Acid Sulfate Soils in Västra Götaland, Sweden

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Abstract

Acid sulfate soils can cause significant economic, environmental, and health-related issues due to acidification and metal leaching. This thesis investigates the presence of acid sulfate soils in the county of Västra Götaland – a region in which the presence of acid sulfate soils has been unknown. A literature review was performed which indicated that acid sulfate soils should occur in organic-rich sediment near drained lakes. Soil sampling and pH measurements at 14 sites around western Västra Götaland revealed three potential acid sulfate soils and one active acid sulfate soil. The three potential acid sulfate soils occurred adjacent to drained lakes and the active acid sulfate soil occurred close to a drained wetland. All soils were hosted in, or below, organic-rich sediment. Isotope analysis by ICP-SFMS revealed increased amounts of sulfur in three of the acid sulfate soils. While the presence of acid sulfate soils in Västra Götaland is now confirmed, their extent remains unknown. Future studies are encouraged to delimitate the extent and impact of acid sulfate soils in Västra Götaland.

Sammanfattning

Sura sulfatjordar kan orsaka betydande ekonomiska, miljö-mässiga, och hälsorelaterade problem genom försurning och metallakning. Denna uppsats undersöker förekomsten av sura sulfatjordar inom Västra Götalands län – vari förekomsten av sura sulfatjordar hittils varit okänd. En litteraturstudie genomfördes som indikerade att sura sulfatjordar borde förekomma i sediment innehållandes organiskt material nära sänkta sjöar. Genom jordprovtagning och pH-mätningar vid 14 platser runtom västra Västra Götaland påvisades tre potentiella sura sulfatjordar och en aktiv sur sulfatjord. De tre potentiella sura sulfatjordarna fanns intill sänkta sjöar och den aktiva sura sulfatjorden fanns nära en dränerad våtmar. Alla jordar förekom i, eller under, sediment innehållandes organiskt material. Vidare visade en isotopanalys med ICP-SFMS förhöjda svavelhalter i tre av de sura sulfat-jordarna. Även om förekomsten av sur sulfatjord i Västra Götaland nu är bekräftad, så är utbredningen fortfarande okänd. Framtida stu-dier uppmuntras avgränsa utbredningen och påverkan av sura sulfatjordar inom Västra Götaland.

Abbreviations

Elements

As – Arsenic
Ba – Barium
Be – Beryllium
Cd – Cadmium
Co – Cobalt
Cr – Chromium
Cu – Copper
Fe – Iron
Hg – Mercury
Mn – Manganese
Ni – Nickel
P – Phosphorus
Pb – Lead
S – Sulfur
Sr – Strontium
V – Vanadium
Zn - Zinc

Sediments

Cl – Clay
fS – fine Sand
GCl – Gyttja Clay
Pt – Peat
Si – Silt
Ts – Topsoil
yFS – young Fluvial Sediment

Contents

1. Introduction

Acid sulfate (a.s.) soils and their adverse effects have drawn scientific interest since at least the 18th century when, as noted by Pons (1973), Linnaeus first described them as *argilla vitriolacea* – or *clay with sulfuric acid* – during his time in the Netherlands. The term acid sulfate soils was first popularized two centuries later, after the first international acid sulfate soils symposium was held in 1972 (Fanning, Rabenhorst & Fitzpatrick, 2017), although the term had been used sporadically before (e.g. Moormann, 1963; Tanaka & Navasero, 1966).

An a.s. soil is generally defined as a sediment that contains sulfides to such an extent that the soil's pH has dropped, or can drop, below 4 due to the production of sulfuric acid [H_2SO_4] caused by oxidation (Boman et al., 2018). Sweden applies the general definition above, with the addition that the pH must drop below 3 in organic soils (e.g. peat and gyttja) for it to count as an a.s. soil. A more detailed definition of the Swedish classification of a.s. soils is presented in Boman et al. (2018).

A.s. soils are commonly divided into *potential* a.s. soils and *active* a.s. soils.

Potential a.s. soil is established when organic-rich sediment settles in the presence of sulfate-reducing bacteria (Queensland Government, 2019). The bacteria oxidize the organic matter by consuming oxygen, and if the oxygen gets depleted, the bacteria proceed to reduce sulfate [SO_4^{2-}] and Fe^{3+}, to sulfide [S^{2-}] and Fe^{2+} respectively. The sulfide and Fe^{2+} can then react to form iron sulfides like pyrite [FeS_2] (Becher, Sohlenius & Öhrling, 2019).

Active a.s. soil is formed when the potential a.s. soil is exposed to atmospheric oxygen (Nordmyr, Åström & Peltola, 2008). The iron sulfides get oxidized which produces sulfuric acid, hydrogen ions [H^+], and iron precipitate [$FeOOH\downarrow$] (Becher et al., 2019).

In short, active acid sulfate soils are the oxidized products of potential acid sulfate soils. Active a.s. soils can severely damage their environment by heavily reducing soil pH, which induces the leaching of metals. The potential a.s. soils cause no adverse effects as long as they are kept under reducing conditions (Queensland Government, 2019).

As mentioned, the reduced pH in the soil increases weathering and, subsequently, the leaching of metals (Sohlenius & Öborn, 2004). Drainage from a.s. soils can therefore acidify and pollute aquatic environments such as lakes, watercourses, and estuaries which can be highly harmful to the biota. For instance, Uhro, Hildén & Hudd (1990) linked the decline of fish species in the Kyrönjoki River estuary to the drainage of a.s. soils, and Jezierska & Witeska (2006) summarized the deleterious effects of metal accumulation in fish living in polluted waters. Adding to the problematic nature of a.s. soils, Pousette (2007) highlighted the geotechnical challenges of handling spoil from excavations, and Fältmarsch, Åström & Vuori (2008) discussed the potential correlation between metals and neurodegenerative disorders like Alzheimer's disease and Parkinson's disease. It is clear that a.s. soils can cause significant economic, environmental, and health-related issues, which is why the mapping of these soils is important.

Most of the a.s. soil-mapping in Sweden has been performed along the coasts of Norrbotten and Västerbotten counties in northern Sweden. Rapid post-glacial rebound in the area has uplifted vast tracts of land which were once covered by the *Littorina Sea* 9,800 – 3,000 cal yr BP. The Littorina Sea was a brackish stage of the Baltic Sea's development defined by an increase in salinity from previous stages (Björck, 2015). Periods of increased productivity coupled with a more pronounced halocline meant that the degradation of organic matter caused anoxic conditions at the seafloor (Björck, 2015). This likely means that extensive amounts of potential a.s. soil was developed in the favorable conditions of the Littorina Sea, which is also substantiated by the large quantities of a.s. soils that have been, and continue to be, uplifted from the Baltic Sea in northern Sweden. Most of the a.s. soils are therefore located below the highest reach of the Littorina Sea – the *Littorina limit*.

Southern Sweden, in comparison, has seen relatively little documentation of acid sulfate soils. A few studies in the Mälaren region have confirmed the presence of *sulfidic soils*, i.e. soils containing sulfides (Sohlenius, Persson, Lax, Andersson & Daniels, 2004), and a.s. soils (Bayard & Karlsson Mood, 2014; Lax, 2005; Sohlenius & Öborn, 2004; Öborn, 1989). A.s. soils have also been discovered in the counties of Skåne and Blekinge (Åbjörnsson, Stenberg & Sohlenius, 2018; Öborn, 1989). Of special remark is the confirmed presence of the first active a.s. soil outside of the Baltic Basin, in Falkenberg (Gustafsson, 2019; Kling Jonasson, 2020; Lindgren, 2020). This discovery demonstrates the need for a survey of a.s. soils on the west coast.

The unknown extent of a.s. soils is worrying as the west coast is already the most acidified region in Sweden (Fig. 1) due to acid rain and logging (Länsstyrelsen i Västra Götalands Län, 2019). Unaccounted for a.s. soils could seriously be damaging the biota. They could also severely hamper several of Sweden's environmental targets. That is why studies from regions of similar geology and climate – like the Norwegian coast, and areas along the St. Lawrence River in Canada – could be important tools in deducing where a.s. soils occur (see chapter 2).

The geographical delimitation of this thesis is constrained to the western part of Västra Götaland county (Fig. 2), and will henceforth be referred to as *WVG* (*Western Västra Götaland*).

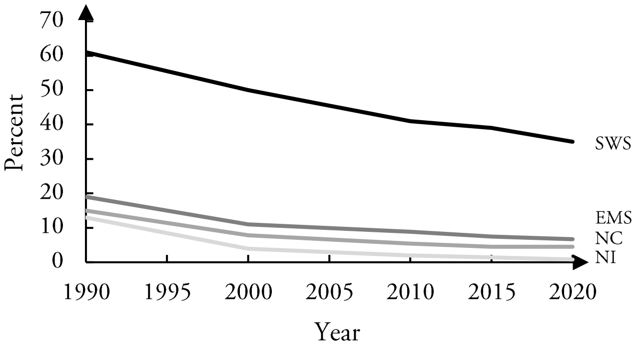

Fig. 1. Acidified lakes > 1 ha in Sweden, categorized into four regions: SWS = Southwestern Sweden, NI = Norrland's Inland, NC = Norrland's Coast, and EMS = East and Middle Sweden.
After: Sveriges Miljömål (n.d. b).

Topographically, the majority of WVG is characterized by Mesozoic fissure valleys, apart from the 'Dalsbo Plain' – a plain located at the indent of western lake Vänern (Trafikverket, 2012). Like all of Sweden, WVG was covered by the Fennoscandian ice sheet during the Weichselian glaciation. After the deglaciation of this ice sheet, and in conjunction with the melting of the Laurentide and Antarctic ice sheets, the absolute sea level rose by 30 m (Andrén et al., 2011; Björck, 2015; Lambeck & Chappell, 2001). The sea level rise was a major driving force behind the Littorina Transgressions in today's Baltic Sea. Around the same time, Sweden's west coast was similarly inundated. The resulting transgression on the west coast is called the *Tapes transgression*, as opposed to the Littorina transgressions on the east coast (Björck, 2015). Rising sea levels due to the Fennoscandian ice sheet's retreat and the, later, Tapes transgression, as well as the geomorphology of the fissure valleys and the anthropogenic impact, all seem to have influenced the deposition and formation of a.s. soils on Sweden's west coast.

The fissure valley floors of WVG are primarily covered by clay and silt. Clay, silt, and exposed bedrock account for approximately 78.2 % of WVG's land surface below the marine

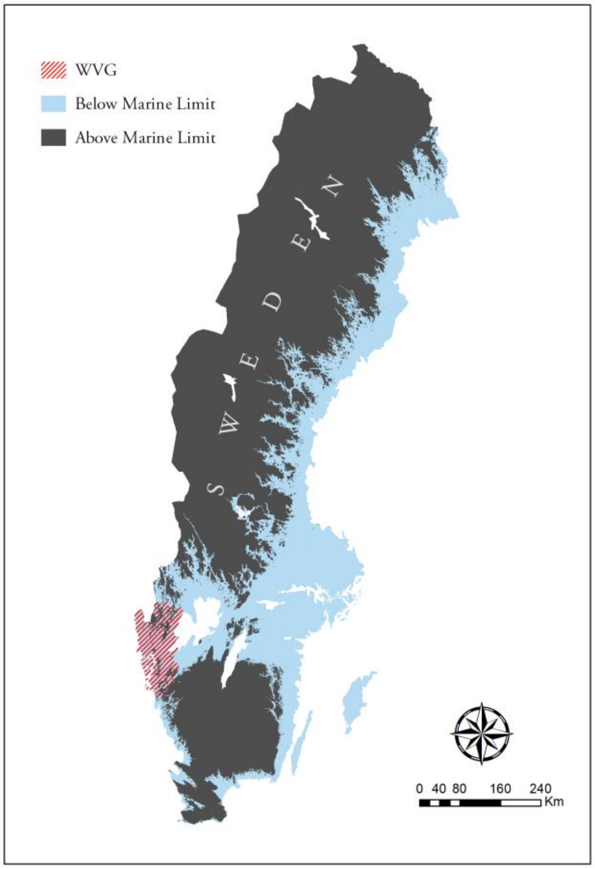

Fig. 2. Marine limit map of Sweden. The light blue area represents the parts of Sweden which were at some point inundated after the retreat of the Fennoscandian ice sheet. The red stripes represent WVG's area (below the marine limit).
Högsta Kustlinjen © Sveriges geologiska undersökning (SGU); Län, kommuner, FA-regioner och LA-regioner © Statistiska centralbyrån (SCB).

limit. The remaining percent consist of till (7 %), peat (6.2 %), sand (5.6 %), gyttja (0.3 %), and miscellaneous (2.7 %). In southern Sweden, a.s. soils often occur in areas mapped as different types of gyttja soils by SGU (Becher et al., 2019). They can also occur in clay, silt, and peat, as well as in soils adjacent to drained or partially drained lakes. Even sand and sandy sediments are of interest when exploring for a.s. soils on the west coast (Kling Jonasson, 2020), which means that over 50 % of the soils in WVG could host a.s. soils. However, the impact from such amounts would be extremely noticeable. Still, the numbers do indicate that areas of a.s. soils that are large enough to impact the biota, or local communities, could exist.

1.1. Aim and research questions

Acid sulfate soils are problematic sediments because they can acidify, and leach metals to, their surrounding environment. Mapping of a.s. soils in Sweden has primarily occured in Norrbotten and Västerbotten. Recent reports of a.s. soils in southern Sweden have highlighted the need for a survey of these soils in less explored parts of the country. Västra Götaland is one of Sweden's largest counties, both by area and population, but the presence of a.s. soils has not been investigated.

First, this thesis aims to compile and review references, both domestic and international, of a.s. soils in similar environments to the Swedish west coast. Secondly, this thesis aims to investigate the existence of a.s. soils in Västra Götaland by collecting soil samples and analyzing them, in order to further elucidate where, and how, a.s. soils can form on the west coast.

The main research questions of this thesis are:

- Is it possible to assess where a.s. soils could occur in Västra Götaland by examining similar regions with a.s. soils?

- Do a.s. soils exist in Västra Götaland?

- If a.s. soils exist, where do they occur and is it possible to estimate their extent?

- If a.s. soils exist, is it possible to estimate their impact

2. Literature Review

Literature related to acid sulfate soils on the west coast of Sweden is scarce. Therefore, this part of the thesis aims to compile and review information relevant to a.s. soils in western Västra Götaland (which is the geographical delimitation of this thesis). By expanding the literature search to areas of similar geology and climate – a larger picture of the formation, location, and consequences of a.s. soils can be obtained.

Regions of similar climate and geology to WVG include, but are not limited to, the Norwegian coast – especially the southern coastline – and parts of the Canadian east coast – particularly the St. Lawrence River area. Additionally, the compiled material in this chapter could prove a beneficial resource of information on a.s. soils in Sweden, Norway, and Canada.

2.1. Coastal Norway

The coast of southern Norway, particularly around Oslofjorden, is in many aspects the most accurate analogy for WVG, mainly due to their shared climate and geological history stemming from their proximity. However, within the context of a.s. soils, the entirety of the Norwegian coast is fairly comparable to Sweden's west coast as the regions were both inundated by the sea after the retreat of the Fennoscandian ice sheet and, to a lesser extent, by the Tapes transgression (Fjeldskaar & Bondevik, 2020). The highest sea level often acts as a delimiter for a.s. soils on the Swedish east coast and a similar delimitation is therefore appropriate for the west coast. Additionally, Norwegian valley floors are often covered by marine deposits (Fig. 3) similarly to the fissure valleys of western Västra Götaland, further emphasizing their similar geology.

However, a.s. soils are rarely mentioned in Norwegian literature. Andersson & Hansen (2019) stated that "the occurrence of [a.s.] soils … in Norway on any scale is unknown", but preliminary surveying during a pilot project in Alta, northern Norway, has since uncovered the presence of a.s. soils in Finnmark county (Andersson, Hansen & Flem, 2021; SGU, 2020;). The soils occurred (Andersson et al., 2021):

- below peat
- in areas less than 10 m above sea level
- in areas with a low surface gradient
- in lagoonal environments
- in fine sand to fine silt

However, they stress that the occurrence of a.s. soils is not given even though an area fulfills

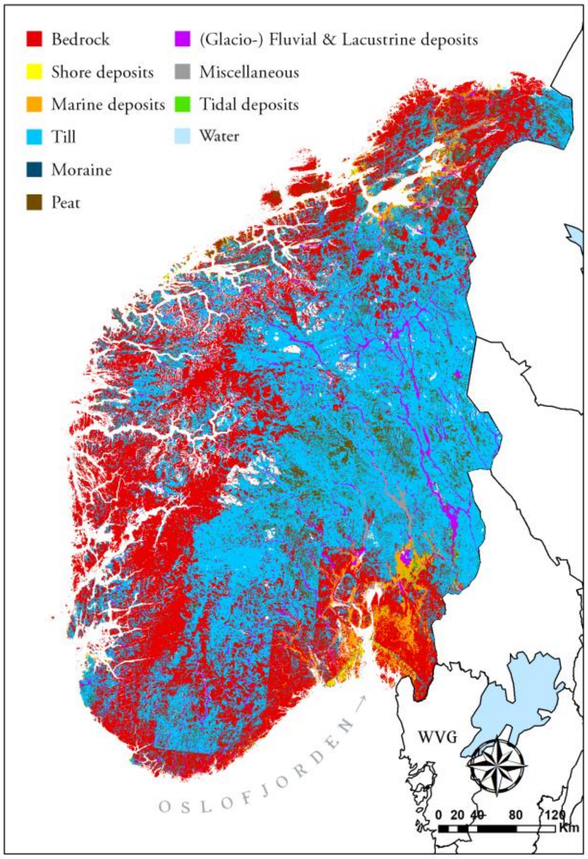

Fig. 3. Simplified map of the depositional environments and landforms in south Norway.
Løsmasser © Norges geologiske undersøkelse; Europe coastline © European Environment Agency.

any of these conditions. Even so, similar environments in WVG could be of interest when exploring for a.s. soils. Areas of peat, sand, and silt are quite abundant in all of WVG (Fig. 4), and lagoonal environments were probably not uncommon when the Fennoscandian ice sheet retreated and the fissure valleys became inundated.

Indications of sulfidic soil in southern Norway primarily come from reports on fish kills. Huitfeldt-Kaas (1922) attributed adverse soil conditions to fish kills when he commented on the mass death of salmon and trout in Frafjordelven in southern Norway. He explained that there had been a dry autumn in 1920, but heavy precipitation followed in November and the color of the otherwise clear river changed to a yellow brown. Two weeks after the rain event, all the fish in the river were dead. Huitfeldt-Kaas described this fish death as seemingly analogous to incidents in northern Sweden in 1914, as detailed by Högbom.

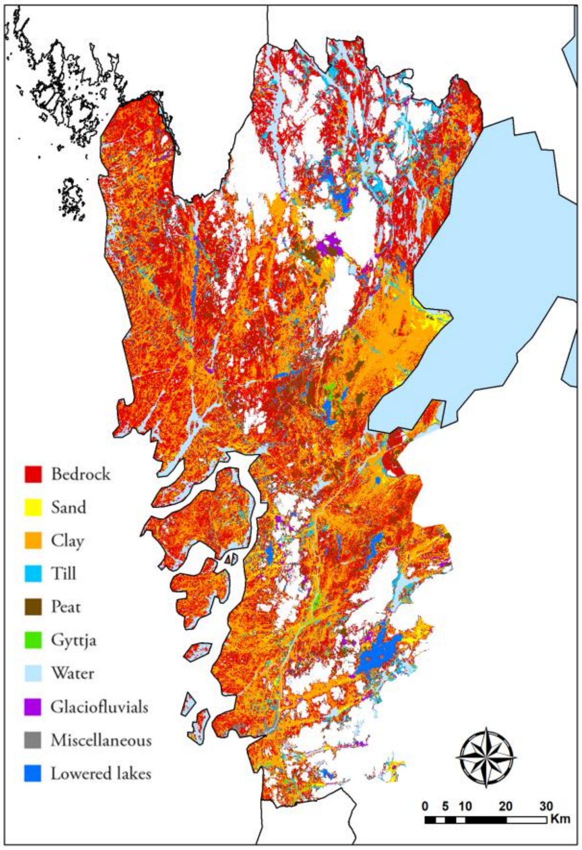

Fig. 4. Simplified surficial map of WVG. Jordarter 1:25 000 – 1: 1 000 000 © SGU; Högsta Kustlinjen © SGU; Vattenytor © Sveriges meteorologiska och hydrologiska institut (SMHI); Län, kommuner, FA-regioner och LA-regioner © SCB.

In the summer of 1914, a change of color in several Swedish water bodies, in conjunction with fish death were observed (Högbom, as cited in Huitfeldt-Kaas, 1922). The water became crystal clear or showed greenish hues. This is noteworthy because crystal clear water can be a diagnostic tool for a.s. soils as the low pH causes suspended material to flocculate and sink. Likewise, a green-blue, milky color might be caused by aluminium precipitate when acid water meets water with a higher pH (Becher et al., 2019). Due to these reports, Högbom surveyed some watercourses. Huitfeldt-Kaas singled out Högbom's results from Avafjärden and Gärde-fjärden in Västerbotten as especially interesting. The waterbodies were surrounded by assorted gyttja and *svartlera* – an archaic Swedish term for sulfide soil (Svartlera, n.d.). The dry summer resulted in lower water levels and oxidation of the soils, which then acidified their environments, thus leaching metals to the water and likely causing the fish kills. Although it should be noted that Högbom attributed the fish kills to suffocation due to humus particles blocking the fish's gills.

As mentioned, Huitfeldt-Kaas (1922) compared the fish kills in Norway with those studied by Högbom. Chemical analysis of the water in Frafjordelven revealed considerable amounts of sulfuric acid and a large proportion of sulfate, thus, he concluded that it was likely that the fish died of *vitriol* (sulfuric acid) poisoning from the adjacent mires.

It is not possible to ascertain the existence of a.s. soils around Frafjordelven from the literature alone, but it does provide an argument for a more thorough investigation of the area, or of similar areas.

Huitfeldt-Kaas (1922) also briefly mentioned a similar fish kill event in 1911, which Dahl (1923) later expounded upon when he described the fish kills of 1911, 1912, and 1913 in Klepp municipality. A period of drought had occurred during the summer of 1911 when a sudden downpour occurred – three days later, ¾ of the fish had died. The same pattern repeated itself in 1912 and 1913. Water samples, taken in conjunction with the fish kills, revealed high concentrations of sulfuric acid and iron in the water. Dahl also identified that drainage channels recently had been constructed in a mire adjacent to the watercourse.

The nearly identical circumstances surrounding all these events, i.e. intense drought, followed by rain and subsequent fish death, coupled with the fact that this sequence of events is an indicator of a.s. soils (e.g. Callinan, Sammut & Fraser, 2005; Uhro et al., 1990), presents a somewhat probable case for the existence of acid sulfate soils in southern Norway. This hypothesis is also strengthened by the confirmed presence of a.s. soils in Alta and Falkenberg. Still, the lack of specific testing for a.s. soils makes it impossible to ascribe the cause of fish death to these soils.

It needs also be mentioned that acid precipitation had started to become a problem in the early 20th century in Norway. The precipitation of sulfur increased throughout the century and culminated during the 80's and mid-90's, after which there was a sharp decline (Miljødirektoratet, 2020).

Several of the previously mentioned reports acknowledged the influence of acid rain on fish health. Yet, they concluded that the effect from acid rain alone would not have been sufficient to cause the fish deaths.

2.2. The St. Lawrence River area, Canada

From a global perspective, Canada has a fairly similar geology and climate to Norway and Sweden. On a more regional note, especially in the interest of acid sulfate soils, the Canadian east coast is somewhat analogous to parts of WVG and Norway. The St. Lawrence lowlands are particularly interesting due to the now drained Champlain Sea.

The Champlain Sea was a massive embayment of the Atlantic Ocean and formed after the last glacial maximum when a major change in climate caused an eustatic sea level rise (Gadd, 1988). The sea extended up the St. Lawrence Valley into southern Quebec and eastern Ontario (Karrow, 2006). This transgression of brackish to nearly normally saline seawater produced depositional conditions akin to that of the transgression on the Scandinavian west coast, as evidenced by the occurrence of quick clays in Västra Götaland, coastal Norway, and the St. Lawrence lowlands (Persson, 2014; Rankka et al., 2004).

The presence of a.s. soils in the St. Lawrence River area was confirmed by Ross and Ivarsson (1981). They found that the soil occurred in the *de l'Anse* soil series of the Gleysol great group (after the Canadian soil classification system). In a subsequent study, De Kimpe, Laverdière and Barril (1988) stated that soils belonging to the de l'Anse soil series in Quebec developed in tidal marshes below 15 m a.m.s.l. along the south shore of the St. Lawrence river. They also specified that the de l'Anse soils in Quebec are acid sulfate soils. In Sweden, gleysols are prevalent adjacent to drained lakes (Gleysol, 2000) but beyond that, they are scarce (SLU, 2020). Today, there are at least 89 partially drained lakes in WVG (Fig. 4; Svenskt Vattenarkiv, 1995). The areas surrounding these lowered lakes are therefore of high interest, especially if the water levels continue to fall, thus oxidizing potential a.s. soils and turning them into active a.s. soils.

It should be emphasized that a.s. soils also occur in other parts of eastern Canada that might be geologically similar to WVG, and not exclusively around the St. Lawrence river. For instance, a.s. soils have been confirmed in the Acadia soil series of the Gleysol great soil group on Nova Scotia (Department of Agriculture and Marketing, 1991; Ross & Ivarsson, 1981).

2.3. The Swedish west coast

Sulfidic soils are thought to be relatively uncommon along the west coast of Sweden (Sohlenius, 2011), but very few areas have been actively investigated. One confirmed locality lies in Falkenberg municipality.

Malfunctioning pumps during construction in Falkenberg led to the first recorded discovery of active a.s. soils on the Swedish west coast (Kling Jonasson, 2020; Lindgren, 2020). The active a.s. soil was located in paleolake Ramsjön in silty fen peat. Potential a.s. soil was found as well and occurred in clay. Kling Jonasson (2020) interpreted the formational environments as shallow protected lagoons and shallow protected bays, respectively.

The fissure valley landscape of WVG could have accommodated numerous such bays and lagoons during the retreat of the Fennoscandian ice sheet 13,000 - 12,000 cal yr BP (Fig. 5), and to a lesser extent during the Tapes transgression 10,000 – 7000 cal yr BP.

There does not appear to be any further explicit research regarding a.s. soils on the west coast. However, indications of a.s. soils do exist in assorted literature. Alén (1888) took three clay samples from two construction sites in Gothenburg. He noted that two of the samples, which were from the same location but at different depths, appeared blueish gray with dark flames or stripes. Both samples contained organic material but only the shallower presented rust. The third sample also contained organic material but showed no pronounced flaming. When Aldén added hydrochloric acid [HCl] to the samples, all three developed a pronounced smell of hydrogen sulfide [H_2S].

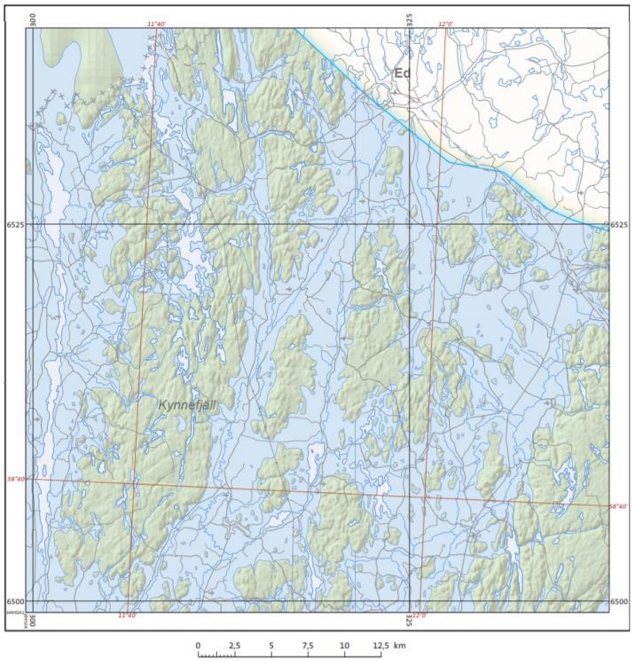

Fig. 5. Sea level during the retreat of the Weichselian ice sheet over WVG's fissure valley landscape 12,000 cal yr BP. The ice sheet is represented in white in the upper right corner of the map. Blue areas are submerged beneath the sea. Lightblue areas are present day lakes. Black gridlines designate coordinates in SWEREF 99 TM and brown gridlines designate latitude and longitude in the reference system SWEREF99.
Strandnivåkartan © SGU; GSD-Översiktskartan © Lantmäteriet.

Other sources of information are archeological reports. Munkenberg (2001) briefly mentions a blue – almost black – clay which turned grey when oxidized, and Aldén Rudd (2016) found a brownish black silt with dark flames. Both a rapid change in color after oxidation, as well as dark bands are indicative of a.s. soils (Becher et. al., 2019). Incidentally, the location mentioned by Munkenberg (2001) was visited during soil sampling for this thesis (see 4.5, site B21011).

Lastly, Geotechnical memorandums might provide valuable information on where to expect sulfidic soil, as such characteristics are sometimes noted (C. Öhrling, personal communication, April 26, 2021).

2.4. Conclusions

Western Sweden, eastern Canada, and coastal Norway share a similar climate and geology, and have all at some point been inundated by the Atlantic Ocean. The highest shorelines from these transgressions seem to be good initial delimitators for a.s. soil deposition. The confirmed presence of a.s. soils in lagoonal deposits in Alta and Falkenberg, and in gleysolic tidal deposits in Quebec, imply that a.s. soils in WVG are most likely to occur in organic-rich sediments – mapped as different peats and gyttjas by SGU – around drained or partially drained lakes. However, due to how few references featured confirmed a.s. soils, this result is tenuous.

3. Method

3.1. Selection of sampling sites with GIS

Soils mapped by SGU as gyttja, gyttja clay (or clay gyttja), peat, peat bog, fen peat, and clay—silt, as well as lakes with lowered water levels, were of primary interest. Soil and lake data were therefore limited to such features with basic geoprocessing tools in ArcMap (version 10.6.1). It should be noted that of the peats and peat bogs, only areas larger than 2,5 ha were considered. Additionally, the peats and peat bogs had to be adjacent to areas of clay—silt (C. Öhrling, personal communication, March 18, 2021).

Data of secondary interest included metal concentrations (Al, Cd, Co, Cu, Mn, Ni, and Zn) in stream plants recorded by SGU, together with water protection areas and Natura 2000 sites. These data were not as critical to the selection of the sampling sites, meaning they were mostly considered during comparison of sites with similar data of primary interest.

31 potential sampling sites were ultimately selected (Fig. 6). The 31 sites were then ranked from 1 (high priority) to 3 (low priority) by comparing primary and secondary data, as well as evaluating the accessibility by car and on foot.

3.2. Collection of field samples and measurements of soil pH

Samples were collected at least 10 m from any manmade objects or till features. The soil profiles were extracted in sections of 10 cm with an Edelman auger, after which the pH of each section was measured with the WTW pH 3110 meter. The pH meter was calibrated once a day by a two-point calibration. As a general rule, soil extraction ceased when two sections in a row, from below the water table, showed a pH

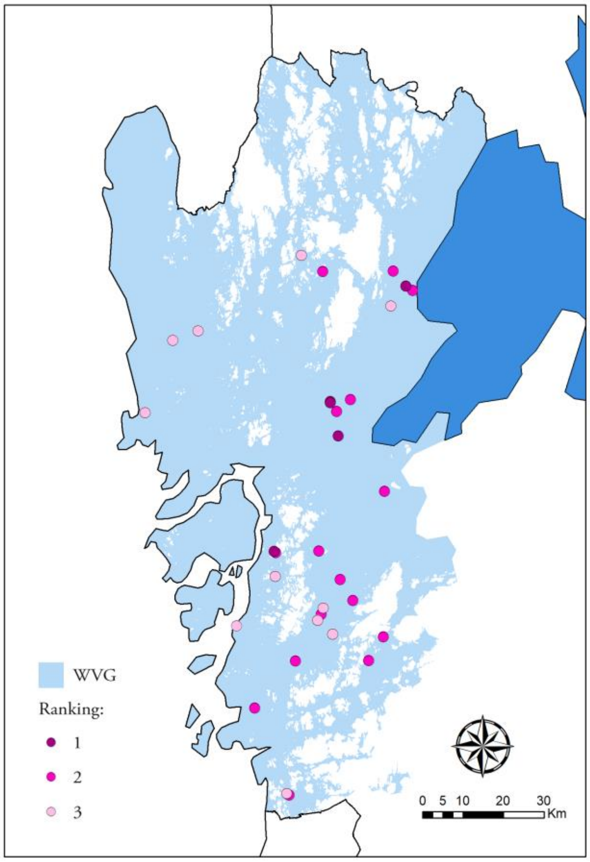

Fig. 6. The 31 proposed sampling sites in WVG. The lightblue area represents WVG below the marine limit. The darkblue area represents lake Vänern.
Högsta Kustlinjen © SGU; Län, kommuner, FA-regioner och LA-regioner © SCB.

greater than 6.

At least one waterlogged soil sample from each location was brought back to test for potential a.s. soil character. Every such sample was thoroughly mixed to homogenize it, after which the pH was measured once again.

3.3. Determination of potential a.s. soil character with H_2O_2-leaching

Samples B21001 through B21005 were analyzed nine days after they were taken in the field. Samples B21006 through B21009 were analyzed after eight days. Samples B21010 and B21011 were analyzed after five days, and samples B21012 through B21014 were analyzed after four days.

Following the procedure in Sullivan, Ward, Toppler & Lancaster (2018), 2 g from each sample was added to a test tube. Diluted sodium hydroxide [NaOH] (aq) was added to 33 % hydrogen peroxide [H_2O_2] (l) until the solution reached a pH of 4.5. 5 ml of the solution was added to each sample. The samples were stirred and left to react. In case of a strong reaction, diluted water was added to the sample to prevent the mixture from boiling over. The samples were left to rest for 60 minutes after the reaction had subsided. Lastly, after the samples had rested, they were stirred once more, after which the pH was measured. If the pH registered below 3, the soil was marked as a potential a.s. soil.

It should be mentioned that the nature of peat renders this method somewhat unreliable and that peat samples should be aerated for at least 9 weeks to ascertain if they are a.s. soils. It is unclear if samples taken from soil layers below peat cause similarly unreliable results.

3.4. Isotope analysis by ICP-SFMS

Soil samples from sites B21001, B21002, B21003, B21005, B21007, B21011, and B21012 were sent to an accredited laboratory for analysis. Each sample was analyzed by ICP-SFMS to assess its respective quantity of As, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, P, Pb, S, Sr, V, and Zn.

4. Results

Of the 31 proposed sites, 14 sites were visited (Fig. 7). Of these 14 sites, three were potential a.s. soils and one was an active a.s. soil. Results from each of the four a.s. soils are presented in more detail, while the remaining 10 non-a.s. soils are shortly summarized.

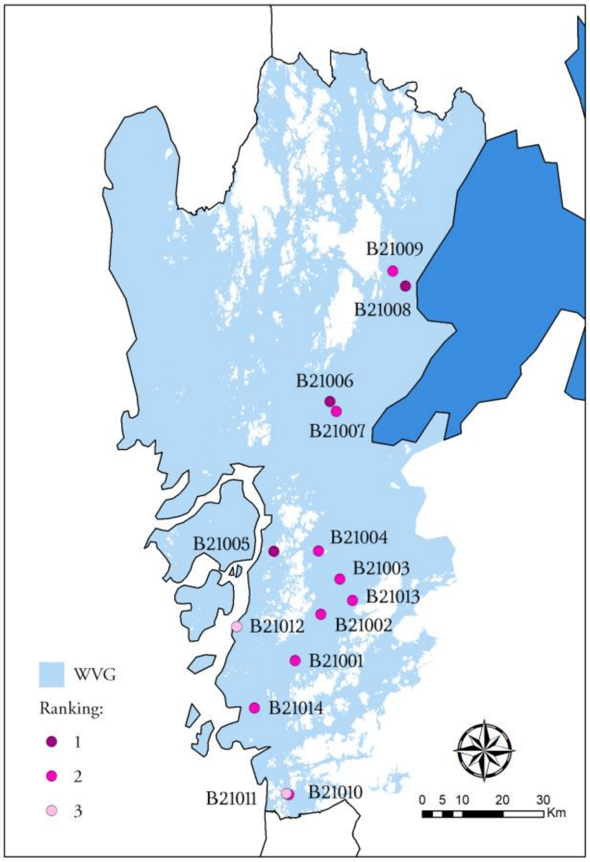

Fig. 7. The 14 sites where pH measurements were done on soil profiles.
Högsta Kustlinjen © SGU; Län, kommuner, FA-regioner och LA-regioner © SCB.

4.1. Site B21003 – Active a.s. soil over potential a.s. soil

Site B21003 was located 29 m a.m.s.l. in a field in a tributary valley to the Göta Älv valley (Fig. 8). The extracted soil column was 1.9 m in total. The soil tended toward gyttja clay between 0.35 m – 0.9 m after which the remainder of the column was clay. Specks of rust appeared at 0.6 m which turned into pea-sized rust granules at 0.95 m. The rust granules disappeared at 0.9 m. The water table was reached at a depth of 0.95 m.

The pH was very low in the upper 1.0 m and rose steadily below the water table (Fig. 9). A soil sample was taken at a depth of 1.5 m and after homogenization, the sample had a pH of 5.8. After the sample had been leached with the H_2O_2, the pH was 1.7.

The results of the ICP-SFMS are presented in Table 1.

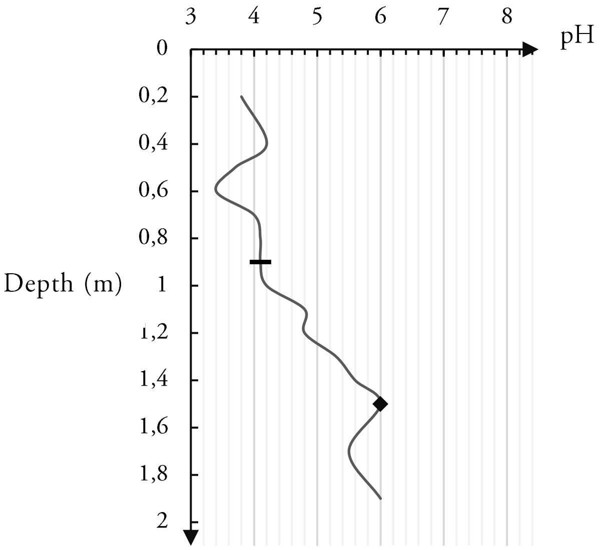

Fig. 9. pH of the soil column extracted at site B21003. The horizontal dash marks the water table and the diamond shape marks where the soil sample for further analysis was taken.

Fig. 8. Sampling site B21003 marked by a black circle with a dot. Visited 2021-05-26.
Coordinates (SWEREF 99 TM):
N: 6441923
E: 336100
Ortofoto 4 band 16 m © Lantmäteriet.

Table 1.
Sample from site B21003. Results of the ICP-SFMS. mg/kg dry matter (dm).

Element	mg/kg	Element	mg/kg
As	6.21	Mn	418
Ba	91.7	Ni	26.3
Be	1.22	P	789
Cd	0.160	Pb	16.1
Co	12.0	S	13500
Cr	33.8	Sr	43.5
Cu	27.3	V	60.7
Fe	32000	Zn	93.2
Hg	<1		

4.2. Site B21002 – Potential a.s. soil

Site B21002 was located 15 m a.m.s.l. adjacent to a lowered lake which drained into Göta Älv. The lake was surrounded by farmland (Fig. 10). The extracted soil column was 1.4 m in total and consisted entirely of gyttja clay. Pea-sized rust granules appeared at 1.1 m and persisted throughout the remainder of the column. The water table was reached at a depth of 1.1 m.

The pH was relatively stable throughout the column (Fig. 11). A soil sample was taken at a depth of 1.4 m and after thorough blending, i.e. homogenization, the sample had a pH of 6.2. After the sample had been leached with the H_2O_2, the pH was 2.2.

The results of the ICP-SFMS are presented in Table 2.

Fig. 10. Sampling site B21002 marked by a black circle with a dot. Visited 2021-05-26.
Coordinates (SWEREF 99 TM):
N: 6432906
E: 331231
Ortofoto 4 band 16 m © Lantmäteriet.

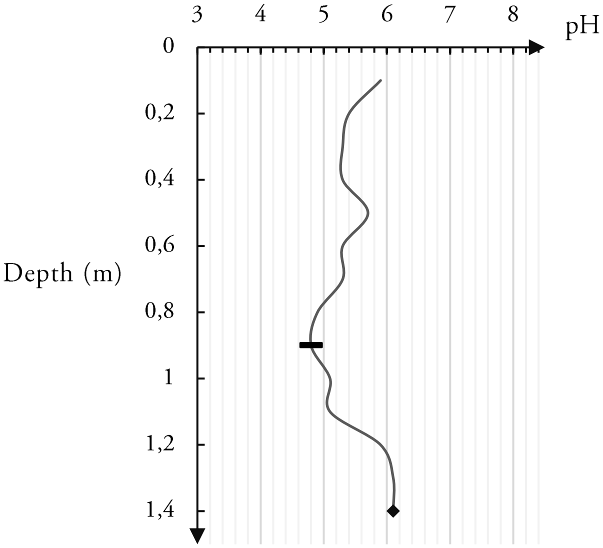

Fig. 11. pH of the soil column extracted at site B21002. The horizontal dash marks the water table and the diamond shape marks where the soil sample for further analysis was taken.

Table 2.
Sample from site B21002. Results of the ICP-SFMS. mg/kg dm.

Element	mg/kg	Element	mg/kg
As	4.76	Mn	348
Ba	65.8	Ni	16.5
Be	0.896	P	646
Cd	<0.1	Pb	11.7
Co	10.6	S	6970
Cr	21.2	Sr	37.4
Cu	12.6	V	48.0
Fe	23700	Zn	72.8
Hg	<1		

4.3. Site B21005 – Potential a.s. soil

Site B21005 was located 42 m a.m.s.l. in a forested area between a large lake and a smaller, overgrown lake (Fig. 12). The forest primarily consisted of deciduous trees. The extracted soil column was 1.95 m in total and the upper 1.0 m consisted of peat. There was gyttja clay between 1.0 m – 1.2 m and clay from 1.2 m to 1.9 m. The remainder consisted of fine sand. Rust granules appeared at 1.7 m. The water table was reached at a depth of 0.55 m.

The pH was low in the upper profile and steadily rose below the water table (Fig. 13). A soil sample was taken at a depth of 1.9 m, but the pH after homogenization was not recorded. After the sample had been leached with the H_2O_2, the pH was 2.6.

The results of the ICP-SFMS are presented in Table 3.

Fig. 12. Sampling site B21005 marked by a white circle with a dot. The lakes have been lowered. Visited 2021-05-26.
Coordinates (SWEREF 99 TM):
N: 6448147
E: 319882
Ortofoto 4 band 16 m © Lantmäteriet.

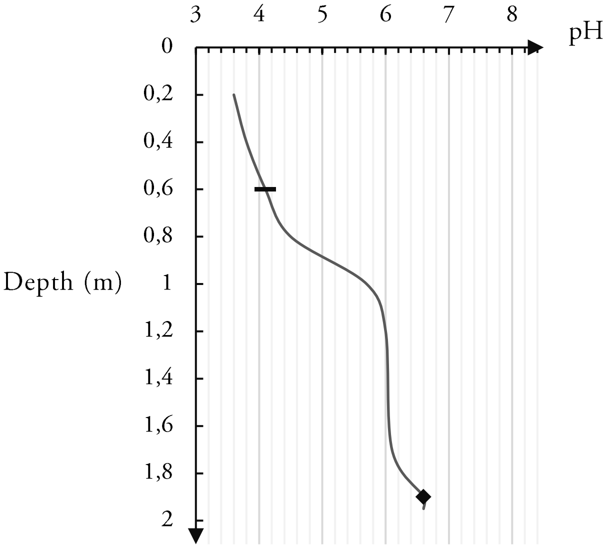

Fig. 13. pH of the soil column extracted at site B21005. The horizontal dash marks the water table and the diamond shape marks where the soil sample for further analysis was taken.

Table 3.
Sample from site B21005. Results of the ICP-SFMS. mg/kg dm.

Element	mg/kg	Element	mg/kg
As	<3	Mn	169
Ba	72.2	Ni	11.9
Be	0.534	P	296
Cd	<0.1	Pb	7.88
Co	7.58	S	489
Cr	20.2	Sr	28.3
Cu	2.93	V	36.5
Fe	14000	Zn	31.9
Hg	<1		

4.4. Site B21007 – Potential a.s. soil

Site B21007 was located 64 m a.m.s.l. between two hillocks in a field adjacent to a country road not too far from a lowered lake (Fig. 14). The extracted soil column was 1.7 m in total and consisted entirely of gyttja clay. There was a substantial amount of organic material throughout the profile. The water table was reached at a depth of 1.2 m.

The pH was relatively stable throughout the column but tended to increase with depth (Fig. 15). A soil sample was taken at a depth of 1.6 m and after homogenization, the sample had a pH of 6.5. After the sample had been leached with the H_2O_2, the pH was 2.6.

The results of the ICP-SFMS are presented in Table 4.

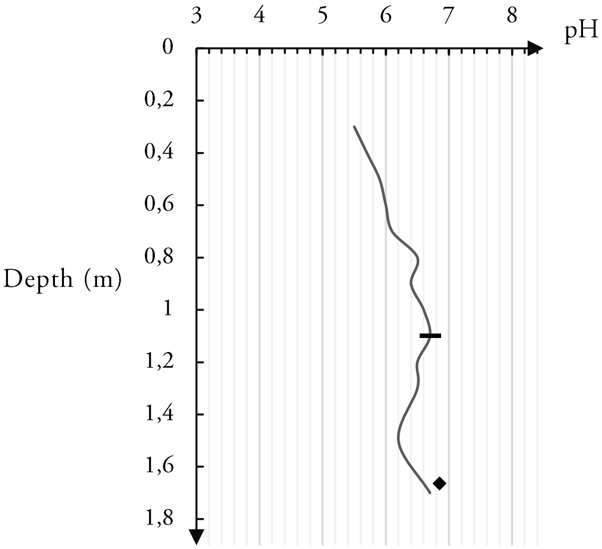

Fig. 15. pH of the soil column extracted at site B21007. The horizontal dash marks the water table and the diamond shape marks where the soil sample for further analysis was taken.

Fig. 14. Sampling site B21007 marked by a white circle with a dot. The lowered lake is in the bottom left of the map. Visited 2021-05-26.
Coordinates (SWEREF 99 TM):
N: 6482943
E: 334963
Ortofoto 4 band 16 m © Lantmäteriet.

Table 4.
Sample from site B21007. Results of the ICP-SFMS. mg/kg dm.

Element	mg/kg	Element	mg/kg
As	3.53	Mn	718
Ba	122	Ni	22.1
Be	1.14	P	838
Cd	<0.1	Pb	13.5
Co	14.2	S	1790
Cr	26.5	Sr	48.9
Cu	18.9	V	60.2
Fe	33700	Zn	88.8
Hg	<1		

4.5. Non-a.s. soils

Samples from sites B21001, B21004, B21006, B21008, B21009, B21010, B21011, B21012, B21013 and B21014 were not a.s. soils. The pH of each respective soil column is presented in Fig. 16 and the pH of each soil sample after H_2O_2-leaching is presented in Fig. 17. Samples from sites B21001, B21006, B21010, and B21014 consisted of gyttja clay. Samples from sites B21004, B21011, B21012, and B21013 consisted of clay. The sample from B21008 consisted of silt and the sample

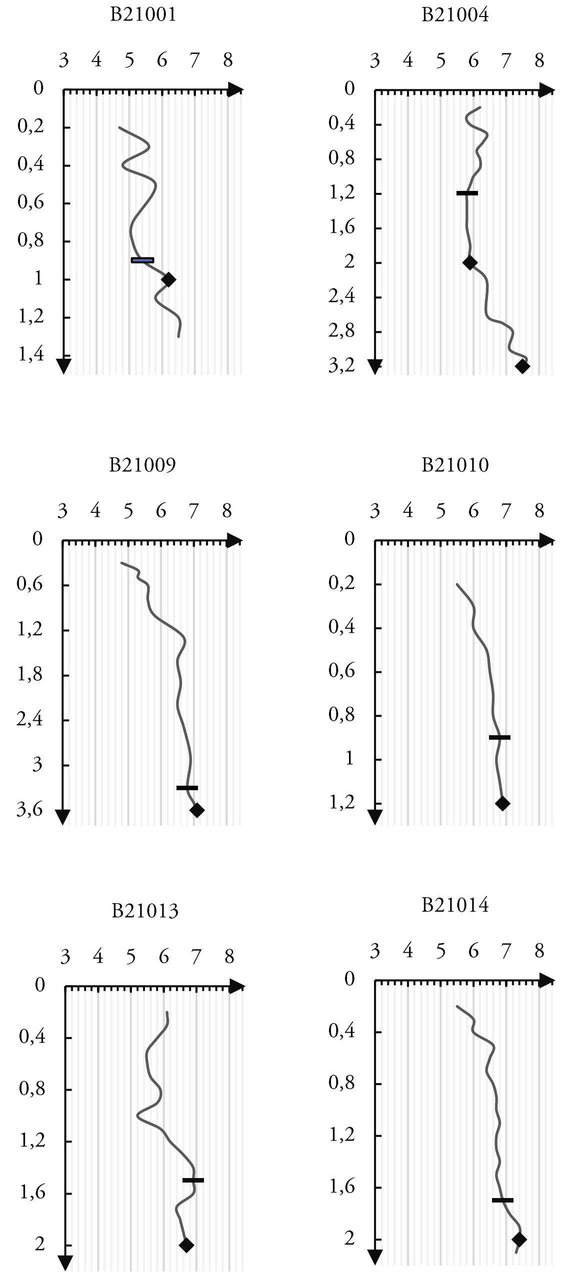

Fig. 16. pH of the soil columns which were not a.s. soils. The y-axis is the depth (m) and the x-axis is the pH. The horizontal dash marks the water table (note that the water table was not reached at site B21011) and the diamond shape marks where soil samples for further analysis were taken (note that two samples were extracted at B21004). Coordinates (SWEREF 99 TM): B21001: N: 6421298 E: 324913; B21004: N: 6448508 E: 330639; B21006: N: 6485425 E: 333586; B21008: N: 6514029 E: 352215; B21009: N: 6517554 E: 348844; B21010: N: 6388192 E: 323381; B21011: N: 6388566 E: 322755; B21012: N: 6429829 E: 310555; B21013: N: 6426134 E: 333068; B21014: N: 6409613 E: 314937

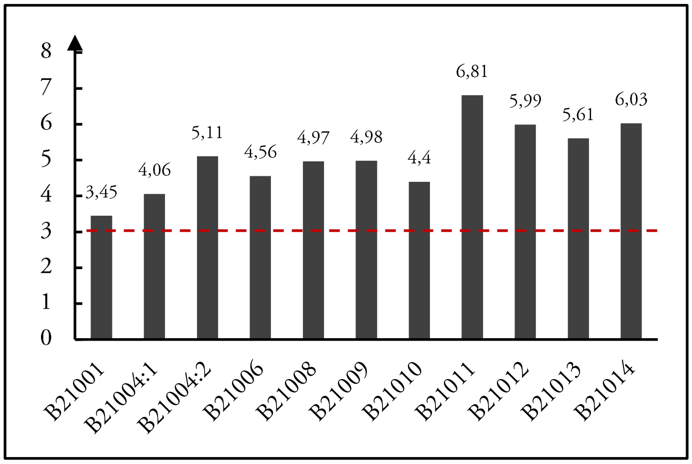

Fig. 17. pH of soil samples after H_2O_2-leaching. The dashed line marks the pH limit for classification of potential a.s. soils by H_2O_2-leaching.

from B21009 consisted of clay—silt. The results from the isotope analysis are presented in Table 5 and the soil types of each entire soil profile are presented in Table 6.

Table 5.
Results of the ICP-SFMS for three non-a.s. soils.

Element	B21001 mg/kg	B21011 mg/kg	B21012 mg/kg
As	<3	7.30	4.57
Ba	99.1	84.9	72.9
Be	0.981	1.39	1.35
Cd	<0.1	<0.1	<0.1
Co	11.3	15.4	13.6
Cr	22.7	38.6	43.9
Cu	11.8	20.6	19.3
Fe	19900	33900	30300
Hg	<1	<1	<1
Mn	324	560	381
Ni	16.2	28.4	30.8
P	536	860	802
Pb	11.6	18.2	17.9
S	215	<50	428
Sr	35.7	99.1	102
V	45.7	69.5	66.6
Zn	72.4	71.0	88.2

Table 6.
Soil types of soil columns with no a.s. soil. Depth in meters.

B21001		B21004		B21006		B21008		B21009	
Depth	Soil	Depth	Soil	Depth	Soil	Depth	Soil	Depth	Soil
0.1 – 1.3	GCl[1]	0.1 – 0.3	Ts	0.1 – 0.2	Ts	0.3 – 0.5	Cl-Si	0.2 – 3.6	Cl-Si
		0.3 – 3.2	Cl[1]	0.2 – 0.5	fS[1]	0.5 – 1.9	fS		
				0.5 – 0.6	Si[1]	1.9 – 2.0	Si		
				0.6 – 0.9	GCl[2,3]				

Table 6.
Continued.

B21010		B21011		B21012		B21013		B21014	
Depth	Soil	Depth	Soil	Depth	Soil	Depth	Soil	Depth	Soil
0.1 – 0.3	Ts	0.1 – 0.2	Ts	0.1 – 0.2	Ts	0.1 – 0.3	Ts	0.2 – 0.3	Ts
0.3 – 1.2	GCl	0.2 – 5.0	Cl[4]	0.2 – 2.0	Cl[4]	0.3 – 1.1	yFS (fS & Si)	0.3 – 2.1	GCl

[1] Presence of rust. [2] Presence of rust granules. [3] Extremely unstable. Possible quick clay. [4] Presence of shells.

5. Discussion

5.1. Spatial distribution and temporal formation

Acid sulfate soils exist in Västra Götaland, Sweden. They occur in organic-rich sediments, often near drained or partially drained lakes, in soils mapped as gyttja clay (or clay gyttja) by SGU. They may also occur in, or below, peat. Peat and gyttja account for 6.5 % of WVG's surface area, which translates to approximately 57,000 ha. Furthermore, a continued lowering of the water level in waters, due to drought or drainage, could expose additional potential a.s. soils. For instance, a two meter reduction of the water level in all major water bodies in WVG could expose up to 1,100 ha of land. In addition, the coast of Västra Götaland is being uplifted by about 4 mm/a (Vestø, Ågren, Steffen, Kierulf, & Tarasov, 2019), thereby exposing additional land. Drought and drainage could also influence a.s. soils in peats, thus turning potential a.s. soils into active a.s. soils through oxidation.

The existence of peat or gyttja does not guarantee the presence of a.s. soils. Gyttja samples from sites B21001, B21006, B21010, and B21014 were not a.s. soils, meaning that gyttja and peat-hosted a.s. soils make up less than 57,000 ha in WVG.

There is a seemingly sporadic nature to the spatial extent of a.s. soils, which becomes especially evident at neighboring sampling sites. Both sites B21001 and B21002 were adjacent to Göta Älv and both soil columns consisted entirely of gyttja clay. Only B21002 proved to be an a.s. soil. Similarly, samples from sites B21006 and B21007 both consisted of gyttja clay which was deposited in paleolake Hästefjorden, but only B21007 was defined as an a.s. soil. Although in this case, the gyttja clay at B21006 was overlain by silt and fine sand while B21007 consisted entirely of gyttja clay.

This somewhat arbitrary distribution seems to agree with Andersson et al. (2021) who stated that a.s. soils are not given, even though an area fulfills the host conditions. The intricacies of where a.s. soils form are beyond this thesis' scope, instead a more overarching process will be discussed.

Kling Jonasson (2020) concluded that the a.s. soils in Falkenberg, south of Västra Götaland, were formed during the Tapes transgression. This is not the case for sites B21005, B21007, and possibly B21003. There was no relative sea level rise in northern Västra Götaland during the Tapes transgression due to the more rapid post-glacial rebound (Påsse, 2003). The eustatic sea level rise resulted only in a decreasing regression. A transgression became noticeable first at the more central coastal latitudes where the relative sea level was stable, or even rose by a few meters (Miller & Robertsson, 1988). The magnitude of the Tapes transgression increased southward, and in southern Västra Götaland the sea level rose by about 10-12 m (Påsse, 2001).

Site B21007 is located in the upper central part of WVG at 64 m a.m.s.l. (Figs. 7 and 14) and sampling revealed potential a.s. soil. However, the gyttja clay contained substantial amounts of organic material which might have skewed the results of the H_2O_2-leaching somewhat. The site is too far north, too far inland, and too elevated to have been reached by the Tapes transgression. The area was, however, inundated by the sea after the retreat of the ice sheet about 13,000 cal yr BP (SGU, n.d.), and later by the *Yoldia Sea* (havet.nu, 2019). It was ultimately cut off from the sea 11,000 – 10,000 cal yr BP to form lake Hästefjorden (SGU, n.d.).

Hästefjorden was partially drained in the 1860's to expose arable land (Aronsson, 1998; Svenskt Vattenarkiv, 1995). It was at this time that the gyttja clay at site B21007 was bared, which means that the soil has been exploited for up to 150 years. Likely, enough time passed to neutralize any active a.s. soil, leaving only potential a.s. soil in the undisturbed, reduced conditions below the water table.

Similarly, site B21005 is located in central WVG, near the coast, at 42 m a.m.s.l. (Figs. 7 and 12) and sampling revealed potential a.s. soil. The Tapes transgression did not affect site B21005 as it only reached about 35 m a.m.s.l. at this location. The area was inundated after the retreat of the ice sheet 13,000 cal yr BP and became cut off from the sea again 11,000 – 10,000 cal yr BP to form lake Hällungen (SGU, n.d.).

Hällungen was partially drained in 1876 (Svenskt Vattenarkiv, 1995) and became Lilla Hällungen and Stora Hällungen. Site B21005 sits between these lakes and seems to have been relatively undisturbed since the partial draining.

The sample from Hällungen is only tentatively classified as a potential a.s. soil since the nature of peat makes the H_2O_2-leaching method somewhat unreliable (C. Öhrling, personal communication, May 5, 2021). Then again, the sample did not consist of peat, but of clay which was overlain by gyttja clay and peat. This raises the question if the peat affected the results in any way. Since this can't be ruled out, doubt remains.

Continuing, site B21003 is located further south, at 29 m a.m.s.l. (Figs. 7 and 8) and sampling revealed active a.s. soil. This area was also inundated by the sea after the retreat of the ice 13,000 cal yr BP (SGU, n.d.). There might have occurred a very slight transgression, but the sea level was generally stable at this site during the Tapes transgression (Fig. 18A). The area likely became a lake, or a shallow protected bay or lagoon 10,000 – 7,000 cal yr BP (Fig. 18B). Thereafter, the water level must have slowly subsided as it seems the site hosted some form of wetland, with a north–south crossing watercourse, until at least 1841 (Fig. 18C). It appears that the wetland was drained, and that the watercourse was rerouted to accommodate farmland, some time before 1897 (Fig. 18D). This means that the active a.s. soil might have existed between 120 – 180 years.

Lastly, site B21002 is located just southwest of B21003 at 15 m a.m.s.l. (Figs. 7 and 10). Sampling revealed potential a.s. soil in gyttja clay. The area was likely submerged from 13,000 cal yr BP until the early 1800's, when construction of the Göta Canal took place or, more likely, until 1910 – when the adjacent lake was partially drained (Svenskt Vattenarkiv, 1995). This means that any active a.s. soil was neutralized in a span of 110 years, leaving potential a.s. soil in the waterlogged section.

It is difficult to say why the a.s. soil was still active at site B21003 when there were only potential a.s. soils at sites B21002 and B21007, since all three were gyttja clays. The depositional environments of all three sites were also similar, i.e. lakes and protected bays, and they have been exposed for roughly the same amount of time (110 – 180 yrs).

One difference between the a.s. soils in WVG and the a.s. soils on the east coast and in Falkenberg is the depositional environment. Most a.s. soils on the east coast were formed in the Littorina Sea and the a.s. soils in Falkenberg were formed during the Tapes transgression. The majority of a.s. soils in WVG, however, were likely formed in lakes or lagoons which were established after the Fennoscan-dian ice sheet's retreat 13,000 – 12,000 cal yr BP.

5.2. Isotope analysis

Samples from sites B21002, B21003, and B21007 showed elevated amounts of S, which is common for a.s. soils. The sample from site B21005, however, did not contain significant amounts of S relative the other three samples. Instead, it contained a similar amount to B21012, which was not classified as an a.s. soil due to a too high pH after H_2O_2-leaching (Fig. 17), and only double the S amount of B21001,

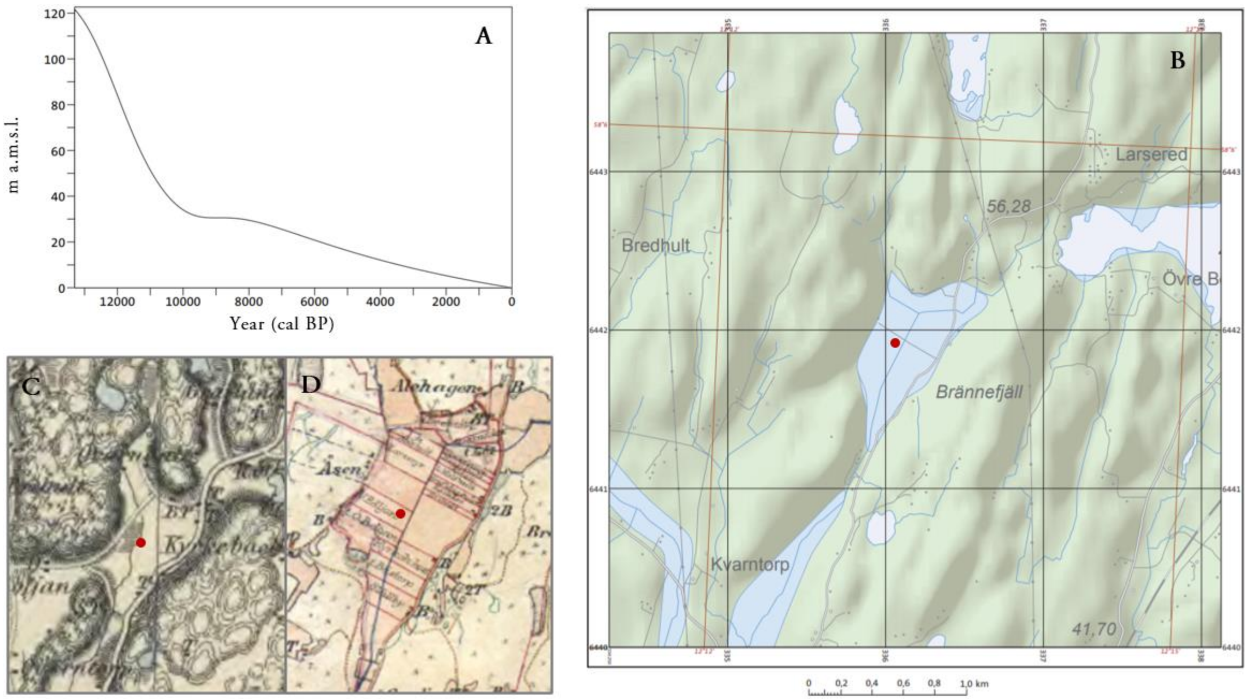

Fig. 18. Site B21003 hosted active a.s. soil in gyttja clay over potential a.s. soil in clay. The site is marked with a red dot in map B, C, and D. A) Shore displacement curve from site B21003, after SGU (n.d.). B) Sea level at site B21003 9,000 cal yr BP. The area likely functioned as a protected bay or lagoon. Blue areas are submerged beneath the sea. Lightblue areas are present day lakes. Black gridlines designate coordinates in SWEREF 99 TM and brown gridlines designate latitude and longitude in the reference system SWEREF99. Strandnivåkartan © SGU; GSD-Översiktskartan © Lantmäteriet. C) Historical map from 1841 depicting site B21003. Generalstabskartan: Vänersborg J243-42-1 (1841) © Lantmäteriet. D) Historical map from 1890-97 depicting site B21003. Häradsekonomiska kartan: Lilla edet J112-42-21 (1890-97) © Lantmäteriet.

which was also a non-a.s. soil. The soil sample from site B21012 did however contain shells which most certainly buffered the sample, and sample B21001 was just above the limit of the leaching procedure (Fig. 17). Thus, even though the S content of sample B21005 was significantly lower than the three other a.s. soils' S content, and closer to the two non-a.s. soils', the amount was likely high enough to cause the acidification rather than an error in the method.

Any other immediate discussion or conclusions of the isotope analysis lies outside the scope of this thesis.

5.3. Potential impact

Site B21002, B21005, and B21007 hosted potential a.s. soils. These soils will only adversely impact their surroundings if their water tables are lowered.

Site B21002 is located adjacent to Göta Älv from where 700,000 people receive their drinking water (Göteborgsregionen, 2019). The river has an average flow rate of 0.5 × 10^6 l/s (Göteborgs Stad, 2021), which means that any drainage from a.s. soils likely would be diluted relatively quickly. However, Göta Älv is lined with heavy industry and agriculture which adds to the pollution. An influx of leached metals from a.s. soils due to drought or drainage, would exacerbate the pollution. Gothenburg's raw water intake is closed approximately 100 days/year due to poor water quality (Göta älvs vattenvårdsförbund, 2015). The leading cause, however, is biological waste. Metal concentrations, meanwhile, are consist-ently within the margins for safe drinking water. It is therefore questionable if a.s. soils could impact the water quality of Göta Älv in an impactful way. A bigger concern is dredging masses, which could create a.s. soil hot spots if deposited on land. 350,000 cubic meters of dredging mass from Göta Älv is currently being extracted to expand a terminal in Gothenburg's harbor (Göteborgs Hamn, 2018). The terminal will be embanked to prevent toxic leakage to the Göta Älv estuary, but care should be taken of the corrosive nature of a.s. soils which could weaken the structural integrity of concrete and other construction material (Concrete Pipe Asocciation of Australasia, n.d.).

Site B21005 is located between Lilla Hällungen and Stora Hällungen. Stora Hällungen is a water protection area and the source of drinking water for Stenungsund municipality. The lake is also rich in fish. A continued lowering of Lilla Hällungen could cause some adverse effects, in the form of leached metals, in northern Stora Hällungen. Acidification, however, is unlikely as Stora Hällungen's lakebed consists of shell-rich clay which acts like a buffer (Hopen, 2007).

The gyttja clay at site B21007 was part of a vast region of gyttja clay, spanning several cultivated fields. Crops grown on a.s. soils have been studied, but the ramifications are not yet well understood (Fältmarsch et al., 2008).

Lastly, site B21003 was an active a.s. soil and thus the most immediate issue. The field at this site did not appear to be limed (Fig. 9), which would have lessened any adverse effects in the upper soil horizons, but again, effects from a.s. soils on crops are poorly understood.

Western Västra Götaland is already one of Sweden's most acidified regions (Fig. 1) due to acid precipitation and a weathering-resistant bedrock (Länsstyrelsen, n.d.). Liming efforts in Västra Götaland culminated in 1993 when 35,000 ton liming material was used, according to Länsstyrelsen (n.d.). Liming continues till this day but budget issues in 2019 has left several lakes and wetlands unlimed (Sportfiskarna, 2020). A.s. soils are not mentioned in the latest acidification and liming report by Västra Götalands county administrative board (Länsstyrelsen i Västra Götalands Län, 2019), likely due to their unknown presence.

The now confirmed presence, but unknown extent, of a.s. soils, coupled with a cut to liming efforts and the already poor buffer capacity of watercourses in WVG – could seriously impact the biota. A.s. soils could also hamper several of Sweden's 16 environmental targets, especially the *Only natural acidification*, *Thriving lakes and watercourses*, and *Quality groundwater* objectives (Sveriges Miljömål, n.d. a).

5.4. The literature review

A lot of the literature, especially the Norwegian literature, was difficult or time consuming to obtain as it was often regionally locked. A few promising references could not be collected in time due to this (e.g. Vigerust, 1965; Vigerust, Haugbotn, Forbord, & Njøs, 1972; Ødelien, 1966; Ødelien, Haddeland, Njølstad, & Selmer-Olsen, 1973; Øien, 1971).

Still, much of the material could be accessed and it was encouraging that the conclusions from the literature review corresponded well with where a.s. soils were found in WVG, i.e. in organic-rich sediments and near drained or partially drained lakes. This suggests that the formational environments of a.s. soils in eastern Canada, coastal Norway, and the west coast of Sweden could be somewhat similar. Combining research on a.s. soils from these three regions could prove beneficial to the understanding of the overarching formational environments of a.s. soils in each respective region.

5.5. Sources of error

Of the 14 extracted soil columns, six did not contain any gyttja (B21004, B21008, B21009, B21011, B21012, and B21013). Because the sites were not randomly selected, i.e. areas of gyttja were sometimes prioritized in the selection process, there could be some bias towards these sediments as hosts for a.s. soils.

Furthermore, it was sometimes difficult to achieve the highest calibration of the pH meter. The calibration works on a four-step scale where three is the highest calibration and zero is the lowest (and *error* means unsuccessful calibration). When measuring the pH of sites B21010 – B21014 a calibration score of two was achieved, and during the H_2O_2-leaching, a score of one was achieved. Still, this is not deemed to have majorly impacted any of the results.

Lastly, the H_2O_2-leaching method should be performed as quickly as possible after sampling (Sullivan et al., 2018). The samples were stored in a sealed chip tray for around one week before sampling. Oxygen in the chip tray might have prematurely caused the acidification of some samples.

6. Conclusions

1. Acid sulfate soils exist in Västra Götaland, Sweden. Of the four confirmed a.s. soils, three were potential a.s. soils and one was an active a.s. soil. They occurred in organic-rich sediments, often near lowered lakes, chiefly in soils mapped as gyttja clay (or clay gyttja) by SGU. All four locations were anthropogenically drained between 110 – 180 years ago.
2. Organic-rich sediments, i.e. peat and gyttja, account for 57,000 ha of western Västra Göta-land's surficial sediments but not all gyttjas and peats are hosts to a.s. soils. Thus, even though the presence of a.s. soils is confirmed, the extent remains unknown.
3. Unaccounted for a.s. soils, coupled with a cut to liming efforts and the already poor buffer capacity of watercourses in WVG – could impact the biota and hamper Sweden's environmental targets.
4. Literature from Norway and Canada could successfully be used to assess where a.s. soils were likely to be found in WVG. This suggests that the formational environments of a.s. soils in eastern Canada, coastal Norway, and the west coast of Sweden could be somewhat similar.

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References

Aldén Rudd, P. (2016). *Kareby 28 m. fl., Kareby socken, Kungälvs kommun Arkeologisk förundersökning i avgränsande syfte* (Rapport 2016:10). Retrieved from http://samla.raa.se/xmlui/bitstream/handle/raa/10960/Rapport%202016-10.%20Kareby.%20LOW.pdf?sequence=1

Alén, J. E. (1888). Undersökning af postglacial lera ("svartlera") från Göteborg. *Geologiska Föreningen i Stockholm Förhandlingar, 117*(5), 341-344. Doi:10.1080/11035898809444213

Andersson, M., & Hansen, L. (2019, April 10). Acid sulfate soils, why would Norway be the exception? [Conference abstract]. General Assembly 2019 of the European Geosciences Union, Vienna, Austria. https://meetingorganizer.copernicus.org/EGU2019/EGU2019-105.pdf

Andersson, M., Hansen, L., & Flem, B. (2021). Pilot investigations of acid sulfate soils in Alta, Norway. Is it a national issue? In H. A. Nakrem & A. M. Husås (Eds), *Abstracts and proceedings of the geological society of norway* (p. 3). Retrieved from https://www.geologi.no/konferanser/vinterkonferanser/item/1108-abstractsvk21

Andrén, T., Björck, S., Andrén, E., Conley, D., Zillén, L., & Anjar, J. (2011). The development of the Baltic Sea Basin during the last 130 ka. In J. Harff, S. Björck, P. Hoth (Eds.), *The Baltic Sea Basin* (pp. 75-97). Berlin, Heidelberg: Springer.

Aronsson, J-E. (1998). *Sänkning av Hästefjorden* (Bachelor's thesis, University of Gothenburg, Gothenburg, Sweden). Retrieved from https://www.varbygd1891.se/wp-content/uploads/2017/03/S%C3%A4nkningarna-av-H%C3%A4stefjorden.pdf

Bayard, C., & Karlsson Mood, L. (2014). Förekomsten av sura sulfatjordar i Mälardalen (Bachelor's Essay). Uppsala: Institutionen för geovetenskaper, Uppsala universitet. Retrieved from https://www.diva-portal.org/smash/get/diva2:729374/FULLTEXT01.pdf

Becher, M., Sohlenius, G., & Öhrling, C. (2019). *Sur sulfatjord – egenskaper och utbredning* (SGU-rapport, 2019:13). Retrieved from http://resource.sgu.se/produkter/sgurapp/s1913-rapport.pdf

Björck, S. (2015). Littorinahavet (ca 9 800 år före nutid – I dag). In P-G. Andréasson (Ed), *Geobiosfären: en introduktion* (pp 501-504). Lund: Studentlitteratur AB.

Boman, A., Becher, M., Mattbäck, S., Sohlenius, G., Auri, J., Öhrling, C., & Edén, P. (2018). *Klassificering av sura sulfatjordar i Finland och Sverige* (Ver. 1.2018). Retrieved from https://vimlavattenorg.files.wordpress.com/2018/07/klassificering_sura_sulfatjordar.pdf

Callinan, R. B., Sammut, J., & Fraser, G. C. (2005). Dermatitis, branchitis and mortality in empire gudgeon Hypseleotris compressa exposed naturally to runoff from acid sulfate soils. *Diseases of aquatic organisms*, *63*(2-3), 247-253. Doi: 10.3354/dao063247

Concrete Pipe Association of Australasia. (n.d.). *Concrete Pipe in Acid Sulfate Soil Conditions*. Retrieved from Hynds Pipe Systems: https://www.hynds.co.nz/wp-content/uploads/CPAASRCPinAcidSulfateSoilConditions.pdf

Dahl, K. (1923). Massedød blandt ørret ved forgiftning med avløpsvand fra myrer. *Norsk Jæger- og Fisker-Forenings Tidsskrift, 52*(2), 77-81.

Dahl, K. (1926). Vandets surhetsgrad og dens virkninger paa ørretyngel. *Tidsskrift for det Norske Landbruk, 33*, 232–242.

De Kimpe, C. R., Laverdière, M. R., & Baril, R. W. (1988). Classification of Cultivated Estuarine Acid Sulfate Soils in Quebec. *Canadian Journal of Soil Science 68*(4), 821-826. Doi:https://doi.org/10.4141/cjss88-081

Department of Agriculture and Marketing. (1991). *Soils of Colchester County, Nova Scotia* (No. 19). Retrieved from https://sis.agr.gc.ca/cansis/publications/surveys/ns/ns19b/ns19b_report.pdf

Fanning, D. S., Rabenhorst, M. C., & Fitzpatrick, R. W. (2017). Historical developments in the understanding of acid sulfate soils. *Geoderma, 308*, 191-206. doi:10.1016/j.geoderma.2017.07.006

Fjeldskaar, W., & Bondevik, S. (2020). The Early-Mid Holocene transgression (Tapes) at the Norwegian coast – comparing observations with numerical modelling. *Quaternary Science Reviews*, *242*. doi:10.1016/j.quascirev.2020.106435

Fältmarsch, R. M., Åström, M. E., & Vuori, K-M. (2008). Environmental risks of metals mobilised from acid sulphate soils in Finland: a literature review. *Boreal Environment Research, 13*(5), 444-456.

Gadd, N. R. (1988). Preface. In N. R. Gadd (Ed.), *The Late Quaternary Development of the Champlain Sea Basin*. Stittsville, Ontario: Love Printing Service Limited.

Gleysol. (2000). In *Skogsencyklopedin*. Retrieved from https://www.skogen.se/glossary/gleysol-sumpjordman-gyttjejordman

Gustafsson, R. (2019, March 6). Sällsynt jordtyp orsak till syraangripna pumpar vid Argus-bygget. *Hallands Nyheter*. Retrieved from https://www.hn.se/nyheter/falkenberg/s%C3%A4llsynt-jordtyp-orsak-till-syraangripna-pumpar-vid-argus-bygget-1.13816248

Göta älvs vattenvårdsförbund. (2015). *Fakta om Göta älv: En beskrivning av Göta älv och dess avrinningsområde nedströms Vänern 2015*. Retrieved from https://www.gotaalvvvf.org/download/18.2f0ad835166c596881356a83/1540998119692/fakta_om_gota_alv_webb.pdf

Göteborgs Hamn. (2018, October 11). *Byggstart för ny terminal i Göteborgs hamn* [Press release]. Retrieved from https://www.goteborgshamn.se/press/pressmeddelanden/byggstart-for-ny-hamnterminal-i-goteborgs-hamn/

Göteborgs Stad. (2021). Råvatten från Göta Älv. Retrieved from https://goteborg.se/wps/portal/start/vatten-och-avlopp/ravatten/ravatten-fran-gota-alv?uri=gbglnk%3Agbg.page.dc9c1fae-a26d-4c0d-9316-c45e83c68fa0

Göteborgsregionen. (2019, October 22). *Nytt vattenskyddsområde ska trygga 700 000 människors tillgång till vatten* [Press Release]. Retrieved from https://goteborgsregionen.se/GR/toppmenyn/om-goteborgsregionen/nyheter--press/nyheter/2019-10-22-nytt-vattenskyddsomrade-ska-trygga-700-000-manniskors-tillgang-till-dricksvatten.html

havet.nu. (2019). Östersjöns geologi – Ett ungt havsområde. Retrieved from https://www.havet.nu/geologisk-historia

Hopen, S. (2007, October 26). Bättre för Öringen i Hällungen. *Göteborgs-Posten*. Retrieved from https://www.gp.se/nyheter/v%C3%A4stsverige/b%C3%A4ttre-f%C3%B6r-%C3%B6ringen-i-h%C3%A4llungen-1.1183307

Huitfeldt-Kaas, H. (1922). Om aarsaken til masseød av laks og ørret i Frafjordelven, Helleelven og Dirdalselven i Ryfylke høsten 1920. *Norsk Jæger- og Fisker-Forenings Tidsskrift, 51*(1/2), 37-44.

Jezierska, B., & Witeska, M. (2006). The metal uptake and accumulation in fish living in polluted waters. In Twardowska I., Allen H.E., Häggblom M.M., Stefaniak S. (eds), *Soil and water pollution monitoring, protection and remediation* (pp. 107-114). Dordrecht: Springer.

Karrow, P. F. (2006). The Champlain Sea: here yesterday, gone tomorrow. Retrieved 2021-04-24 from https://uwaterloo.ca/wat-on-earth/news/champlain-sea-here-yesterday-gone-tomorrow

Kling Jonasson, I. (2020). *Acid sulphate soil in Falkenberg on the west coast of Sweden - The first discovery of active acid sulphate soil outside the Baltic Basin* (Master’s thesis). Gothenburg: Department of Earth Sciences, University of Gothenburg. Retrieved from https://gupea.ub.gu.se/bitstream/2077/66395/1/gupea_2077_66395_1.pdf

Lambeck, K., & Chappell, J. (2001). Sea level change through the last glacial cycle. *Science, 292*(5517), 679-686. Doi:10.1126/science.1059549

Lax, K. (2005). Stream plant chemistry as indicator of acid sulphate soils in Sweden. *Agricultural and Food Science, 14*(2005), 83-97. doi:10.2137/1459606054224165

Lindgren, A. (2021). *Acid sulphate soils and its influence on metal concentrations in adjacent water bodies - A case study from Halland, SW Sweden* (Master’s thesis). Gothenburg: Department of Earth Sciences, University of Gothenburg. Retrieved from https://gupea.ub.gu.se/handle/2077/68009

Länsstyrelsen i Västra Götalands Län. (2019). *Försurning och kalkning i Västra Götalands län* (Rapport 2019:32). Retrieved from Länsstyrelsen: https://www.lansstyrelsen.se/download/18.35db062616a5352a22a25683/1560836831100/2019-32.pdf

Länsstyrelsen. (n.d.). Kalkning av försurade vatten. Retrieved from https://www.lansstyrelsen.se/vastra-gotaland/miljo-och-vatten/vattenverksamhet/vagledning-for-olikavattenverksamheter/kalkning-av-forsurade-vatten.html

Miljødirektoratet. (2020). Sur nedbør. Retrieved from https://miljostatus.miljodirektoratet.no/tema/forurensning/sur-nedbor/

Miller, U., & Robertsson, A-M. (1988). Late Weichselian and Holocene environmental changes in Bohuslän, south-western Sweden. *Geographia Polonica*, *55*, 103-113. Retrieved from: https://rcin.org.pl/Content/4202/WA51_13400_r1988-t55_Geogr-Polonica.pdf#page=111

Moormann, F. R. (1963). Acid sulfate soils (cat-clays) of the tropics. *Soil Science*, *95*(4), 271-275. Doi: 10.1097/00010694-196304000-00009

Munkenberg, B-A. (2001). *Åtta fornlämningar i Heljereds dalgång* (UV Väst rapport 2001:13). Retrieved from http://samla.raa.se/xmlui/bitstream/handle/raa/3554/rv2001_13.pdf?sequence=3

NGU. (2021). Kart på nett: løsmasser og marin grense. Retrieved 2021-04-22 from https://www.ngu.no/emne/kart-pa-nett

Nordmyr, L., Åström, M., & Peltola, P. (2008). Metal pollution of estuarine sediments caused by leaching of acid sulphate soils. *Estuarine, coastal and shelf science*, *76*(1), 141-152. doi:10.1016/j.ecss.2007.07.002

Persson, M. (2014). *Predicting Spatial and Stratigraphic Quick-clay Distribution in SW Sweden* (Doctoral dissertation, University of Gothenburg, Gothenburg, Sweden). Retrieved from https://gupea.ub.gu.se/handle/2077/35632

Pons, L. J. (1973). Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. In H. Dost (Ed.), *Proceedings of the International Symposium 13-20 August Wageningen* (pp. 3-27). Retrieved from https://library.wur.nl/isric/fulltext/isricu_i3637_001.pdf#page=15

Pousette, K. (2007). *Råd och rekommendationer för hantering av sulfidjordsmassor* (Teknisk rapport 2007:13). Luleå: Luleå tekniska universitet.

Påsse, T. (2001). *An empirical model of giacio-isostatic movements and shore-level displacement in Fennoscandia* (SKB Rapport R-01-41). Retrieved from U.S. Department of Energy Office of Scientific and Technical Information: https://www.osti.gov/etdeweb/servlets/purl/20206307

Påsse, T. (2003). Strandlinjeförskjutning i norra Bohuslän under holocen. In P. Persson (ed.). *Strandlinjer och vegetationshistoria. Kvartärgeologiska undersökningar inom Kust till kust projektet, 1998-2002* (pp. 31-87). Gothenburg: Arkeologiskt Naturvetenskapliga Laboratoriet

Queensland Government. (2019). Acid sulfate soils explained. Retrieved from https://www.qld.gov.au/environment/land/management/soil/acid-sulfate/explained

Rankka, K., Andersson-Sköld, Y., Hultén, C., Larsson, R., Leroux, V., & Dahlin, T. (2004). *Quick clay in Sweden* (No 65). Retrieved from https://www.sgi.se/globalassets/publikationer/rapporter/pdf/sgi-r65.pdf

Ross, G.J., & Ivarson, K.C. (1981). The occurence of basic ferric sulfates in some Canadian soils. *Canadian Journal of Soil Science*, *61*(1), 99-107. Doi: https://doi.org/10.4141/cjss81-011

SGU. (2020). Haz Arctic. Retrieved from http://sgu.test.knowitis.se/om-sgu/verksamhet/samarbeten/haz-arctic/?acceptCookies=true

SGU. (n.d.). Kartgeneratorn. Retrieved from https://www.sgu.se/produkter/kartor/kartgeneratorn/

SLU. (2020). Jordmåner. Retrieved from https://www.slu.se/miljoanalys/statistik-och-miljodata/miljodata/webbtjanster-miljoanalys/markinfo/markinfo/markprofil/jordman/

Sohlenius, G. (2011). Sulfidjordar och sura sulfatjordar – vad gör SGU? (SGU-rapport, 2011:12). Retrieved from http://resource.sgu.se/produkter/sgurapp/s1112-rapport.pdf

Sohlenius, G., & Öborn, I. (2004). Geochemistry and partitioning of trace metals in acid sulphate soils in Sweden and Finland before and after sulphide oxidation. *Geoderma, 122*, 167-175. doi:10.1016/j.geoderma.2004.01.006

Sohlenius, G., Persson, L., Lax, K., Andersson, L., & Daniels, J. (2004). Förekomsten av sulfidhaltiga postglaciala sediment (SGU-rapport, 2004:9). Retrieved from http://resource.sgu.se/produkter/sgurapp/s0409-rapport.pdf

Sportfiskarna. (2020). Nivån på kalkningen bibehölls I Västra Götaland. Retrieved from https://www.sportfiskarna.se/Om-oss/Aktuellt/ArticleID/10129/Niv%C3%A5n-p%C3%A5-kalkningen-bibeh%C3%B6lls-i-V%C3%A4stra-G%C3%B6taland

Sullivan, L., Ward, N., Toppler, N., & Lancaster, G. (2018). *National Acid Sulfate Soils guidance: National acid sulfate soils sampling and identification methods manual*. Retrieved from https://www.waterquality.gov.au/issues/acid-sulfate-soils/sampling-and-identification-methods-manual

Svartlera. (n.d.). In *Nationalencyklopedin*. Retrieved from https://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/svartlera

Svenskt Vattenarkiv. (1995). *Sänkta och torrlagda sjöar* (Hydrologi 62). Retrieved from https://www.smhi.se/publikationer/sankta-och-torrlagda-sjoar-1.2550

Sveriges Miljömål. (n.d. a). Miljömålen. Retrieved from https://www.sverigesmiljomal.se/miljomalen/

Sveriges Miljömål. (n.d. b). Andel försurade sjöar (>1 ha) klassade enligt bedömningsgrunder. Retrieved from https://www.sverigesmiljomal.se/miljomalen/bara-naturlig-forsurning/forsurade-sjoar/

Tanaka, A., & Navasero, S. A. (1966). Growth of the rice plant on acid sulfate soils. *Soil science and plant nutrition*, *12*(3), 23-30. Doi: 10.1080/00380768.1966.10431192

Trafikverket. (2012). *Landskap i långsiktig planering: Pilotstudie I Västra Götaland*. Retrieved from https://trafikverket.ineko.se/Files/en-US/11473/Ineko.Product.RelatedFiles/2011_122_landskap_i_langsiktig_planering.pdf

Urho, L., Hildén, M., & Hudd, R. (1990). Fish reproduction and the impact of acidification in the Kyrönjoki River estuary in the Baltic Sea. *Environmental Biology of Fishes*, *27*(4), 273-283. doi:10.1007/bf00002746

Vestøl, O., Ågren, J., Steffen, H., Kierulf, H., & Tarasov, L. (2019). NKG2016LU: a new land uplift model for Fennoscandia and the Baltic Region. *Journal of Geodesy*, *93*(9), 1759-1779. Doi: https://doi.org/10.1007/s00190-019-01280-8

Vigerust, E. (1965). Noen problemer ved oppdyrking av innsjøsedimenter. *Ny Jord*, *52*, 3-12.

Vigerust, E., Haugbotn, O., Forbord, I., & Njøs, A. (1972). Undersøkelser av jorda innenfor området for de tidligere Lesjavatna. *Ny Jord*, *59*, 3-17.

Åbjörnsson, K., Stenberg, M., & Sohlenius, G. (2018). *Järn- och aluminiumurlakningar från invallningar – en undersökning av tre områden i Skåne*. Skåne: Länsstyrelsen, Ekoll AB.

Öborn, I. (1989). Properties and classification of some acid sulfate soils in Sweden. *Geoderma, 45*(3-4), 197-219.

Ødelien, M. (1966). Undersøkelser over utvaskingen av sulfat fra jorda. *Forskning og Forsøk i Landbruket*, *16*, 39-70.

Ødelien, M., Haddeland, I., Njølstad, A., & Selmer-Olsen, A. R. (1973). Eksempler på svoveloksydasjon og reduksjon av svovelforbindelser i jord og vann. *Ny Jord*, *60*, 3-12.

Øien, A. (1971). Undersøkelse av vannprøver fra bekker, vassdrag og innsjøer i områder med forskjellig geologisk opphavsmateriale. *Meldinger fra Norges landbrukshøgskole*, *50*(19), 9.