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Effect of droughts on future weathering rates in Sweden

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Abstract. In a future warmer climate, extremely dry, warm summers might become more common. In Scandinavia, the extreme summer of 2018 was such an event. Soil weathering is affected by temperature and precipitation, and climate change as well as droughts can therefore affect soil chemistry and plant nutrition. In this study, climate change effects on weathering were studied on seven forest sites across widely different climate zones in Sweden, using the dynamical model ForSAFE. Two climate scenarios were run, one climate change base scenario and one drought scenario. The model results show a large geographical variation of weathering rates for the sites. There is, however, no geographical gradient, despite the strong dependence of temperature on weathering, as also soil texture and mineralogy have strong effects on weathering. There is a pronounced seasonal dynamic, with much lower weathering rates during winters than during summers, and with more variable summer weathering rates depending on more variable soil moisture and temperature. According to the climate change base scenario, the weathering rates will increase by 5–17 % per degree of warming. The relative increase is largest in the two south-eastern sites, with low total weathering rates caused by relatively coarse soils and often dry summers. Changes in seasonal dynamics due to climate change differ between regions. At sites in southern Sweden, future weathering increase occurs throughout the year, though generally most in spring and summer. In the north the increase in weathering during winters is almost negligible, even though the temperature increase during winter is high, as the winter temperatures still will mostly be below zero. The drought scenario has the strongest effect in southern Sweden and here weathering can temporally become as low as winter weathering during drought summers. Soil texture also has an effect on how fast the weathering decrease during drought occurs, as well as how fast the soil rewets and resume normal weathering rates after the drought, where coarse soils respond quicker. Yearly weathering during the drought years in the most affected site is only 78 % of the weathering of the base scenario. In the north, the soils do not dry out as much despite the low precipitation, and in the northernmost site weathering is not much affected. The study shows that it is crucial to take seasonal climate variations and soil texture into account when assessing the effects of a changed climate on weathering rates and plant nutrient availability.

1 Introduction

In some regions of the world, the risk for plant nutrient deficiencies is high, for example in regions with low weathering rates and/or where anthropogenic sulfate and nitrogen deposition have caused acidification and leaching of base cations (BC: Ca, Mg, K and Na) from soils (Johnson et al., 2018). Large parts of southern Sweden are such sensitive and acidified areas with decreasing levels of base cations (Akselsson et al., 2013). Measurements of nutrient concentrations in pine and spruce needles in southern Sweden between 1985 and 1994, as well as in leaves in Europe between 1992 and 2009, have shown signs of base cation imbalances (Thelin et al., 1997; Jonard, et al., 2015).

Future societal demands for forestry products are expected to increase with the need of replacing fossil energy and materials (Böttcher et al., 2012). Increased harvesting of forest biomass would magnify nutrient removal from forests, decrease nutrient stores in soils (Kaarakka et al., 2014) and potentially worsen nutrient deficiency, making trees more vulnerable to stressors such as insects, diseases and climate change (de Oliveira Garcia et al., 2018). Moreover, increasing levels of CO_2 in the atmosphere, raised temperatures and elevated nitrogen deposition lead to increasing forest growth in temperate latitudes, unless it is too dry (Restaino et al., 2016). Increased forest growth means an increased need for nutrients, exacerbating the risk of nutrient deficiencies even further.

Base cations originate to a large extent from weathering of minerals in the soil (Brantley et al., 2008). Weathering rates increase with temperature, but also with soil moisture (Brady and Weil, 1999). Increasing temperatures increase evapotranspiration, and soils in a warming climate can therefore become drier, even if the amount of precipitation is unchanged. Furthermore, climate change can lead to changes in precipitation amounts or in seasonality of precipitation, so that e.g. less of the precipitation falls during the warmer months. For some minerals, weathering is also dependent on concentrations of weathering products in soil solution (Brantley et al., 2008), so that enhanced uptake by trees can lead to enhanced weathering rates. A warming climate could thereby lead to decreasing or increasing weathering rates of base cations, depending on whether soil moisture decreases or increases during the warmer seasons and on how trees grow in the new climate. This in turn leads to higher or lower risk of nutrient deficiencies in forest trees in a specific stand.

When climate gets warmer, not only does the average precipitation change, but extreme events like droughts become more likely and more extreme (Kellomäki et al., 2008). One such example is the drought in Sweden during the summer of 2018 (Toreti et al., 2019). This kind of droughts might affect weathering and the nutrient situation as well as the forest growth and tree mortality (Hartman et al., 2018). It is therefore vital to know more about how weathering rates react to climate change and droughts. It is not possible to measure weathering rates *in situ* and weathering rates measured in a lab setting differs a lot to actual rates in undisturbed soils in nature (Brantley et al., 2008). Weathering rates therefore need to be modelled, for example by using biogeochemical models.

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1.1 Aims

The aims of this paper are to describe how weathering of base cations (Ca, Mg, K and Na) develops in a future climate (the A1B scenario), and to investigate how it is further affected by five consecutive years of warm summer drought. For this we use the biogeochemical model ForSAFE to simulate weathering rates under two climate scenarios in different climate regions of Sweden up to 2100.

2 Methods

The ForSAFE model (Belyazid et al., 2006; Wallman et al., 2005) was applied to seven managed spruce forest sites located in seven different climate regions of Sweden (Table 1 and Fig. 1). The sites have been monitored for many years within the Swedish Throughfall Monitoring Network (SWETHRO) (Pihl Karlsson et al., 2011). The sites' development was modelled from 1900 to 2100 with a daily time step.

2.1 ForSAFE

The ForSAFE model is a dynamic process based biogeochemical model developed to study the effect of atmospheric deposition, climate change and forest management on tree growth, soil and runoff water chemistry and C and N cycling. It includes dynamic feedbacks between soil chemistry, hydrology, forest growth and organic material in the soil and consists of integrated modified versions of four models: SAFE, a geochemical soil model (Alveteg et al., 1995; Martinsson et al., 2005), the hydrological PULSE model (Lindström and Gardelin, 1992), the PnET model of tree growth (Aber and Federer, 1992) and the DECOMP model for decomposition of soil organic matter (Wallman et al., 2006; Walse et al., 1998). The ForSAFE model is continuously being developed in order to better answer new research objectives (Erlandsson Lampa et al., 2020; Lucander et al., 2021; Kronnäs et al., 2019; Belyazid et al., 2011; Phelan et al., 2016; Zanchi et al., 2016; Zanchi et al., 2021b; Yu et al., 2018). In this study, ForSAFE with daily time steps and one soil profile per site was used. A new subroutine with regards to hydrology, with an internal smaller time step in the calculation of the water flow, was implemented to make its handling of heavy rainfalls more reliable.

2.2 Site descriptions

Most of Sweden has a (mildly) continental climate, with southern Sweden on the border of or transitioning into a temperate climate, in the Köppen-Geiger climate classification (Kottek et al., 2006). Of the seven climate regions of this study (Fig. 1), the four regions in southern Sweden are near the border between climate classes Cfb and Dfb (warm-summer humid temperate and continental climate, both with no large seasonal differences in precipitation, four or more summer months with a monthly average temperature above 10 °C and the difference between C and D being whether the average temperature of coldest month is above or below -3 °C). The three northern climate regions, except parts of the mountain area, are in the class Dfc (subarctic climate, same criteria as Dfb except that less than four months has a monthly average temperature above 10 °C).

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The sites (Fig. 1 and Table 1) are covered with spruce (*Picea abies*) forest and have typical Swedish conifer forest soils – thin, young, coarse tills, usually with relatively low weathering rates of base cations for their ages, mostly formed during and after the last deglaciation. The Caledonian mountain region in the north western part of the country has a more varied and more base rich mineralogy than most of the country. The site in this region, Ammarnäs, is a representative example of this, with 97 % base saturation and high soil water concentrations of especially calcium (Greiling et al., 2018).

At the sites, measurements of deposition under the canopy and (for most sites) on an open field nearby are carried out on a monthly basis within the framework of the SWETHRO monitoring network. Three times per year, soil water chemistry at 50 cm depth in the mineral soil is measured using suction lysimeters. Soil properties, e.g. texture and total chemistry of the soil, have been measured once per site in four to five soil layers (including an organic upper layer). At most of the sites, forest biomass has been measured a few times. In Ammarnäs, the measured total chemistry from the dug soil pit had too low calcium content for it to be possible to match the measured soil water chemistry, which indicates that there is a local variability in soil composition at the site, with either higher calcium content where the lysimeters are placed than in the soil pit, or a lateral flow from a much more calcium rich soil somewhere outside or within the site. A high calcium content has been found in rock samples in the Ammarnäs area (Grimmer et al., 2016) and it is thus likely that there is a variation in calcium content in the soils at the site too. The sites Västra Torup, Södra Averstad and Holmsvattnet were clear cut recently. In Västra Torup and Södra Averstad, soil water measurements continued after the clear cut. In Västra Torup, a strong increase of soil water concentrations of several elements was recorded after the clear cut, whereas in Södra Averstad, with fewer post-clear cut measurements, only an increase in potassium was recorded. Six of the sites are also described in Zanchi et al. (2021a).

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Table 1. Measured data for the modelled sites, ordered from south to north. BC stand for $Ca^{2+}+Mg^{2+}+K^{+}+Na^{+}$. ANC is acid neutralizing capacity, ANC = $[BC] + [NH_4^+] - [SO_4^{2-}] - [NO_3^-] - [Cl^-]$.

	V. Torup	Bordsjö	S. Averstad	Hyttskogen	Holmsvattnet	Högbränna	Ammarnäs
Average deposition on open field							
years *	1997-2010	1996-2001	1991-2019	1993-2019**	1992-2019	1996-2019	1992-2000
SO_4^{2-} ($kg*ha^{-1}*yr^{-1}$)	6.4	5.0	3.8	3.2	2.0	0.9	1.3
$NO_3^-+NH_4^+$ ($kg*ha^{-1}*yr^{-1}$)	12.0	8.0	6.2	5.0	2.1	1.2	1.4
Cl^- ($kg*ha^{-1}*yr^{-1}$)	29.1	12.7	7.6	3.7	1.7	1.3	3.4
BC ($kg*ha^{-1}*yr^{-1}$)	24.7	12.6	7.3	5.8	2.4	2.8	2.9
Average soil water chemistry							
years	1996-2017	1996-2018	1990-2015	2002-2018	1998-2010	1996-2018	1991-2018
pH	4.6	4.8	4.8	6.1	5.2	5.8	6.6
ANC ($\mu eq*l^{-1}$)	-165	-19	1	139	25	56	395
SO_4^{2-} ($\mu eq*l^{-1}$)	153	138	118	85	177	37	85
Cl^- ($\mu eq*l^{-1}$)	197	168	166	52	41	22	53
NO_3^- ($\mu eq*l^{-1}$)	0.8/292 +	0.9	3	3	3	0.2	0.1
BC ($\mu eq*l^{-1}$)	270	281	288	254	244	114	532
Al-tot ($mg*l^{-1}$)	1.9	0.9	1.0	0.2	0.6	0.1	0.1
DOC ($mg*l^{-1}$)	7.3	9.9	11.9	8.6	7.0	2.8	12.2
Base saturation at 50 cm	6.5%	12%	13%	16%	28%	31%	97%
Soil texture at 50 cm depth							
stones and gravel (%)	32.0	40.0	19.3	80.4	52.8	48.8	36.8
sand (%)	54.4	51.0	66.5	16.8	40.5	47.2	55.2
silt (%)	10.4	5.3	10.5	0.8	3.8	1.6	6.4
clay (%) ++	1.6	1.5	1.9	0.4	0.8	0.8	0.8
organic matter (%)	1.6	2.3	1.9	1.6	2.3	1.6	0.8

* Deposition of BC was sometimes measured only part of the period

** Data on open field deposition for Hyttskogen is from nearby sites Kvisterhult and Karsbo

\+ Before and after clear cut

++ Except in Västra Torup, clay content has been estimated, since clay and silt were not analysed separately (Lucander et al., 2021)

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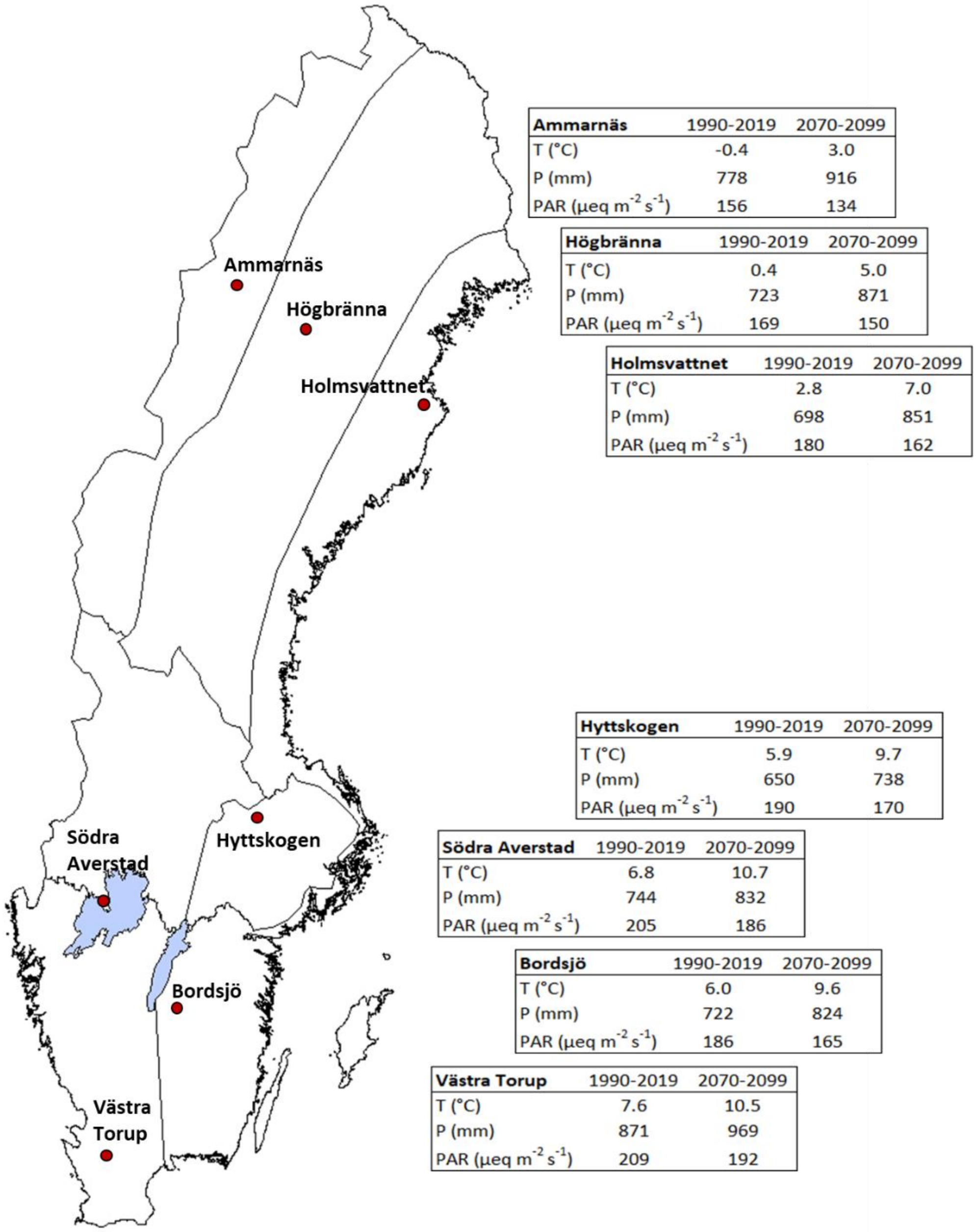

Figure 1. The seven SWETHRO sites in their seven climatic regions, with climatic parameters (T: temperature, P: precipitation and PAR: photosynthetic active radiation) as yearly averages for the time period 1990–2019 to the left and projected climate for the A1B scenario for the time period 2070–2099 to the right.

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2.3 Model input data and scenarios

The ForSAFE model requires data on soils, forestry, deposition of ions from the atmosphere and climate. The three latter are given as time series for the time period 1900–2100, while the soil data show the state of the soil in one specific year. In this paper, two scenarios have been modelled, with differing future climate during four of the future years, but the same forestry and deposition.

Soil input data

Soil layer thicknesses, soil texture and soil chemistry were taken from measurements at the sites in a measurement campaign 2010–2011, described in Zanchi et al. (2014). For the mineral soil layers, possible mineralogy was calculated from the total chemistry, using the A2M model (Posch and Kurz, 2007). The average mathematical solution of mineralogy was used. For the small mineralogic part of the organic layer, the mineralogy for the next layer was used. In Ammarnäs, for the modelling to be able to match the base cation content in soil water (as an average) and the base saturation, the calcite content of the soil was increased to 12 % (with quartz content reduced accordingly). This calcite content has been seen in the Ammarnäs area (Grimmer et al., 2016). The seven sites are different in texture, with Hyttskogen being very coarse textured and Västra Torup, Södra Averstad and Ammarnäs being a bit finer textured, although still with high sand and low clay content (Table 2).

Forest management

All sites are modelled with future clear cuts with stem only harvesting every 70 to 115 years, with increasing intervals to the north, and up to three thinnings between clear cuts, according to forestry recommendations. The exact years of harvest depend on the historical clear cut years, which were obtained from the SWETHRO Network. The forestry scenarios used are the same as in Zanchi et al. (2021a).

Deposition data

The model needs time series of yearly deposition of acidifying and base ions. In the model, the yearly data are distributed to days with precipitation from the climate input data. The data, deposition of SO_4^{2-}, Cl^-, NO_3^-, NH_4^+, Ca^{2+}, Mg^{2+}, K^+ and Na^+, was based on both measurements and modelling: Open field and beneath canopy deposition are measured monthly at the sites, and on some SWETHRO sites across Sweden, the relation between wet- and dry deposition for the more biologically active substances (NO_3^-, NH_4^+, Ca^{2+}, Mg^{2+}, K^+) are also measured (Karlsson et al., 2019). From this, wet- and dry deposition at the sites were calculated for years with measurements, as described in Erlandsson Lampa et al. (2019).

For the years before and after measurements were made at the sites, deposition of base cations and chloride were kept constant, and the deposition of SO_4^{2-}, NO_3^- and NH_4^+, relative to the measurement years, were obtained from the CLEO program (Naturvårdsverket 2016), where they were developed in parallel by the Swedish Meteorological and Hydrological Institute (SMHI) with the same GCM model and climate scenario (A1B), and from the ECLAIRE program (Effects of Climate Change on Air Pollution and Response Strategies for European Ecosystems; ECLAIRE 2021), were SMHI was a partner organization. Data from ECLAIRE were used from 1900 to 1960 and from CLEO from 1961 to 2100.

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In order to simulate the effect of clear cutting on deposition, dry deposition was lowered to zero at clear cut and was progressively increased for 30 years back to what it would have been without clear cutting.

Climate data

The climate parameters needed for the ForSAFE modelling are time series of daily average, minimum and maximum temperature, daily precipitation, daily average photosynthetic active radiation (PAR) and daily average CO_2 concentration of the atmosphere, from year 1900 to 2100. The future part of the time series are the climate scenarios. In this paper we use two climate scenarios: a base scenario with climate based on the IPCC scenario A1B (Nakićenović et al., 2000) and a drought scenario where the climate parameters for five consecutive years have been changed to years with very warm and dry summers, but all other years follow the A1B scenario.

The climate parameters are not measured at the SWETHRO sites. Instead, measured temperature data from nearby climate stations was downloaded from SMHI for the period 1981–2010 and used in bias correction of data from CLEO. The daily climate data from CLEO, average temperature and precipitation, covered the years 1961–2099, using the A1B scenario for the future years (see below). We constructed data for the years 1900–1960 by randomly assigning each year with one of the years 1961–1970. For the year 2100 the same values were assumed as for 2099. The PTHBV database that was used by SMHI for the bias correction of climate data in CLEO only included daily average temperatures (SMHI 2019), therefore the bias corrected data was lacking Tmin and Tmax temperatures. Hence, a bias correction of the modelled uncorrected Tmin and Tmax values was performed. The method for the bias correction was retrieved from Hempel et al., (2013; algorithms 25–26). Observed data of the period 1981–2010 was downloaded from SMHI and interpolated over Sweden and thereafter used in the bias correction. Daily values of PAR from 1960 to 2100 were retrieved from ECLAIRE. The data consisted of short-wave radiation for the years 1960–2100 for Europe and were developed by the Rossby Centre at SMHI 2012/2013 (pers.comm. Magnuz Engardt). The data was converted from W/m2 into PPFD (Photosynthetic Photon Flux Density) and reduced to only contain the PAR spectra (400–700 nm) (see further Montieth and Unsworth 2008 in Klingberg et al., 2011). For the years 1900–1959, PAR data from 1961 to 1970 was assigned in the same way as was done for the temperature and precipitation. Monthly averages of these data were lower than the monthly data used in previous ForSAFE modelling (e.g. Kronnäs et al., 2019), but comparison with modelled PAR data from SMHI (Landelius et al., 2001), and measured PAR data from the ICOS network (Carrara et al., 2018) showed that the ECLAIRE data were on the right level and that the older data (which were downscaled from a global model in a simpler way) had most likely not been adjusted enough for the effect of cloudiness.

For CO_2, the same values were used for all sites. The yearly trend was taken from the A1B scenario and daily values were constructed with a schematic within year variation, to get lower than yearly average CO_2 concentration during the growing season.

Scenario A1B

The IPCC climate scenario A1B (Nakićenović et al., 2000) with a regional down scaling (Simpson et al., 2012) was used as the base scenario. In this medium severe climate change scenario, in line with current emissions (Schwalm et al., 2020) yet far more severe than what is accepted in the Paris agreement (United Nations, 2015), the CO_2 concentration in the atmosphere

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increases to about 720 ppm in the year 2100. In Sweden, this increase leads to a warmer and wetter climate with slightly lower incoming radiation, as averages over 30 years (Fig. 1). The changes are not uniform throughout the year: both increase in temperature and precipitation and decrease in PAR values are largest during winter months. In part of southern Sweden, monthly precipitation is projected to decrease slightly during some summer months. The larger increase in precipitation during winter than during summer together with the warmer temperatures might, in some regions, lead to drier conditions during summertime.

In the Köppen-Geiger climate classification, in 2070–2100 according to the A1B scenario, the four southern sites will be well into the Cfb class and even the northern coastal site will have transitioned into it. The northern inland site will have shifted into Dfb and only the northernmost site will still be in the Dfc class.

Drought scenario

In addition to the A1B scenario, a scenario with extreme drought events was simulated. This scenario was identical to the base scenario except for five consecutive years of extreme summer drought events inspired by the very dry summer of 2018 (described e.g. in Toreti et al., 2019). The dry years occurred in the second half of the 21st century, at a time when the forests were mature. Due to differing planting and clear cutting years for different sites and thus different periods with mature forest, the extreme drought years could not be the same years for all seven sites. The drought was modelled to occur in 2070–2074 in Västra Torup and Södra Averstad, and in 2090–2094 for the other sites. During April to July of these dry years, temperature and PAR were increased and precipitation was decreased according to Table 2, compared to the averages for each site of the previous ten years. August to March of the five drought scenario years had the average climate of the respective month of the ten previous years, since precipitation, temperature and PAR-values were normal in 2018 during those months. The numbers in Table 2 were based on the difference between 2018 and 2008–2017 in SMHI:s measuring sites at Osby and Växjö in southern Sweden (SMHI, 2021) and Fig. 2 shows the resulting temperatures and precipitation values for the sites.

Table 2. Increase in temperature and PAR and decrease in precipitation (P) during the dry years of the drought scenario, compared to the ten previous years.

	ΔT (°C)	**P drought/P base**	**PAR drought/PAR base**
Jan-Mar	0.0	100 %	100 %
Apr	1.6	72 %	94 %
May	4.2	25 %	121 %
June	3.0	39 %	114 %
July	3.5	26 %	128 %
Aug-Dec	0.0	100 %	100 %

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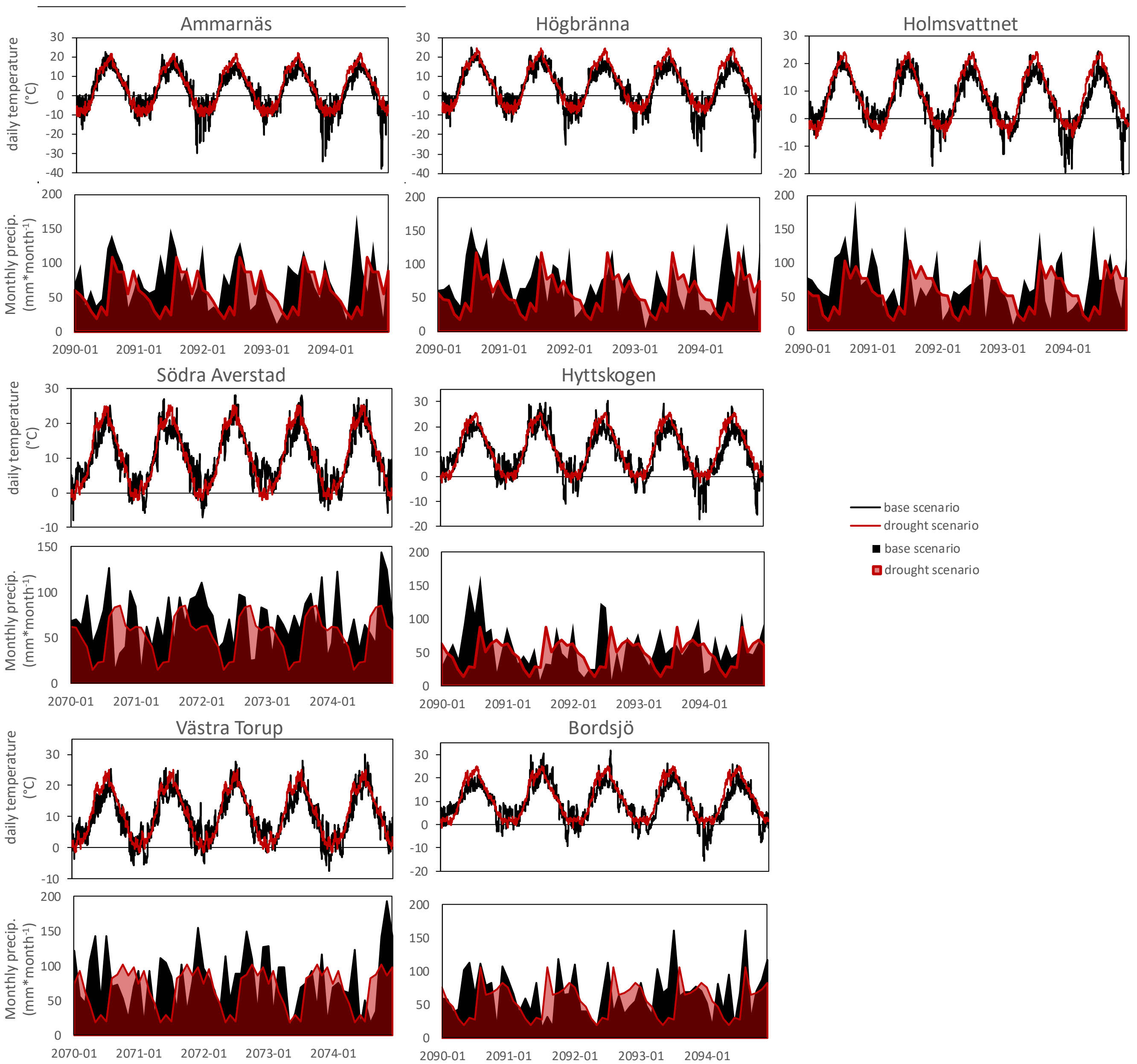

Figure 2: Temperature and precipitation during the extreme drought scenario (red) and the base scenario (black). For Södra Averstad and Västra Torup, the drought occurs during the five years 2070–2074 and for the other sites it occurs during 2090–2094.

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3 Results

3.1 Weathering rates 1990–2100, base scenario

Weathering at all sites is very dependent on season (Fig. 3), with lower and less variable winter weathering and higher and more variable summer weathering. Daily weathering rates averaged over a 30 year period show a broader, more cut off summer peak of weathering in southern Sweden, and a higher, narrower peak for the northern sites. This difference is explained by longer warm periods and greater inter-annual variability of summer weathering in southern Sweden due to relatively dry summers being common. Soil moisture is almost always adequate at northern sites and soil temperature, which depends on air temperature, is thus determining for the weathering there.

Weathering also depends strongly on texture and mineralogy of the site, and therefore there is no clear north to south pattern in the size of weathering within the considered group of sites despite the strong temperature gradient between the sites (Fig. 1). For instance, the site in the coldest climate, Ammarnäs, with a favourable mineralogy, has more than ten times as high weathering as the southern site Bordsjö, with coarse texture and less easily weathering minerals.

Weathering increase according to the simulations at all sites for all seasons between the time periods 1990–2019, 2030–2059 and 2070–2099 (Fig. 3 and Table 3). Depending on future soil moisture changes and forestry at the site, the largest increase will take place between 1990–2019 and 2030–2059 or between 2030–2059 and 2070–2099 (Fig. 3). The average yearly change will be 2 %–8 % per decade, or 5 %–17 % $°C^{-1}$ of yearly average warming. In absolute values, Ammarnäs has by far the largest increase in weathering, as it has by far the largest weathering.

The largest future increase in weathering will generally occur during the summer months when weathering is largest. In southern Sweden, the increase in weathering during spring and autumn will also be large and even during winter there will be an increase in weathering of 6 %–8 % between the time periods 1990–2019 and 2070–2099. In Västra Torup, the relative weathering increase is projected to be largest during spring due to dry conditions during summer and autumn, whereas in dry and coarse textured Hyttskogen, weathering increase during summer is calculated to 26 %, due to less dry conditions in the future than today. In northern Sweden, temperature increase during winter is projected to be larger than during any other season at the sites, but weathering increases are still projected to be very small, since temperatures will be well below zero for most of the season. The northern sites will also normally have sufficiently high soil moisture during summer to not inhibit weathering.

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Table 3. Increase in temperature and weathering rates (per degree of warming) during different seasons, averages for 30 year periods.

	V. Torup	Bordsjö	S. Averstad	Hyttskogen	Holmsvattnet	Högbränna	Ammarnäs
Increase in temperature 2070-2099 compared to 1990-2019 (°C)							
winter	3.5	4.2	4.4	4.5	5.8	5.9	4.5
spring	2.1	3.5	4.1	3.3	3.5	3.8	3.0
summer	2.8	3.3	3.4	3.3	3.4	3.6	2.5
autumn	2.7	3.1	3.2	3.4	4.0	4.7	3.3
year	2.8	3.5	3.8	3.6	4.2	4.5	3.3
Increase in BC weathering 2070-2099 compared to 1990-2019 (°C^{-1})							
winter	8%	6%	7%	7%	1%	2%	2%
spring	11%	11%	11%	15%	3%	8%	7%
summer	6%	22%	15%	26%	8%	16%	15%
autumn	4%	11%	10%	15%	5%	8%	8%
year	7%	13%	11%	17%	5%	9%	8%

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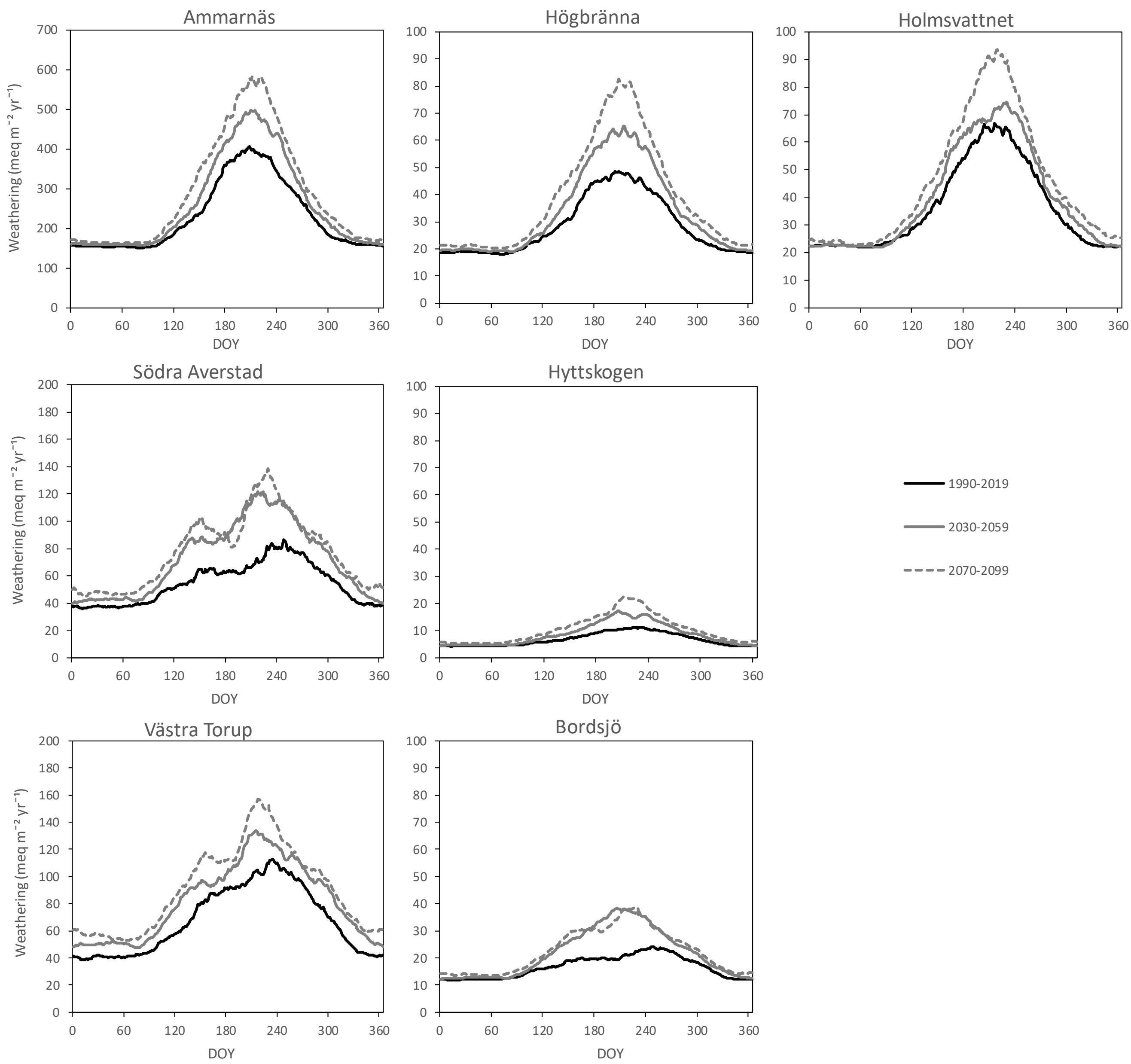

Figure 3. Weathering variation over the year (day of the year on the x-axis), average for three different 30 year periods in the base scenario. Weathering rates are the sum of Ca, Mg, K and Na for the humus layer and the upper 50 cm of mineral soil. Note that the sites in the left-hand column have different y-axis scales than the other four.

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3.2 Effect of droughts

In the drought scenario, the added precipitation during May to July is much lower and the temperature higher than in the base scenario (Fig. 2), leading to drastically decreasing levels of soil moisture during the summer, with a much lower summer average than in the base scenario (Table 4) and lower weathering rates at all sites (Fig. 4, Table 4). In the southern sites, soil moisture is relatively close to the wilting point during large parts of the summer, whereas in the northern sites, soil moisture does not decrease as fast and thus does not reach as low levels. Precipitation returns to normal in August, which causes weathering rates to increase towards normal levels in late summer, autumn and winter. When normal precipitation resumes in August, soil texture influence how fast the soil rewet. Soil moisture reaches field capacity at 50 cm depth in just three weeks in the two sites with very coarse texture, Hyttskogen and Högbränna, and weathering thus increases quickly to normal summer values for those sites. In the less coarse soil of Västra Torup, soil moisture increases more slowly, and when field capacity is reached after two months, autumn temperatures have set in. This means that weathering is affected faster and stronger by the drought and the rewetting in the more fine grained soils, but as a yearly average, that can even out. The weathering during the drought years is 2 %–22 % lower for individual base cations than under the base scenario.

There are some individual years on some sites when weathering in the base scenario is as low as in the drought scenario, because of a drought or a relatively cool summer. All the southern sites have at least two years with some summer drought already in the base scenario, but usually not as severe as in the drought scenario. For instance, Hyttskogen has four dry summers in the base scenario. At the northern sites, years with low summer weathering in the base scenario are instead years with relatively cold summers. The corresponding years in the drought scenario have much warmer temperatures, which in these northern sites compensate for the drier conditions.

The effect of the drought is slightly smaller on magnesium weathering and slightly larger on potassium and sodium weathering, but these differences vary depending on what minerals are present in the soils (Table 4).

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Table 4. Comparison of soil moisture and weathering in the base scenario and in the drought scenario. Averages, with standard deviation around the average in parenthesis. The time period is the five years when the drought scenario differs from the base scenario – 2070–2074 for Västra Torup and Södra Averstad and 2090–2094 for the other sites.

	V. Torup	Bordsjö	S. Averstad	Hyttskogen	Holmsvattnet	Högbränna	Ammarnäs
Number of dry summers							
Base scenario	2	2	3	4	0	0	0
Drought scenario	**5**	**5**	**5**	**5**	**5**	**5**	**5**
Average summer soil moisture (%)							
Base scenario	**14.6 (4.0)**	**12.2 (5.0)**	**12.8 (3.7)**	**9.1 (1.4)**	**14.0 (2.0)**	**16.0 (1.6)**	**20.1 (1.6)**
Drought scenario	8.9 (2.7)	6.4 (2.4)	8.3 (3.1)	7.9 (0.7)	8.5 (1.9)	10.7 (2.1)	14.7 (2.5)
Average yearly weathering (meq m^{-2} yr^{-1})							
Ca base scenario	19.4 (9.2)	4.5 (2.4)	17.6 (8.6)	2.7 (1.7)	12.3 (7.5)	7.9 (5.0)	272.3 (140.2)
Ca drought scenario	16.9 (6.0)	4.2 (1.8)	13.7 (6.2)	2.5 (1.4)	10.6 (5.1)	6.6 (3.4)	262.9 (123.4)
Ca drought/base	87%	93%	78%	92%	86%	84%	97%
Mg base scenario	5.2 (2.5)	1.3 (0.6)	3.7 (1.6)	1.2 (0.7)	10.0 (5.8)	4.7 (2.7)	4.0 (2.3)
Mg drought scenario	4.5 (1.6)	1.2 (0.5)	2.9 (1.1)	1.1 (0.6)	8.8 (4.0)	4.0 (1.9)	4.0 (2.1)
Mg drought/base	87%	94%	80%	93%	88%	85%	98%
K base scenario	17.4 (7.3)	4.9 (2.2)	13.6 (5.3)	2.9 (1.5)	4.9 (2.4)	7.1 (3.6)	2.6 (1.3)
K drought scenario	14.7 (5.1)	4.5 (1.5)	10.6 (3.9)	2.6 (1.1)	4.2 (1.5)	5.9 (2.5)	2.5 (1.1)
K drought/base	85%	92%	78%	91%	85%	84%	96%
Na base scenario	41.5 (17.2)	11.0 (4.7)	38.0 (14.7)	3.2 (1.6)	17.7 (8.8)	19.5 (10.0)	14.3 (6.3)
Na drought scenario	35.1 (11.8)	10.2 (3.4)	29.5 (10.1)	3.0 (1.2)	15.1 (5.4)	16.5 (6.9)	13.6 (5.4)
Na drought/base	85%	93%	78%	92%	85%	85%	95%
BC base scenario	83.5 (36.0)	21.6 (9.9)	72.8 (30.1)	10.0 (5.5)	45.0 (24.4)	39.2 (21.2)	293.3 (150.1)
BC drought scenario	71.3 (24.2)	20.1 (7.1)	56.6 (21.1)	9.2 (4.3)	38.8 (15.7)	33.1 (14.7)	283.0 (132.0)
BC drought/base	85%	93%	78%	92%	86%	84%	96%

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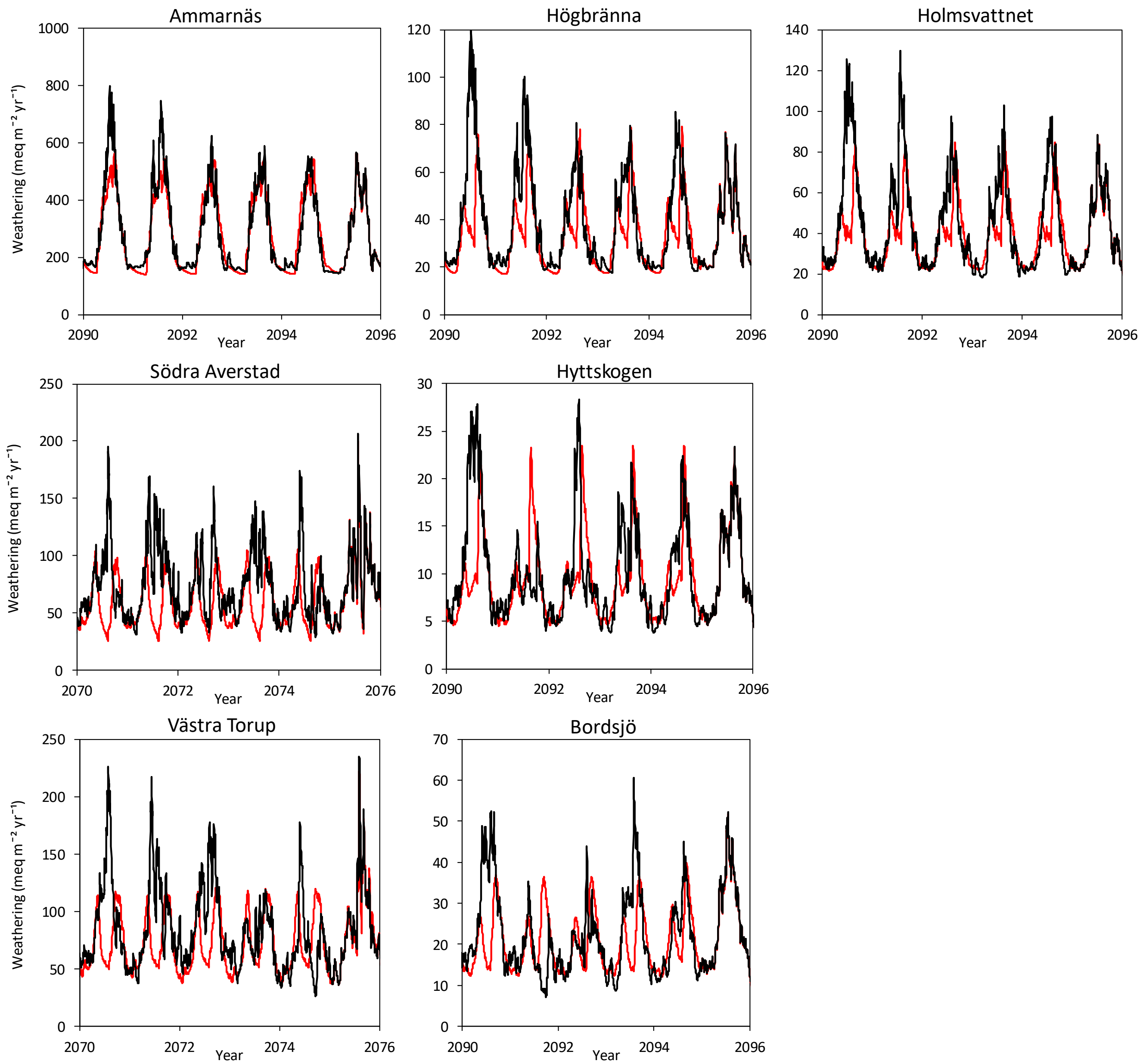

Figure 4. Weathering under the drought scenario (red) compared to the base scenario (black). The first year after the drought is also included. Weathering rates are the sum of Ca, Mg, K and Na for the humus layer and the upper 50 cm of mineral soil. For Södra Averstad and Västra Torup, the drought occurs during the five years 2070–2074 and for the other sites it occurs during 2090–2094.

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4 Discussion

4.1 Weathering rates in a future climate

This study clearly shows that weathering rates will increase under future climate change in Sweden and that the largest future increase in weathering will generally occur during the summer months when weathering is largest. Summer weathering will consistently increase in the north, where water availability will not decrease, whereas in the south summer weathering will depend on the combined effect of higher temperatures and change of soil moisture. The effect of warmer winters on weathering will be largest in the south, where above zero winter temperatures will become more and more common. Despite large increases in winter temperatures in the north, winter temperatures there will still usually be well below zero and thus weathering will still be low. The different seasonal distribution of the weathering increase has implications for plant nutrition. In southern Sweden, part of the weathering increase due to climate change occurs in late autumn, winter and early spring time, when plants are inactive, whereas in northern Sweden, there is almost no weathering increase in winter and little in spring and autumn. At the same time, with climate change, the growing season lengthens dramatically (Jin et al., 2019), and thus precipitation and weathering during spring, autumn and in southern Sweden even winter, will have an increasing significance for the ecosystem, especially in areas with high occurrence of summer droughts. This highlights the importance of using dynamic models with high resolution temporal climate data to assess effects of climate change on weathering rates and plant nutrition.

Weathering responds to soil temperature rather than air temperature. Soil temperature follows air temperature, with a dampening and delay in time, except for when there is a snow cover, at which time the soil is insulated and temperature remains higher than the air temperature. As a yearly average, the soil temperature is higher than the air temperature in areas with winter snow. Houle et al. (2020) found that yearly average soil temperature at 28 cm soil depth at 21 sites in Canada was on average 2 °C higher than air temperature (-0.19–4 °C depending on site). The ForSAFE model simulates soil temperature in the different soil layers. At these Swedish sites, the yearly average difference between air and soil temperature in 1990–2019 is also 2 °C (0.6–4.1 °C), but decreases to 0.8 °C (0.1–2.4 °C) in 2070–2099. Since the difference between air and soil temperature is largest during cold winter temperatures when weathering rates are very low, the diminishing difference between air and soil temperature has a negligible effect on weathering.

In the southern sites, except Västra Torup, the soil water is successively acidifying during the 21st century, according to the model (Fig. A.1 in Appendix A). The future growth of the forest is faster in the base scenario than today in this modelling. The inputs of base cations to the ecosystem through weathering and deposition are not large enough to fulfil the needs of the vegetation without depleting the stores in the soils and increasing the future risk of nutrient deficiencies, despite of the increased weathering rates. Such sites are common in southern Sweden according to Akselsson et al. (2016). Soil acidification itself also affects weathering rates, increasing it or decreasing it (thereby decreasing or increasing the soil acidification), depending on the changing pH, dissolved organic carbon and concentrations of dissolved aluminium, where aluminium inhibits weathering and the other two increase it (Kronnäs et al., 2019).

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According to this study, there is no decrease of soil moisture due to climate change in the future for these sites. The four sites in the south experience summer droughts and limitations of tree growth because of water stress already today, which, according to Ruiz-Pérez and Vico (2020) is common in southern Scandinavia. The model results indicate no increased growth limitation due to water stress in the future, as plants become more water efficient at higher concentrations of atmospheric CO_2 (Toreti et al., 2020) and this compensates for the effect of higher temperature of the base scenario summers. Another ForSAFE modelling study in Sweden, where the more extreme A2 scenario was used, show increasing water stress in southern Sweden in the future (Belyazid and Zanchi, 2019). In Cheng et al. (2017), most models show decreasing soil moisture in southern Sweden for the future scenario RCP4.5 (less severe than the A1b scenario) and for all of Sweden in the very severe RCP8.5 scenario. If soil moisture decreases in southern Sweden, as these studies indicate, the projected increase in weathering might be an overestimation and risk for nutrient deficiencies and acidification of the soils in southern Sweden would be even higher than the result in this paper indicate.

4.2 Effect of extreme drought event

The severe drought leads to a lower weathering than the base scenario in all climate zones. This happens despite the southern sites having summer drought to some extent already in the base scenario, and the northern sites not drying out as much during the drought as the southern sites, because of lower evapotranspiration.

The lower weathering increases the risk of BC depletion and nutrient imbalances in trees, which in its turn can decrease their capacity to cope with droughts (Hartmann et al., 2018).

The texture of the soils influences how they respond to drought and precipitation. Coarser textures dry out quicker, but precipitation also infiltrate to deeper soil layers faster. In this drought scenario, normal precipitation resumes during August to March. In the site with the coarsest texture, Hyttskogen, this leads to a period of normal summer level of weathering before autumn temperatures set in. In the more fine-grained site Västra Torup on the other hand, weathering rates are normal in early summer, despite lack of precipitation, as the soil holds water better. The weathering falls to low levels slower during the summer as the soil dries and do not increase as fast in August as in the coarsely textured soils. On the other hand, the more fine-grained soils always have a higher weathering rate than the coarsely textured soils, even when the coarsely textured are rewetted and the fine grained are dry.

The extreme drought scenario in this study is based on the real extreme drought summer of 2018, related to the average temperature, precipitation and PAR of the previous ten years. It gives the sites a May to July precipitation that is lower or about equal to the lowest precipitation in the time series used in the base scenario (Södra Averstad has lower precipitation at one occasion in the A1B scenario and in Holmsvattnet measured precipitation is of the same size at one occasion). This means that every growing season of the drought event starts with normal levels of soil water according to the model. The measured summer of 2018 itself is not included in the climate time series, as the time series were produced before 2018. Therefore, 2018 has modelled values. A future extreme drought event might have low precipitation during all months of the years and thus

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have an even larger effect on weathering rates, vegetation and long-term soil water and ground water stores, but we chose to base our scenario on an existing event.

4.3 Comparison with other studies

For six of the sites in this study, weathering has previously been calculated using the steady state model PROFILE (Västra Torup in Kronnäs et al. (2019); Bordsjö, Södra Averstad, Hyttskogen, Högbränna and Ammarnäs in Akselsson et al. (2021)), Ammarnäs without extra calcite to match measured soil water chemistry. PROFILE gives steady-state values of the weathering rates, without temporal resolution between and within years. A comparison with 30 year averages from ForSAFE for the six sites showed comparable weathering rates in the different studies, except for Ammarnäs, where mineralogy inputs were handled differently.

The future weathering increase for the whole year from the present study, 6 % °C^{-1} as an average for all sites, is close to the value of 7 % °C^{-1} in a ForSAFE modelling of Västra Torup in Kronnäs et al. (2019). A larger Swedish ForSAFE study (Belyazid et al., 2022) with over 500 sites, found that the average BC weathering increase for all sites was 6.7 % °C^{-1}. The same average value was found in a Canadian study (Houle et al., 2020), in which a small decrease in soil water content and an increase in BC weathering (around 7 % °C^{-1} as an average for the sites in the study) was found.

In Zanchi et al. (2021a), ForSAFE was applied on the same input data as in the present study, with the difference that the internal hydrology time step was not used. The results are very similar, although weathering rates are not in the focus of Zanchi et al. (2021a). Measured and modelled ANC for the seven sites are shown and discussed in Appendix A.

4.4 Model and measurement limitations and development

Discrepancies between measured and simulated water chemistry can be due both to limitations in the model and in the measurements. The measured temporal variations in soil water concentrations are larger than in the model results for most sites, both for ANC and most modelled ions (Appendix A; Zanchi et al., 2021a). This indicates that the variation in soil water chemistry is underestimated in the model, which may indicate that the variation in weathering rates is also underestimated.

Measurements of different variables at the same site, during roughly the same time period, can sometimes give concentrations and flows that do not add up, because of the variability in nature, both in space and time. For instance, in Ammarnäs, the measurements of total chemistry of the soil layers, taken from one soil pit, gave a mineralogy that could not by themselves lead to the measured soil water chemistry in the lysimeters, because of low weathering capacity. There might be different mineralogies in different parts of the site or there might be water influx from an area with more easily weathered mineralogy outside of the site. Other studies confirm that the area has a larger variation in mineralogy than usual for Sweden (Grimmer et al., 2016; Greiling et al., 2018). Measurements of soil properties in more locations within and around the site, as well as mapping of soil water flows, would be needed to be able to understand how the site functions and how large the weathering rates are in different parts of the site.

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Södra Averstad also shows the importance of the soil moisture on the weathering rates. The site is estimated by the SWETHRO field workers to be slightly wet, which probably is because of its placement low in the landscape, close to the large lake Vänern. ForSAFE, on the other hand, models soil water content dynamically, using water inputs, texture and slope along a transect. In this study, we did not have enough data for modelling transects, but settled for modelling a single soil profile for each site. Because of the texture of Södra Averstad, ForSAFE modelled the site as having recurrent dry summers, which seems to be incorrect. The weathering rates in this site might therefore be higher than the model indicates.

The model cannot simulate effects of pests, forest fires, individual trees or whole forest stands dying of natural causes, nor other tree species spontaneously growing in the modelled forest stand and gradually becoming the dominant species. This means that the effect of climate change on the vegetation is underestimated, since for example drought or nutrient imbalances might lead to vulnerability to pests, leading to the tree species at the site being replaced by other tree species, which in its turn can have large effects on soil chemistry, soil moisture, vegetation nutrient needs and therefor on weathering rates (Augusto et al., 2014). All the modelled sites are planted *Picea abies* stands, but in southern Sweden, it is likely that such stands will not be feasible in the future, especially a future according to the A1B or another high climate change scenario (Grundmann et al., 2011). A future change of forestry practices or tree species might enhance or decrease weathering rates and vulnerability to droughts.

Increasing concentration of atmospheric carbon dioxide leads to a fertilisation effect on the vegetation, which is accounted for in the ForSAFE model and has effects on soil moisture and thus weathering. The combined effects of high temperatures, water stress, carbon dioxide fertilisation, water need and heat tolerance of the plants are complex (Ruiz-Peréz et al., 2020) and there are signs that the fertilisation effect of carbon dioxide will be lower in a changing climate than what has been previously assumed (Duffy et al., 2021) and that the fertilisation effect already is declining (Wang et al., 2020).

5 Conclusions

The dynamic modelling in this study shows that weathering rates can be substantially affected by climate change, and that the size and direction of the effect varies in time and space. According to the A1B scenario, weathering rates will increase to 2100 due to higher temperatures, but the increase is distributed differently over seasons. For example, there will be almost no change in winter weathering in northern Sweden, although the temperature change is the highest in winter, since the temperature still will be below zero. Thus, dynamic models like ForSAFE, where seasonal variation is considered, are required for credible assessments of climate change effects on weathering rates and nutrient sustainability.

Weathering rates, and how they are affected by climate change, depends strongly on soil properties. Coarser textures lead to more severe effects of droughts, but also to a more rapid rewetting of the soil during precipitation. This leads to greater fluctuations in weathering rates at drought and rewetting events in coarse textured soils, and means higher risk for negative drought effects in forests on coarse grained soils. There is also a difference between regions, where southern sites have more summer drought already today and in the future base scenario, with restricting effect on weathering. The difference between sites because of soil properties are stronger than the climatic effects between regions.

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Code/Data availability Soil, soilwater chemistry, deposition and biomass input data were collected at the Swedish Throughfall Monitoring Network (SWETHRO) and is available on the web-site (https://krondroppsnatet.ivl.se/), or on request to IVL, the Swedish Environmental Research Institute or to the authors of the paper. Climate and deposition scenario data were derived from simulations by SMHI (Swedish Meteorological and Hydrological Institute), which is also data host for the data.
The code of the ForSAFE model is freely available upon request to the model developers: salim.belyazid@natgeo.su.se; giuliana.zanchi@nateko.lu.se. Earlier collaborations with other research groups have shown that new users need an initial period of guidance to be able to independently run the model. Therefore, an initial period of collaboration with the model developers is encouraged with the intent to support new user in the initial stage of their work with the ForSAFE model.

Conflict of interest The authors declare no conflict of interest.

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Appendix A

Observed and modelled soil water ANC in the seven sites

ANC calculated from measured soil water concentrations are more varied with time, than modelled ANC values during the same time period (Fig. A.1), even though modelled Na and sometimes Cl are more varied with time than the measured values (not shown). At the sites with high sea salt input (especially Västra Torup and Södra Averstad), both Na and Cl have a high variability in the modelled values, but they partly cancel out in the ANC expression. In the model, deposition of all ions varies with the precipitation, with the same concentration in precipitation throughout a whole year, which means that ANC vary less than it would do if the different ions were deposited more independently of each other and of the precipitation throughout the year.

Only the northernmost site, Ammarnäs, always has ANC values well above zero in both observed and modelled values. The next northernmost site, Högbränna, with its more typical BC poor Swedish forest soil, has a lower ANC, but seems mostly unaffected by acidification both in observed and modelled ANC, both during the period of high atmospheric acidifying pollution (1950–2000) and in the future. Holmsvattnet, the coastal northern site situated close to large industries, is affected by acidification during the 1980s, with lowered pH and ANC and raised concentrations of aluminium (not shown). According to the model, it is already recovered by 2000. It is then clear cut, temporarily acidifies and recovers again.

All of the four southern sites are to some extent affected by acidification. Observed ANC is sometimes or usually (Västra Torup) below zero. In Västra Torup, measurements from after the clear cut show the large effect a clear cut has on soil water chemistry, mostly due to leaching of nitrogen. In this application, the model does not manage to reproduce this high nitrogen leaching, leading to lower modelled than observed ANC. Modelled ANC in Södra Averstad show clear acidification in the higher soil layers (not shown), but not at the soil depth where the measurements are made. Except for Bordsjö, the model also shows some recovery of soil water ANC during at least some part of the period 1980–2020. All southern sites except Västra Torup acidify further during the second half of 21st century, even though acidifying deposition is low. This shows that weathering, even though it increases with the warmer climate, is not high enough to compensate for the forest uptake in the future.

ANC responds to drought with an increased value in the soil water. This increase does not, however lead to export of acid buffering capacity to lower layers or to surface waters, since there is no runoff during droughts.

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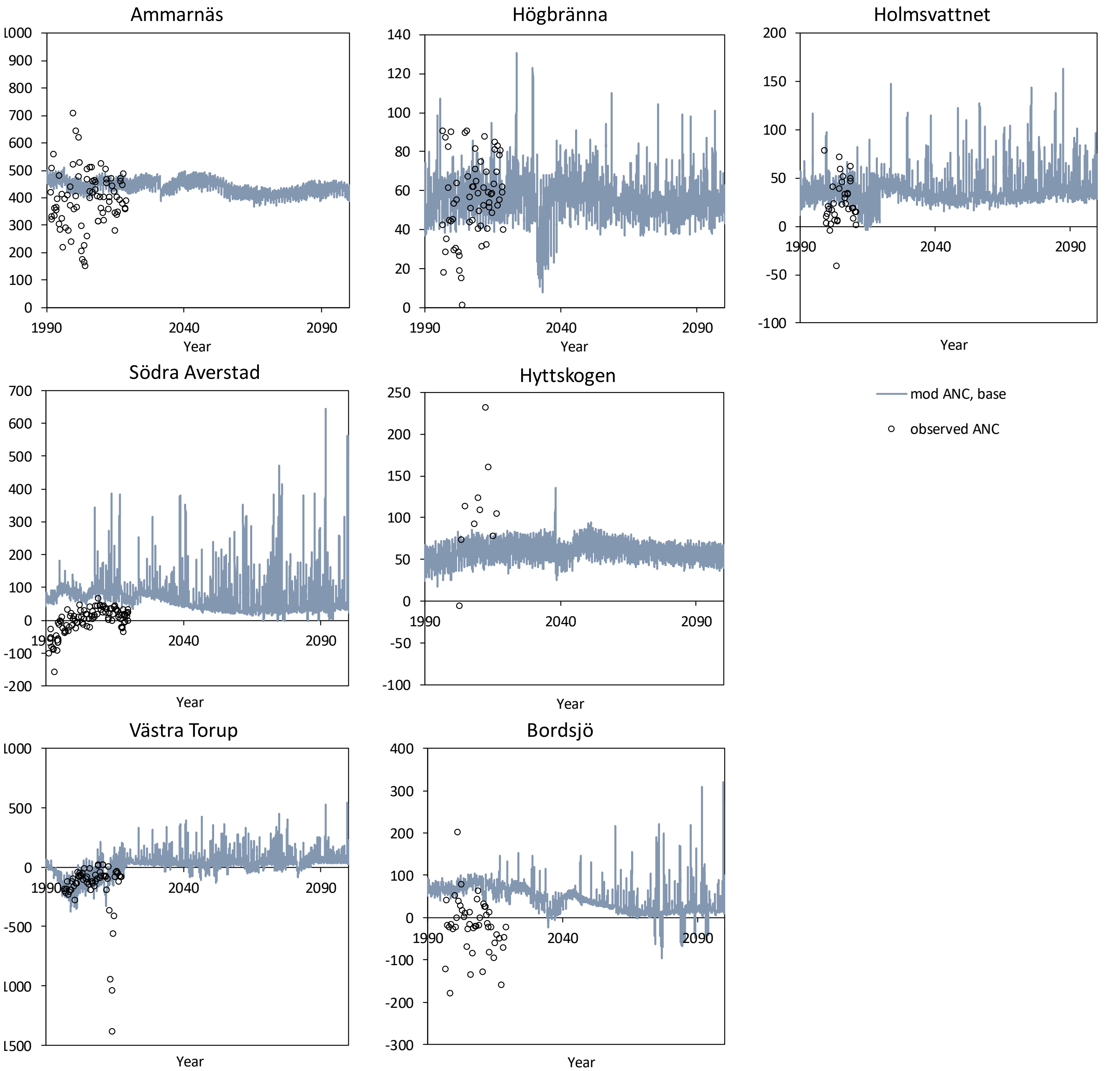

Figure A.1. Development of soil water chemistry – daily modelled ANC from 1990 to 2100 and observed values three times a year, from lysimeters at 50 cm depth, in the seven sites.