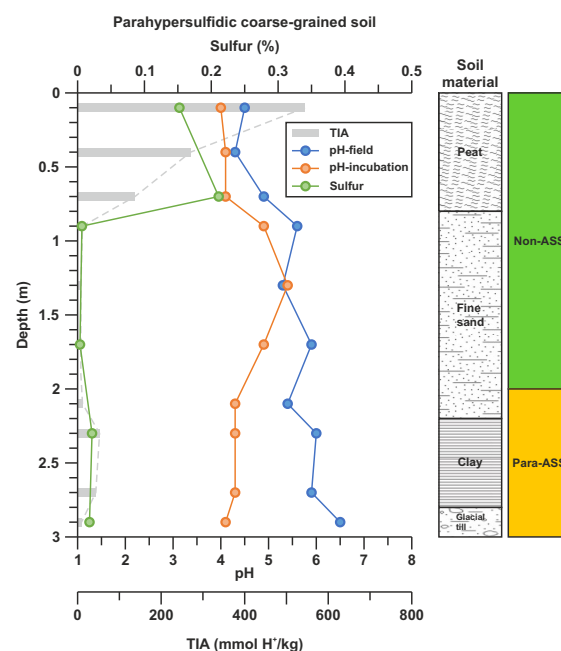


Figure 11. An example of a parahypersulfidic coarse-grained soil subtype, where the para-acid sulfate soil (para-ASS) properties (parahypersulfidic material) are present in the fine sand, clay, and glacial till. Note the differences in sulfur (S%) and titratable incubation acidity (TIA) between the organic (non-ASS material) and mineral soil materials.

Unsorted ASS may be important in areas where the sulfidic material has been eroded from the bedrock, transported, and deposited as glacial till.

### 5.1.2 Subaqueous acid sulfate soils and para-acid sulfate soils

Soil forming processes also occur in sediments in shallow water environments (Demas & Rabenhorst 1999). If the sediment is permanently covered by water too deep for the growth of rooted plants, it is not considered soil. However, a clear distinction between soil and non-soil is often difficult to make as the change from soil to non-soil may be too gradual (Demas & Rabenhorst 1999). Therefore, an arbitrary water depth of  $\leq 2.5$  m is commonly used as a limit for subaqueous soils. The definition of subaqueous soils by Demas & Rabenhorst (1999) have been included in the KST (Soil Survey Staff 2022) as well as in the ASC

classification (Isbell & NCTS 2021). It is suggested that subaqueous ASS are included in the Finnish-Swedish ASS classification system, and that the prefix “subaqueous” is included in the soil name when classifying the soil type (e.g., subaqueous ASS) or soil subtype (e.g., subaqueous organic para-ASS). In Finland and Sweden, subaqueous ASS are quite common in shallow coastal areas subjected to postglacial land uplift (especially in western Finland and in Ostrobothnia), and have also been encountered in inland lakes (e.g., Lake Inarinjärvi, Finland). Examples of subaqueous ASS (i.e., subaqueous hypersulfidic soils) have previously been described in Boman et al. (2010) who studied the impact on land uplift on the formation of sulfuric soils and in Toivonen & Österholm (2011) who investigated the acidifying effect of dredged material. In Finland and Sweden, subaqueous ASS may be of importance if they are disturbed for instance in dredging activities. Another reason for recognizing subaqueous ASS in shallow coastal areas is that they will ultimately be isostatically uplifted above the sea surface, thus turning into “normal” ASS. It is estimated that about 700 ha of new land is emerging from the sea every year in Finland and Sweden due to the postglacial land uplift (Poutanen & Steffen 2014), of which a large part may potentially turn into new sulfuric soils if not managed properly.

## 6 Summary

Established international soil taxonomy systems do not exclusively accommodate acid sulfate soils (ASS) and ASS materials present in Finland and Sweden. There is also no harmonious way to express the environmentally relevant ASS properties present in many of these soils using the current criteria of these soil classification systems. It has been discovered that there is a need for using a lower pH-limit of < 3.0 for classification of ASS materials in organic-rich soil materials (> 20% organic matter, e.g.,

peat and gyttja). Another addition in the Finnish-Swedish ASS classification is the re-introduction of para-acid sulfate soils (para-ASS), which are comprising acidic and potentially acidic soil materials that are not fulfilling the diagnostic pH-criterion ( $\text{pH} < 4.0$ ) in the established international soil taxonomy systems, but which nonetheless may have a severe negative environmental impact due to the mobilization of acidity and Al (plus other potentially harmful elements). Para-acid sulfate soil materials include parasulfuric (oxidized material) and parahypersulfidic material (reduced material), which has diagnostic pH-criteria (both field and incubation) of  $\text{pH} 4.0\text{--}4.5$  and  $3.0\text{--}3.5$  for mineral and organic soil materials, respectively. These new terms are not currently recognised in any international soil classification systems. Similar soil materials, also named “pseudo acid sulfate soils”, have previously in the 1960s and 1970s been identified in other areas worldwide and points to a need to incorporate these materials in international soil taxonomy systems.

Acid sulfate soils and para-ASS are divided into sulfuric and hypersulfidic soils and parasulfuric and parahypersulfidic soils, respectively. These are further divided into: 1) organic ASS/para-ASS, 2) fine-grained ASS/para-ASS, 3) coarse-grained ASS/para-ASS, and 4) unsorted ASS/para-ASS. These ASS and para-ASS subtypes can, in turn, be subdivided into soil subtypes, where the diagnostic ASS/para-ASS properties are indicated. Subaqueous ASS and para-ASS are also included and are defined as soils that are covered by a water depth of no more than 2.5 m. Such areas are especially common and important in shallow coastal areas and lakes.

This paper is the first attempt to draw up guidelines for classifying ASS profiles and it is proposed that these guidelines, as well as the new diagnostic ASS materials and modified criteria for some ASS materials, may serve as a framework for establishing a unified ASS classification globally.

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