Human exposure to chemicals in Sweden in a changing climate

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Human exposure to chemicals in Sweden in a changing climate

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Sammanfattning

The possible effects of climate change on human exposure to chemicals in Sweden were investigated in this report based on a targeted literature review. Exposure of the Swedish population to chemicals under climate change was assessed, with a focus on indoor air quality, floods, droughts, landslides, pesticide use, environmental contaminants in food, and UV radiation. Results of the literature review were summarized for each of the focus areas as factors that could drive changes in chemical exposure, and were then synthesized into a set of three narrative scenarios for alternative future paths for chemical exposure in Sweden under climate change.

These scenarios describe alternative pathways for the development of human exposure to chemicals in drinking water, food, the indoor environment, and usage of sunscreen products for the Swedish population and were inspired by the Shared Socioeconomic Pathways (SSPs) scenario framework used for global change research.

Exposure of the Swedish population to chemicals in the future in these possible scenarios increases in many cases, but possibilities for decreased chemical exposure are also identified in some scenarios.

Human exposure to chemicals in Sweden in a changing climate

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DEET	N,N-dimethyl-3-methylbenzamide
Dioxins	polychlorinated dibenzo-*p*-dioxins and dibenzofurans
DOC	dissolved organic carbon
EDO	European Drought Observatory
FAO	United Nations Food and Agriculture Organization
HCHO	formaldehyde
Natechs	Natural Hazard triggering Technological Disasters
NO_2	nitrogen dioxide
PAHs	polycyclic aromatic hydrocarbons
Pb	lead
PBDEs	polybrominated diphenyl ethers
PCBs	polychlorinated biphenyls
PCDDs	polychlorinated dibenzo-*p*-dioxins
PCDFs	polychlorinated dibenzofurans
PFAAs	perfluoroalkyl acids
PFAS	perfluoroalkyl and polyfluoroalkyl substances
PFHxS	perfluorohexane sulfonate
PFOA	perfluorooctanoate
PFOS	perfluorooctane sulfonate
PNEC	predicted no-effect concentration
POPs	persistent organic pollutants
SGU	Sveriges Geologiska Undersökning (Geological Survey of Sweden)
SMHI	Swedish Meteorological and Hydrological Institute

SO_4^{2-}	sulphate
SSPs	Shared Socioeconomic Pathways
SVOCs	semivolatile organic chemicals
TiO2	titanium dioxide
VOCs	volatile organic compounds
WFD	Water Framework Directive

SAMMANFATTNING

Sverige kommer att påverkas av klimatförändringar på en mängd olika vis under kommande decennier. I den här rapporten undersöker vi med hjälp av en litteratursammanställning hur exponeringen för kemikalier i Sveriges befolkning kan komma att påverkas av klimatförändringar. Studien undersöker exponering för kemikalier i ett förändrat klimat med fokus på inomhusluft, översvämningar, torka, ras och skred, användning av bekämpningsmedel, föroreningar i mat, samt UV-strålning. För vart och ett av dessa områden summerar vi resultaten av litteratursammanställningen i faktorer som kan driva på förändringar i exponering för kemikalier. Vi applicerar sedan resultaten på tre olika scenarion som syftar till att visualisera alternativa vägar i framtiden, och som på olika vis påverkar exponering för kemikalier i Sverige med ett förändrande klimat. Exponering av den svenska befolkningen för kemikalier i framtiden ökar i många fall, men i några scenarion identifierar vi också möjligheter för minskad kemikalieexponering.

Ett varmare klimat i Sverige kommer troligen öka efterfrågan på mer energieffektiva byggnader, både vid nybyggnation och vid renovering av existerande byggnader. Mer energieffektiva byggnader kommer troligen ha lägre naturlig ventilation via fönster och otäta fasader, men istället ha installerade ventilationssystem för att följa gällande riktlinjer. Vid skador och temporära uppehåll i ventilationssystemet kan exponering för kemikalier inomhus öka. Å andra sidan kommer troligen exponering för semivolatila föroreningar via byggnadsmaterial att minska när gamla material byts ut mot nya. Den svenska befolkningen, och speciellt känsliga grupper som äldre och barn, förväntas spendera mer tid inomhus vid extrema väderhändelser (som värmeböljor eller köldperioder), vilket kan öka exponeringen för kemikalier via inomhusluft. Ökad frekvens av skogsbränder kommer troligen också att föra med sig en ökning av tiden spenderad inomhus, med konsekvensen att människor exponeras för kemikalier via inomhusluft, samtidigt som exponeringen för PAHer och luftburna partiklar från skogsbränder ökar.

Översvämningar förväntas bli vanligare i Sverige. Myndigheten för Samhällsskydd och Beredskap (MSB) har identifierat de områden som är extra utsatta. Översvämningar kan mobilisera föroreningar i industriområden, förorenade områden och från hushåll, vilket kan öka föroreningen av ytvatten i områden påverkade av översvämningar. Detta kan i sin tur öka mänsklig exponering för kemikalier.

Klimatförändringar bidrar redan till ökad frekvens av torkperioder i Sverige, vilket leder till torrare jordar. I torra jordar ökar transport av tungmetaller till grundvatten och ytvatten och därmed förorening av vattenförekomster. Torka och vattenbrist kan också leda till policyförändringar som innebär ökad användning av både behandlat och obehandlat avloppsvatten och slam på jordbruksmark. Detta kan leda till ökad exponering för föroreningar via upptag i grödor.

Klimatförändringar förväntas leda till en ökad förekomst av jordskred i vissa delar av Sverige. En ökad exponering för kemikalier är dock bara trolig vid jordskred som sker vid industri-, eller förorenade områden. På nationell nivå finns inget större överlapp mellan områden med ökad risk för jordskred och områden med större deponier eller industriell expandering. Risken för exponering för kemikalier orsakad av jordskred bör därför utredas på lokal snarare än nationell nivå, vid platser med deponier och potentiellt förorenad mark.

I norra Europa och Sverige förväntas klimatförändringar bidra till en ökad förekomst av skadedjur, som insekter men också patogener som är skadliga för växter. Bekämpning av skadedjur och patogener kan kräva ökad användning av pesticider som redan används idag, men också driva på introduktionen av nya pesticider på marknaden, och därmed också dess användning i Sverige. Ett varmare klimat kan också komma att förlänga växtperioden och därmed tiden då pesticider appliceras.

Högre frekvens av extremväder kan bidra till att odling av vissa grödor istället kommer att odlas i växthus, vilket kan öka användning av pesticider som är förbjudna för användning på fält utomhus, men inte i växthus. Flera olika faktorer relaterade till klimatförändringar kan därmed leda till att pesticidanvändningen ökar, och därmed ökad exponering för pesticider hos befolkningen. Exponeringen sker via intag av grödor förorenade med bekämpningsmedelsrester, samt direkt exponering av jordbrukare vid applikation på fält och i växthus. Högre temperaturer och kraftig nederbörd kan också påverka hur pesticider transporteras i miljön. Effekten av högre exponering för pesticider orsakad av ökad rörlighet av olika pesticider på grund av nederbörd kommer dock troligen motverkas av ökad nedbrytningshastighet vid högre temperaturer. Effekten av dessa båda processer (mobilitet och nedbrytning) förväntas dock vara liten i jämförelse med förändringar i exponering orsakad av ökad användning och applicering av pesticider.

Avrinningen från land till ytvatten förväntas öka, trots förväntad ökad vattenbrist inom jordbruket, vilket lokalt kan leda till ökad exponering för kemikalier via förhöjda koncentrationer av föroreningar i dricksvatten och fisk. Förändringar i vattenbalansen i Sverige kan kräva förändringar i förvaltningen av dricksvattenreservoarer, vilket kan bidra till ökad exponering för persistenta och mobila föroreningar som perfluorerade alkylsubstanser (PFAS). En förändrad diet med större vikt på växtbaserad kost förväntas minska exponeringen för bioackumulerande föroreningar som flera persistenta POPs. Det kan å andra sidan istället leda till ökad exponering för bekämpningsmedelsrester och tungmetaller.

Nedan följer sammanfattningar av vår litteraturstudie om hur exponering för kemikalier via dricksvatten, mat och inomhusmiljö, och via applikation av solskyddsprodukter och insektsmedel kan komma att påverkas av klimatförändringar.

1) **Dricksvatten**

   I ett förändrat klimat kan frekvensen av översvämningar och torkperioder komma att öka i Sverige. Översvämningar kan bidra till transport av kemikalier till grundvatten och ytvatten. Högre frekvens av torkperioder kan öka frisättningen av tungmetaller och läckage av kemikalier till grundvatten. Graden av klimatförändringar kommer därmed spela en stor roll för hur exponering för kemikalier via dricksvatten kommer att förändras.

2) **Mat**

   Användning av pesticider förväntas öka på grund av klimatförändringar, vilket kommer att leda till ökad exponering för bekämpningsmedelsrester via intag av förorenade grödor. Exponering för kemikalier via mat påverkas av användningen av pesticider i jordbruket, vilket förväntas öka på grund av klimatförändringar. En ökad odling av vissa typer av grödor i växthus kan resultera i nya eller förändrade exponeringsvägar för pesticider. En ökad användning av avloppsvatten och slam på jordbruksmark i Sverige och Europa kan också bana väg för nya och eventuellt större exponeringsvägar för kemikalier.

3) Inomhusmiljö

I ett varmare klimat förväntas efterfrågan på energieffektiva byggnader öka. Användning av luftkonditionering i privata boenden kommer troligen öka, vilket kan leda till lägre ventilationshastighet i framtida byggnader på grund av minskad ventilering via öppnade fönster. Med lägre ventilation är det troligt att koncentrationer av kemikalier i inomhusluft ökar. Extrema väderhändelser som värmeböljor och bränder kan föra med sig att befolkningen (speciellt känsliga grupper som äldre och barn) spenderar mer tid inomhus under dessa perioder, vilket i så fall kan leda till högre exponering för kemikalier i inomhusmiljö.

4) Användning av solskyddsprodukter och insektsmedel

På grund av klimatförändringar kan användningen av olika typer av solskyddsprodukter komma att öka, vilket i sin tur leder till ökat upptag över huden av kemikalier i dessa produkter. Dessutom kan den geografiska utbredningen av myggor och andra insekter och leddjur förändras på grund av klimatförändringar. Detta kan leda till ökad användning av insektsmedel, vilket, om de används tillsammans med solskyddsprodukter, kan öka upptaget över huden av kemikalier i båda produkttyper.

Utifrån litteraturstudiens resultat utvecklade vi möjliga scenarios (Tab. 1) baserade på ’the Shared Socioeconomic Pathways (SSPs)’, vilket är ett scenarioramverk som används inom forskningen om globala förändringar. Det första scenariot (SSP1), som kallas ”Den gröna vägen”, simulerar en global utveckling mot ett hållbart samhälle, med hållbar och rättvis fördelning och användning av gemensamma resurser. Det andra scenariot (SSP2), ”Medelvägen”, beskriver en väg mellan två extremer som innebär en långsam utveckling mot anpassning till och åtgärder mot klimatförändringar. Det tredje scenariot (SSP3) kan jämföras med att ta ”Motorvägen” i en utveckling av fortsatt användning av fossila bränslen, vilket i sin tur ställer höga krav på anpassning och åtgärder för att hantera effekter av klimatförändringar. Dessa scenarios beskriver alternativa vägar också för exponering av befolkningen för kemikalier i dricksvatten, mat, inomhusmiljö och via användning av solskyddsprodukter i Sverige.

Table 1 Sammanfattning av förändringar i exponering för kemikalier orsakade av klimatförändringar och dess effekter inom olika 'Shared Socioeconomic Pathways' (SSP)-scenarier.

Exponeringsväg	SSP 1 Gröna vägen	SSP 2 Medelvägen	SSP3 Motorvägen
Dricksvatten	- Ökad andel ekologisk odling, minskad risk för exponering för pesticider mobiliserade till yt-, och grundvatten. -Ökad andel renat dagvatten, minskade utsläpp av behandlat avloppsvatten till vatten, minskad exponering för kemikalier. - Tillfälliga torkperioder och översvämningar som leder till mobilisering av kemikalier till yt-, och grundvatten.	- Ökad och kraftigare nederbörd och frekvens av torkperioder, mobilisering av kemikalier och exponering för föroreningar, särskilt via dricksvatten.	- Översvämning av avloppsvatten sker med ökad frekvens vid stark nederbörd. - Återanvändning av avloppsvatten för att hantera brist på vatten, spridning av kemikalier på jordbruksland. - Förekomst av kraftig nederbörd och torka som transporterar kemikalier till yt-, och grundvatten.
Mat	- Omställning till mer växtbaserad kost, reducerad exponering för bioackumulerande kemikalier via köttprodukter och importerat foder. - Uppströmsarbete för att minska tillförsel av kemikalier till reningsverken, avloppsslam används på jordbruksmark utan att öka exponering för kemikalier.	- Mer och kraftigare nederbörd, högre exponering av kemikalier som transporterats från land till dricksvatten, samt till akvatiska näringsvävar. - Högre efterfrågan på jordbruksprodukter, svag utveckling av hållbara lösningar för kemikalieanvändning, ökad exponering för kemikalier vid applikation av slam på jordbruksmark.	- Långvariga perioder med kraftig nederbörd eller torka, ökad transport av kemikalier vid avrinning till ytvatten och akvatiska näringsvävar. - Användning av pesticider inom jordbruket ökar. - Återanvändning av avloppsvatten och slam på jordbruksmark, ökad exponering för kemikalier via mat.
Inomhusmiljö	- Hållbara byggnads-, och inredningsmaterial, kemikalier som VOCs eller flamskyddsmedel undviks, minskad exponering inomhus. - Extrema väderhändelser som får människor att spendera mer tid inomhus är mer sällsynta. - Energieffektiva byggnader, mindre ventilering genom öppet fönster, högre kemikalieexponering inomhus.	- Övergång till hållbara material, vilket minskar exponering för farliga kemikalier inomhus, dock inte tillräckligt för att förbättra den genomsnittliga luftkvaliteten inomhus. - Temperaturen stiger, tillfälliga värmeböljor och köldperioder, ökad tid som spenderas inomhus, exponering för kemikalier.	- Inga åtgärder för omställning till hållbart samhälle, ökad exponering för kemikalier inomhus, pga volatilisering av kemikalier från byggnadsmaterial och en ökad vistelse inomhus vid extrema väderhändelser. - Skogsbränder ökar i frekvens och intensitet, vilket leder till försämring av luftkvalitet också i stadsmiljö, ökad exponering inomhus.
Användning av solskyddsprodukter och insektsmedel	- Förändringar i exponering för kemikalier i solskyddsprodukter och insektsmedel kommer att domineras av hur allmänhetens attityd och acceptans för att använda den typen av produkter utvecklas.		

EXECUTIVE SUMMARY

In coming decades, climate change will impact Sweden in a myriad of ways. The possible effects of climate change on human exposure to chemicals in Sweden are investigated in this report based on a targeted literature review. Exposure of the Swedish population to chemicals under climate change was assessed, with a focus on indoor air quality, floods, droughts, landslides, pesticide use, environmental contaminants in food, and UV radiation. Results of our literature review are summarized for each of these focus areas as factors that could drive changes in chemical exposure, and we synthesize these findings into a set of three narrative scenarios for alternative future paths for chemical exposure in Sweden under climate change. Exposure of the Swedish population to chemicals in the future in these possible scenarios increases in many cases, but possibilities for decreased chemical exposure are also identified in some scenarios.

A warming climate in Sweden is likely to drive demand for more energy-efficient buildings, both in the construction of new buildings and renovation of existing buildings. More energy-efficient buildings will likely have lower natural ventilation via windows and leaky facades, but instead have installed ventilations systems to comply with the building requirements. In the event of damage and temporary interruptions of the ventilation systems, exposure to indoor chemicals may increase. However, exposure to building materials that contain semi-volatile organic chemicals will likely decrease as they are removed and/or avoided in newly constructed buildings. The population, and particularly vulnerable subgroups such as the elderly and children, are expected to spend more time indoors during extreme weather events such as heatwaves and coldwaves, which will increase exposure to chemicals in the indoor environment. Increasing incidence of forest fires will likely also drive the population to shelter indoors, with consequent increases in the exposure to chemicals in indoor air as well as exposure to PAHs and particulate matter from forest fires that are transferred from outdoor air to indoor air.

Floods are expected to occur in Sweden with higher frequency, especially in susceptible areas that have been identified by the Swedish Civil Contingencies Agency (Myndigheten för Samhällsskydd och Beredskap, MSB). Floods can drive the mobilization of chemical contaminants from industrial areas, contaminated sites and households, which will increase the exposure of surface water in affected areas to chemical contaminants, and which could drive increased human exposure.

Climate change is already driving an increase in droughts in Sweden, which will lead to drier soils in the future. In dry soils, heavy metals are more effectively mobilized into groundwater and surface water, which increases the exposure of water resources. Droughts may also lead to policy changes that will allow more usage of treated or untreated wastewater and sewage sludge on arable land to compensate for shortages of irrigation water for crops, which could increase exposure to contaminants through the agricultural food chain.

An increase in the frequency of landslides in some areas of Sweden is anticipated due to climate change. However, chemical exposure is only likely to result from landslides if they occur at industrial or contaminated sites, and at the national level in Sweden, landslide risk areas and areas with landfills and large industrial developments do not generally overlap. The potential for chemical exposure due to landslides is therefore best assessed on a site-specific basis at

landfills and industrial areas rather than at the national level. Climate change is expected to drive more and different pests (i.e., insects and pathogens harmful to plants) into Northern Europe and Sweden. Pest control could require increased application of established pesticides and also increase the pace of introduction of new pesticides to the market, and into use in Sweden. And, warmer temperatures will increase the duration of the seasonal period when pesticides are applied in Sweden.

There is potential that a higher incidence of extreme weather conditions could drive luxury and high-value crop production to be moved indoors, which would lead to usage of pesticides that are banned in other use contexts. Thus, a variety of climate change drivers have the potential to increase pesticide use, and increase human exposure to pesticides due to the consumption of pesticide residuals on crops and direct exposure of agricultural workers in fields and greenhouses. Higher temperatures and heavy rain events will also affect the environmental fate of pesticides. However, higher human exposure caused by higher mobility of pesticide chemicals is likely to be countered by increased rates of degradation, and the magnitude of these changes are expected to be small, relative to potential changes in human exposure that could result from changes in use and application of pesticides.

Despite a foreseen water scarcity on arable lands, the runoff from land to waterbodies (e.g., rivers, lakes) is expected to increase, which locally may lead to increased chemical exposure through higher concentrations of pollutants in fish as well as in source water for drinking. Changes in the water balance in in Sweden could require changes in the management of source water for drinking, which in turn, could drive increased exposure to persistent and mobile contaminants such as perfluoroalkyl substances (PFAS). A shift in diet towards less meat is expected to reduce exposure to bioaccumulative contaminants such as many of the POPs. However, it could coincidently increase exposure to pesticide residues and heavy metals.

Summaries of global warming-related changes in chemical exposure via drinking water, food, the indoor environment and from applications of sunscreens and insect repellents that can be anticipated based on our literature review are below.

1) **Drinking water**

   With the changing climate, Sweden is likely to suffer from more floods and droughts in the future. Floods may transport chemical contaminants into groundwater and surface water. More frequently occurring droughts will increase the mobilization of heavy metals and leakage of all chemicals into groundwater. The extent of the changing climate will thus largely determine the extent of changes in human exposure to chemicals through drinking water.

2) **Food**

   Pesticide usage is forecasted to increase due to climate change, leading to higher human exposure to pesticide residues through the consumption of contaminated crops. Chemical uptake via food can be influenced by pesticide treatment of crops and is foreseen to increase with climate change. More widespread adoption of indoor agriculture for high-value specialty crops could result in new pathways for human exposure to pesticides. And, in a scenario where applications of wastewater and/or sewage sludge to agricultural fields becomes more extensive in Sweden and Europe, new pathways for chemical exposure through agricultural will be opened.

3) **Indoor environment**

With the warming climate, increasing demand for energy-efficient buildings is expected. The use of air-conditioning in private households is likely to increase, which will translate into lower ventilation rates in buildings in the future, as open-window airing will be reduced to contain the conditioned air. With poorer ventilation, concentrations of chemicals in indoor air are likely to increase. Additionally, extreme weather events and wildfires will drive the population (particularly vulnerable subgroups such as the elderly and children) to spend more time indoors during these periods, which can increase their exposure to contaminants indoors.

4) **Usage of sunscreen products and insect repellents**

With a warming climate, the Swedish population is likely to spend more time during the summer outside in the direct sunlight. The usage of sunscreen and sun blockers will increase, leading to an increase in dermal uptake of chemicals in these products. Additionally, the geographic distribution of mosquitos and other insects and arthropods in Sweden will change due to the warming climate. This will lead to higher usage of insect repellent products, which, if applied simultaneously with sunscreen productions, will increase the dermal uptake of chemicals ingredients from both products.

Using the information identified within the scope of this literature review, we developed possible scenarios (Tab. 2) inspired by the Shared Socioeconomic Pathways (SSPs) scenario framework used for global change research. The first scenario (SSP1), entitled “Taking the Green Road”, simulates a global community that has developed into a sustainable society with sustainable and equal use of common resources. The second scenario (SSP2), “Taking the Middle of the Road”, describes a path in between two extremes were slow progress towards mitigation and adaption to climate change is adopted. The third scenario (SSP3) compares to “Taking the Highway” in fossil-fuel development which will entail high challenges to mitigation and to adaptation. These scenarios describe alternative pathways for the development of human exposure to chemicals in drinking water, food, the indoor environment, and usage of sunscreen products for the Swedish population.

Table 2 Overview of global-warming related changes in chemical exposure in Sweden under different Shared Socioeconomic Pathways (SSP) scenarios.

Exposure pathway	SSP 1 The Green Road	SSP 2 The Middle Road	SSP3 The Highway
Drinking water	- Shift towards higher percentage of organic farming, reducing exposure to pesticides. -Increase in the percentage of treated surface runoff, reducing release of untreated wastewater and thus exposure to chemicals. - Occasional droughts and floods with consequent mobilization of chemical pollutants into surface, and groundwater.	- More and stronger rain events and droughts in Sweden leading to mobilisation of chemicals and exposure to contaminants, particularly through drinking water.	- Overflow of wastewater occurs more frequently during heavy rain events - To address higher need for water, reuse of wastewater is implemented, leading to distribution of chemicals on arable land - Extensive rain incidents and droughts may transport more chemical pollutants to surface and groundwater.
Food	- Shift towards a plant-based diet reduces exposure to bioaccumulating chemicals through agricultural food chains, and to chemicals present in imported feed. - Effective upstream measures reduce chemicals entering wastewater treatment plants and sewage sludge can be applied to arable land without increasing exposure to chemicals.	- More and stronger rain events in Sweden lead to higher exposure to chemicals transported from land to drinking water, and to aquatic food webs. - Higher demand for agriculture, in combination with poor development of sustainable solutions for chemical use and management lead to chemical exposure through the reuse of sludge on arable land.	- Prolonged heavy rain and drought events lead to higher runoff of chemicals to surface water and aquatic food webs. - Pesticide use in agriculture increases. - Reuse of sewage sludge and wastewater on agricultural land leads to higher chemical exposure through food.
The indoor environment	- More sustainable construction materials and furnishings are adopted, avoiding hazardous substances such as VOCs or flame-retardants, resulting in reduced exposure indoors. - Extreme weather events, e.g., elevated temperatures during summer periods, drive people indoors, but do not last for extended time periods. - Buildings are more energy efficient, but open-window-ventilation rates are set to decrease, leading to higher potential for chemical exposure via indoor air.	-Transition to more sustainable construction materials and furnishings limits exposure to hazardous substances in the indoor environment but not sufficiently to improve the average indoor air quality in buildings -Temperatures rise and occasional heatwaves or coldwaves occur, which increase the time spent indoors and, therefore, exposure to chemicals present in the indoor environment.	- No change toward sustainability or to mitigate extreme weather events has been implemented, increasing the indoor chemical exposure due to volatilization of chemicals from building materials and the population spending more time indoors to shelter from extreme weather events - Forest fires increase in frequency and intensity, leading to urban air quality decline, and even more sheltering indoors.
Use of sunscreen and insect repellents	- Changes in exposure to chemicals in sunscreen and insect repellents are expected to be dominated by trends in public attitudes towards the use of these products in all scenarios.		

1. INTRODUCTION

By 2100, climate change is predicted to cause yearly mean temperatures to rise by 3-6°C in Sweden[1]. Higher frequency of extreme weather events, such as droughts, heatwaves, and heavy rain, are also expected[2].

There is clear potential for health impacts in Sweden during heatwaves and other climate-change-related extreme weather events[3]. In Stockholm alone, the incidence of heatwave events has doubled in the last 40 years, and population mortality caused by extreme heat and cold has increased significantly, with 288 (95% confidence interval 161 - 417) deaths in Stockholm attributable to climate change[3]. In Sweden, the 2018 summer heatwave caused 635 more heat-associated deaths in comparison to 2017, which corresponds to an 8.2% increase during the entire heatwave, and a 13.5% increase during the warmest week (16-22 July 2018)[4].
Sweden's population of elderly and other vulnerable groups is expected to increase in the future, coincident with the increasing effects of climate change, and thus the mortality associated with climate change is expected to increase in the future[3].

Climate change could further impact the health and well-being of Swedish citizens by affecting the amount and types of chemicals that they are exposed to in their daily lives, in indoor and outdoor air, and through food and water. For example, the increasing temperature has been identified as an important driver of increased emissions from persistent organic chemicals to the atmosphere[5]. Assuming no change in chemical use patterns, concentrations of chemicals in the air increased by up to a factor of 2.8 in response to increased temperature under climate change in model scenarios for Sweden and the Baltic Sea drainage basin[5]. Climate change is likely to also increase human exposure to chemicals through agriculture[6]. And climate change has the potential to modify the organisation and functioning of environmental systems (e.g., changing trophodynamics in food webs), which in turn may alter bioaccumulation and biomagnification of persistent organic pollutants and, thereby, the risk of negative effects on the environment and on humans[7,8].

This report presents a literature review conducted to assess how the Swedish population's exposure to chemicals might change due to climate change. We examine potential climate change-related drivers of change in chemical exposure that were identified by the report's authors and scientists at the Swedish Environmental Protection Agency, the Swedish Public Health Agency, and the Swedish Chemicals Agency and which are described in the following sections. The climate change-related drivers include changes in indoor air quality, changes in chemical exposure due to increased exposure to UV radiation, flooding, droughts, and landslides, and exposure via food to environmental contaminants and pesticides.

2. METHODS

We conducted literature searches using Google Scholar (scholar.google.com) from October-December 2021, using multiple keyword combinations (Tab. 3). Results were reviewed in a list sorted according to the “sort by relevance” function of the Google Scholar search engine. Documents are ranked by the Google Scholar algorithms based on the full text of each document, where it was published, the author(s), how often and how recently it has been cited in other scholarly literature[9]. The relevance of each publication was further assessed by the authors of this report by reading the title and abstract, considering studies in the order of the Google Scholar relevance list until very low or no relevance to the search topic was evident in the title and abstract.

Peer-reviewed journal articles, book chapters, and public reports from governmental agencies written in English or Swedish were assessed in the search results. Publications were included or excluded according to the relevance of the criteria: (1) temperature change, (2) indoor air quality, (3) floods, (4) droughts, (5) landslides, (6) pesticides, (7) environmental contaminants in food, and (8) UV radiation. The full texts of studies that were identified as relevant were obtained and critically reviewed to identify content relevant to each sub-topic (Tab. 4, 6-8, 10-12). The relevant content was then synthesised into this literature review, which is the basis for the future exposure scenarios that are proposed in the final section of the report.

Table 3. Literature research. Keywords that were used to search the platform “Google Scholar” per section topic.

	Temperature Change	**Indoor quality**	**Flooding**	**Drought**
Keywords	climate change Sweden	indoor chemical	flood chemical	drought chemical release
	temperature global warming	indoor air quality climate change	hurricane chemical	drought metal release
	climate change temperature	household contamination	Natech	drought Sweden
	climate change temperature Europe	indoor contamination	storm chemical	drought Sweden contaminants
	climate change temperature Scandinavia	dust contamination	flood contamination	peat Sweden
	climate change temperature Sweden	indoor air quality		peat Sweden drought
	indoor chemical exposure	indoor air contamination		wastewater drought Sweden
				droughts Sweden climate change

	Landslides	**Pesticides**	**Contaminants in food**	**UV radiation**
Keywords	landslide Sweden	pesticide Sweden	HOC food Sweden	sunscreen allergy
	landslide	invasive plants Sweden agriculture	hydrophobic organic contaminants food Sweden	sunscreen allergy dermal uptake
	landslide Sweden climate change	pesticides climate change	contaminants in food Sweden	sunscreen toxicity
		degradation of pesticides temperature		
		volatilisation of pesticides temperature		
		climate change pesticide food		

3. LITERATURE REVIEW OF HUMAN EXPOSURE TO CHEMICALS IN SWEDEN IN A CHANGING CLIMATE

3.1 Indoor air quality

The quality of the indoor environment, and especially indoor air quality, depends on many different factors, such as the presence of mould, the occurrence of pets and dust mites, the cleaning agents used and smoking habits[10]. Chemical emissions from furnishings and construction materials contribute significantly to determining indoor air quality[11]. Emissions of chemicals from building materials are positively correlated with temperature[12] and humidity[13]. Some of the chemicals contained in building materials and furnishings, such as plasticizers[14], flame retardants[15], and volatile organic chemicals (VOCs)[16], may cause negative health effects, such as allergies and chronic asthma[17,18] and have endocrine disrupting[19,20] or carcinogenic[16] properties. Some semi-volatile organic chemicals (SVOCs), such as phthalates, have been linked to an increased risk of suffering from asthma, allergy, or wheeze in children[21–23], malformation of the male genitalia[24], neuropsychiatric effects, such as autism[25], body fat development and weight gain[26], and risk of diabetes[27].

Volatilisation is the main source of VOC emission from building materials, and inhalation is the major exposure pathway[28]. Pathways for human exposure to Ss in indoor environments are skin contact, ingestion, and inhalation of dust[29,30]. Particularly for low volatility SVOCs[31–34], such as brominated flame retardants[35], inhalation of dust and unintentional dust ingestion (mainly by small children crawling on the ground)[36] are the dominant exposure pathways[28,37,38].

Some SVOCs, such as polybrominated diphenyl ethers (PBDEs), have been found in indoor environments at concentrations several orders of magnitude higher than outdoors[39,40]. Exposure to chemicals indoors was identified as a potential human health problem in the early 1990s, when cases of "sick building syndrome"[41] were documented in which health issues (e.g., headaches, nausea, and irritations in the eyes, nose, and throat) occurred indoors but disappeared shortly after leaving a building[17].

How and when a building was constructed influences the indoor air temperature, relative humidity, and the air change rate. Air exchange rate, in particular, is a critical parameter determining levels of indoor air pollution. In Sweden, buildings constructed between 1960 and 1980 generally have lower ventilation rates in comparison to both older and newer buildings[42]. In a Norwegian cohort study, the highest concentrations of chlorinated paraffins in settled household dust were identified in houses built between 1978 and 2002 in comparison to other time periods[43]. Another study showed that higher concentrations of both formaldehyde (HCHO) and nitrogen dioxide (NO_2) were found in the air in newer buildings that were built from concrete in comparison to older wood houses. The differences were attributed to both differences in sources of emission (e.g., building material or heating system used) and to higher air ventilation rates in the older wood buildings that are not as airtight built as the newer buildings with concrete walls[44].

Many different materials contribute to the overall pollution of the indoor environment, which makes it difficult to identify specific materials as a major emission source[44]. Additionally, human activities, such as cleaning routines and change in furniture, add to the complexity of pinpointing emission sources[45]. Furthermore, air pollution concentrations determined in different studies may vary strongly depending on the sampling procedure. For example, indoor air samples may have up to five-fold lower concentrations of pollutants than personal air collected directly from the resident[43].

However, despite these challenges, renovation of concrete buildings and construction of new buildings has been estimated to reduce air pollution by a factor of 2-5 more than only phasing out articles and materials that contain pollutants[36]. Renovation of building to remove materials that are subject to new restrictions and replace them with approved alternatives is seen as one step to reduce indoor air pollution and, thus, improve human and environmental health[36]. Air pollutant concentrations, of e.g., organophosphate flame retardants and selected brominated flame retardants, can be minimised in air and dust by using approved building materials in new construction[46,47]. In general, 1) building new, 2) renovating older buildings, and 3) removing SVOC-containing articles are proven to be effective ways to reduce human exposure to SVOCs in indoor environments[36].

In the context of climate change, increasing demands for energy efficiency, changes in pollutant identity and emissions, and more extreme weather events will drive changes in indoor air quality[48]. Building and renovating with the goal to lower energy consumption will likely lead to more airtight buildings with lower ventilation rates and changing behaviour towards less airing of rooms with open windows. These changes would lead to worse indoor air quality[48]. Additionally, particularly elderly people are likely to spend more time indoors with the changing climate, leading to higher exposure to indoor air pollution[48].
Increased incidence of wildfires is anticipated under climate change, which will result in episodes of high concentrations of airborne particles that are capable of rendering respiratory health effects[49]. Forest fires pose a health risk, particularly to the elderly, infants, and people with pre-existing respiratory disease (e.g., asthma or chronic pulmonary disease), and especially these susceptible groups would be advised to shelter indoors during forest fire-induced episodes of poor outdoor air quality. Thus, climate change may drive vulnerable populations to spend an even higher amount of their time indoors, with consequently increases in exposure to indoor pollution[50]. Particle filtration systems, such as those installed in forced-air heating and cooling systems, may help to mitigate effects on vulnerable populations due to increased exposure risks from indoor pollutants and pollutants transferred from outdoors to indoors during episodes of poor outdoor air quality[50].

In conclusion, the warming climate in Sweden is likely to drive demand for more energy-efficient buildings, both in the construction of new buildings and renovation of existing buildings (Tab. 4). More energy-efficient buildings will likely have lower ventilation rates, which will increase exposure to chemicals in indoor air, and through the indoor environment in general. However, exposure to SVOC-containing building materials will likely decrease as they are removed and/or avoided in newly constructed buildings. The population (particularly vulnerable subgroups such as the elderly and children) will spend more time indoors during extreme weather events (i.e., heatwaves or coldwaves), but the usage of sunscreens will increase too, due to longer summer periods, which will increase the risk of exposure to the indoor environment and UV radiation, respectively. Increasing incidence of forest fires will also drive the population to shelter indoors, with consequent increases in the exposure to chemicals in indoor air as well as exposure to PAHs and particulate matter from the fires that is transferred from outdoor air to indoor air.

Table 4. Results indoor air quality. Climate change-associated drivers, responses, and consequent influence on chemical exposure indoors, most notably through indoor air. Arrows pointing up (↑) indicate increased exposure and arrows pointing down (↓) indicate decreased exposure.

Climate Change-associated driver	Response	Influence on chemical exposure indoors
Demand for increased energy efficiency of buildings	New construction and renovation	↑ due to lower number of air changes per hour
		↓ due to removal of known SVOC-containing materials
Increased incidence of forest fires	Sheltering indoors due to poor outdoor air quality	↑ due to bad air quality episodes and more exposure to PAHs and particulate matter

3.2 Flooding

Floods are often triggered by heavy rain that oversaturates the soil[51]. Globally, floods have been identified as the most prominent increasing natural disaster threat to humanity due to socio-economic growth and climate change[52]. In Northern Europe, average precipitation rates are projected to increase with climate change[53,54] , and extreme weather events are expected to be more common. Depending on the season, precipitation rates are also projected to increase in Sweden[55].

Industrial accidents caused by natural extreme weather events such as floods are known as Natechs (Natural Hazard triggering Technological Disasters)[56,57] and often involve the release or transport of hazardous materials[56,58]. Exposure of water resources to chemical substances may occur due to leakage from contaminated soil. Floods can release and transport hazardous substances from landfills and contaminated sites and from untreated sewage water released through overflow events. Additionally, flooded buildings are at higher risk of developing mould and high airborne spore counts, which are a health hazard[59]. Increases in both population density and industrial development in areas subject to natural disasters increase both the possibility of future disasters and the potential for human exposure to hazardous materials during these events[60].

Semi-volatile compounds (e.g., PAHs or PCBs) and non-volatile compounds such as heavy metals (lead, arsenic) can be mobilized by floodwaters and deposited at locations other than their origin (Tab. 5), as storms like the hurricanes Sandy[61] or Florence[62] in the United States of America have shown. However, the lack of environmental samples prior to floods often makes it difficult to make a direct comparison before and after flooding events[59]. A recent study revealed that the influence of flooding rivers on the mobility of potentially toxic elements still remains after the floodwater subsides, and, thus, floodplains cannot be considered as the final sink for chemical contaminants after floodevents[63]. Flood events may result not only in the chemical contamination of surface waters but also carry the contamination further on to both soil and ground water[64].

Chemical plants, petroleum refining facilities, construction material storage areas (e.g., lumber preserved with creosote, pentachlorophenol, and arsenic) and contaminated soils are areas where floods could mobilize chemical contaminants. A review by Krausmann and Mushtaq highlighted that chemical storing facilities are particularly at risk of releasing hazardous substances in the event of flooding[65]. Private households have also been classified as a general hazard by the European Directive on dangerous substances (Tab. 5) due to the presence of, for example, gasoline and oil from automobiles[59].

Beginning in the late 1990s and onwards, the awareness of climate change and its effects on flood frequency and intensity increased in Sweden[66]. Floods are forecast to increase, particularly in the south of Sweden[67]. As part of the realisation of Directive 2007/60/EC on the assessment and management of flood risks in Sweden, areas with probabilities of floods and significant consequences thereof were identified in 18 of 290 municipalities in Sweden (Fig. 1)[66,68]. In Stockholm, half of the storm- and meltwater is led to wastewater treatment plants, while the other half is channelled to proximate lakes (i.e., watercourses and Saltsjön)[69]. However, the capture capacity of wastewater treatments plans in Stockholm can be exceeded in heavy rainfall events, so untreated wastewater is discharged together with stormwater to receiving water bodies[69]. The annual precipitation in Stockholm county is estimated to increase by 20-30 % by the year 2100[70], which will increase the occurrence of releases of untreated wastewater in the future if stormwater management practices remain unchanged.

In summary, higher frequencies of floods, especially in areas of Sweden identified as most susceptible (Fig. 1), are likely to drive the mobilisation of chemical contaminants from industrial areas, contaminated sites and households, which will increase the exposure of surface water in affected areas to chemical contaminants (Tab. 6).

Table 5. Chemical hazards in floods. Hazardous substances and preparations involved in accidents triggered by floods and related hazards based on the general hazard classification defined by the European Directive on dangerous substances. Adapted from[64] with[71] therein.

Category	Hazard
Chlorine	Toxic, dangerous for the environment
Oil, diesel fuel, gasoline	Extremely flammable, dangerous for the environment
Cyanides	Toxic, dangerous for the environment
Propane, butane, and liquefied petroleum gas	Extremely flammable, dangerous for the environment
Explosives	Reacts violently with water
Fertilizers	Dangerous for the environment, toxic
Acid products	Toxic, dangerous for the environment
Calcium carbide	Contact with water liberates extremely flammable gases
Soap and detergents	Dangerous for the environment
Liquid hydrocarbons	Extremely flammable, dangerous for the environment
Liquid aromatics	Extremely flammable, dangerous for the environment
Oxides	Explosive with or without contact with air, reacts violently with water

Figure 1. Areas identified as vulnerable to significant flood risks in Sweden. The red circles represent the areas of identified risks of flooding in Sweden. Map adapted and in courtesy of MSB[72].

Table 6. Results of floods. Climate change-associated drivers, their responses, and consequent influence on chemical exposure in floods. Arrows pointing up (↑) indicate an increase and arrows pointing down (↓) indicate a decrease of the exposure.

Climate Change-associated driver	Response	Influence on chemical exposure in floods
More frequent floods in identified areas in Sweden	Mobilization of chemicals from industrial areas, construction sites and contaminated soils	↑ due to contaminated surface water in affected areas
More frequent occurrence of heavy precipitation events	Higher incidence of release of untreated stormwater directly to surface water in urban areas	↑ due to direct transfer of chemical in urban run-off water to surface water

3.3 Droughts

Droughts are week-to-month long episodes of warmer than normal temperatures and lower than normal precipitation, which cause depletion of soil moisture[73,74]. As a consequence of climate change, droughts are expected to happen more frequently and with higher intensity in Europe in the near future[75,76] (Fig. 2). Using precipitation measurements, satellite observations, and modelled soil moisture content, the European Drought Observatory (EDO) offers information relevant to droughts on the European scale[77]. The Swedish Meteorological and Hydrological Institute (SMHI) showed that higher (30-60%) precipitation and net precipitation (difference between precipitation and evaporation) in Sweden do not prevent droughts (i.e., 20-40% less precipitation) in the following summer, particularly in the south of Sweden[78]. High temperatures are likely to increase the effects of droughts as they elevate the evapotranspiration[78].

During the years 1975, 1976, and 1983 Sweden suffered from severe droughts during summer, and the drought in 1992 was likely the most severe drought in Sweden over the past 100 years[79]. In 2013, the south of Sweden experienced a summer drought leading to lower groundwater levels in comparison to normal years[80]. In 2017, Sweden suffered a drought followed by stark groundwater loss in comparison to non-drought years[81]. Sweden experienced extreme temperatures and drought in the summer of 2018; some parts of Sweden, such as Öland, have suffered droughts for three consecutive years since then[82]. Droughts in central-eastern Sweden are forecasted to occur more frequently in the future, driven by lower precipitation and higher temperatures[2].

Modelling studies have shown that droughts in Sweden can have severe effects on crop yield, with up to 50% loss in comparison to no drought conditions[83]. Climate change and, consequently, drought can affect the water supply used for food production, particularly in areas where groundwater is used for agricultural irrigation, and, thus, increase the energy consumption [84].

Droughts, causing groundwater scarcity, may also be linked to contaminant exposure through increased usage of wastewater. In Sweden, there is an ongoing debate about whether treated wastewater may be used to compensate for water scarcity during droughts[85]. Wastewater treatment plants in Sweden process wastewater to a specific level that allows release into the environment, however, direct reuse of cleaned wastewater as source water for drinking in Sweden is not considered to be an option at the moment[85]. In water-stressed areas of Europe, both treated and untreated wastewater are used for irrigation of crops, which can introduce contaminants into agricultural systems[6].

During droughts, more oxygen can enter soils which leads to more oxidation of organic matter and reduction of inorganics (e.g., sulphides)[86]. This oxidation causes acidification of the soil, mobilizes metals, and negatively impacts the quality of water receiving runoff[86]. Studies have shown that non-contaminated wetlands with lower metal concentrations than industrial or urban areas can still increase their metal concentration above the water quality guidelines through drought-induced metal mobilization[87]. Accordingly, metal-contaminated areas may pose even higher risks of reaching harmful metal concentrations after drought events[87]. It is estimated that more than 600km^2 of acid sulphate soils are located in Västerbotten and Norrbotten alone, and, thus, posing the risk of large metal emissions to the environment if brought up to air[88]. Droughts may also lead to a decrease of dissolved organic carbon (DOC) concentrations, which in turn decreases some metal concentrations, such as copper or aluminium, that are heavily complexed with organic acids[89].

In Sweden, peatlands make up an area of between 63000 and 66700 km[90], corresponding to approximately 14% of Sweden's surface[91]. Peat in Sweden exhibits levels of Pb that were likely caused by atmospheric transport from the European continent in the form of both soil dust and atmospheric pollutants from metal burning and production[92]. In peat, sulphate concentrations are higher after droughts due to the oxidation of organic, reduced forms of sulphur when the soil was dry and warm[93]. The pH is linked to the sulphate dynamics in the soil and may decrease during drought-associated acidification[93]. Further, droughts can lead to the export of sulphate (SO_4^{2-}) that has been re-oxidated in wetlands[94]. Those acidifications of peat drainage water can be induced by drought conditions, leading to the mobilisation of aluminium species and heavy metals (Ni, Cu, Zn, Cd, Pb[95], and methylmercury[96]). Thus, at least two kinds of atmospherically deposited pollutants (heavy metals and sulphur) can be mobilised from peatlands in Sweden by the effect of climate change[95].

A case study at highly contaminated steel and ironwork sites in southern Sweden shows that exposure of 4-year-old children to cadmium might increase by up to 27% in the future due to climate change-induced drought effects (e.g., changes in soil moisture or groundwater recharge)[97]. A recent review from Barthel et al.[98] demonstrates that research on groundwater recharge in Sweden has been scarce over the past decade and that it remains challenging to connect groundwater resources with global climate change and, thus, Sweden is not well prepared to anticipate climate change-induced effects on groundwater reserves[98].

In summary, climate change is driving an increase in droughts in Sweden, which will lead to drier soils. In those dry soils, heavy metals will be more effectively mobilized into groundwater and surface water, which increases the exposure of water resources. Droughts may also lead to a potential usage of treated or untreated wastewater and sludge on arable land to compensate for the undersupply of irrigation water for crop fields, which would increase exposure to contaminants through the agricultural food chain (Tab. 7).

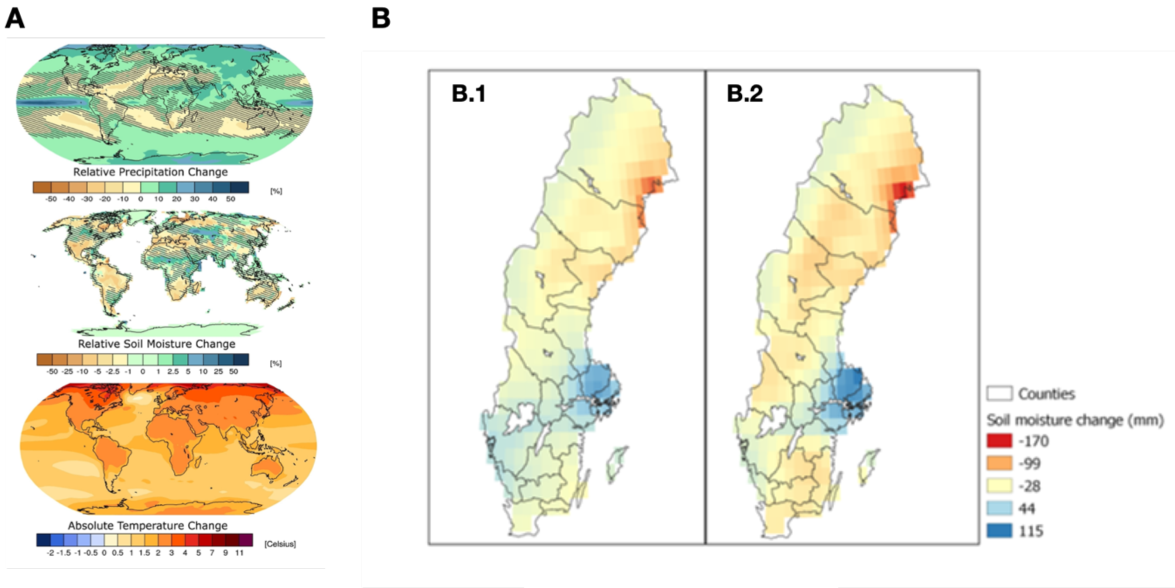


Figure 2 Predicted drought distribution in Europe in the future. **A.** Climate change predictions relevant to future drought impacts to 2100; specifically, relative projected changes in precipitation and soil moisture and absolute changes in near-surface temperature. These projections are from the International Panel for Climate Change (IPCC) fifth phase of the Coupled Model Intercomparison Project (CMIP5) for Representative Concentration Pathway (RCP) scenarios 4.5[99]. These outputs were obtained from the KNMI climate change atlas (see https://climexp.knmi.nl/plot_atlas_form.py), where other outputs and RCP scenarios are also available. The differences are from 2081 to 2100 projections minus 1986–2005 data. Figure adapted from Stirling et al. (2020)[86]. **B.** Annual change in soil moisture during the period 2050-2070 in relation to 1980-2000 with B.1) RCP 4.5 and B.2) RCP 8.5. Figure adapted from Långsamma kontinuerliga risker från klimatförändringar i Sverige 2050[84].

Table 7. Results droughts. Climate change-associated drivers, their responses, and consequent influence on chemical exposure for droughts. Arrows pointing up (↑) indicate an increase and arrows pointing down (↓) indicate a decrease of the exposure.

Climate Change-associated driver	**Response**	**Influence on chemical exposure in droughts**
Increased droughts with drier soils	Heavy metal mobilization into groundwater + surface water	↑ due to contamination of drinking water
Not sufficient water for irrigation of crop fields	Potential usage of sewage sludge/water on arable land	↑ due to contamination of crops

3.4 Landslides

Landslides occur when soil loses surface stability, such as on steep hillsides and when the motion is self-reinforcing and becomes a mass movement of material[100]. Landslides can result in the movement of a wide range of geological materials, including soil, rock, sand, silt, clay, and gravel, and also a range of man-made materials and debris[100].

In Sweden, landslides are considered a serious natural geo-hazard[101,102]. The Geological Survey of Sweden (SGU) has mapped areas of Sweden that are prone to landslides based on conditions of the soil and the slope[103,104]. Areas of Sweden at high risk for landslides are mostly steep slopes in proximity to rivers or in gorges, where masses of potentially mobile soil are located on elevated flat terrain[105].

The risk of landslides increases with higher precipitation[106]. Due to changing climate and the resulting precipitation increase, some sites such as the Göta älv (Göta river)[102] valley in the south of Sweden, the Krokvåg area, located in the Indalsälven valley in northern Sweden, and the soft clay habitat in Vagnhärad[107] in the southwest of Sweden, may, in particular, see an increased risk of landslides[108] (Fig. 3).

Chemical exposure as a result of landslides is only likely if the landslide occurs in a polluted area or an area where chemicals are used or stored. For example, exposure to chemical substances could occur due to landslides that affect industrial land or old landfills. However, comparing the results of the SGU assessment with the location of landfills in Sweden indicates that landslides in Sweden are not predicted in areas where landfills are located[109].

In summary, despite an anticipated increase in the frequency of landslides in some areas of Sweden due to climate change, chemical exposure is only likely to result if landslides occur at industrial or contaminated sites. However, at the national level in Sweden, landslide risk areas and areas with landfills and large industrial developments do not generally overlap (Tab. 8). The risk of chemical exposure due to landslides is thus best assessed on a site-specific basis at landfills and industrial areas rather than at the national level.

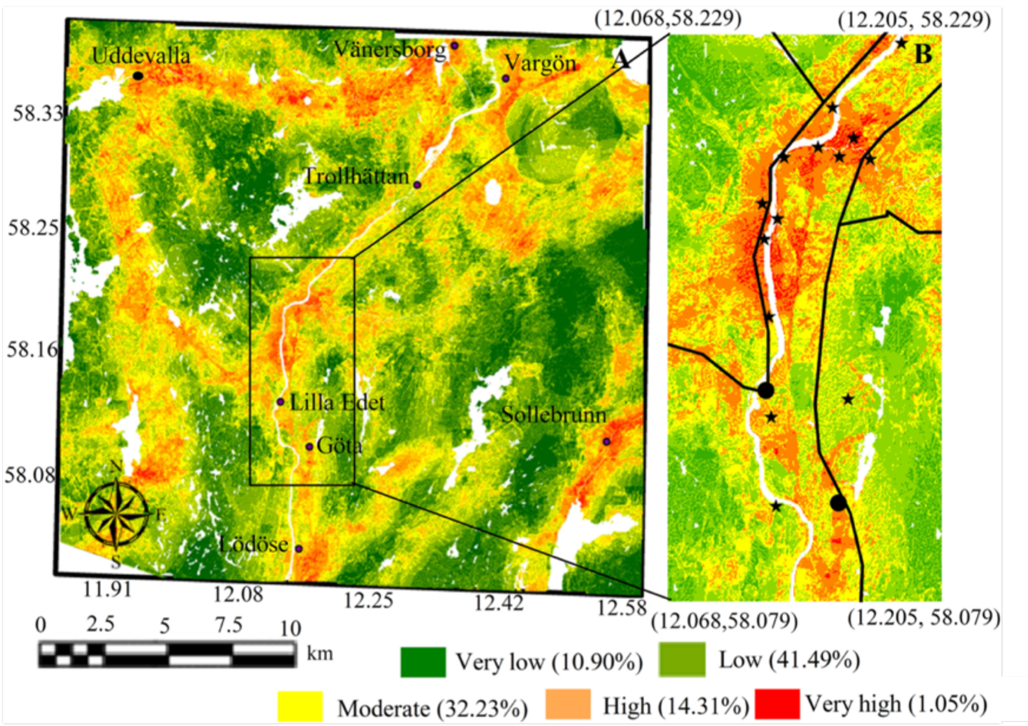


Figure 3 Landslide areas in Sweden. Landslide susceptibility map of the Göta river area based on all considered factors. Percentages indicate the fraction of the total area on each susceptibility level. The magnified map shows one subdivided zone with transport networks and validated landslides. Figure adapted from Shahri et al. (2019)[110].

Table 8. Results landslides. Climate change-associated drivers, responses, and consequent influence on chemical exposure for landslides. A pointy symbol (•) indicates no changes in the exposure.

Climate Change-associated driver	Response	Influence on chemical exposure in landslides
Higher frequency of landslide occurrence in the south-west of Sweden	Potential mobilization of contamination if landslide occurs at e.g., landfills or industrial sites	• No significant change in exposure at the national level is anticipated, as landslide risk areas do not overlap with landfills and industrial areas in Sweden.

3.5 Pesticide use

Pesticides are used to control pests that are harmful to crops and can be subdivided into several groups, including insecticides (to control insects), herbicides (to control weed and plant growths), and fungicides (to control fungi). A recent study by Tang et al. estimated that 24.5 million km^2 of agricultural land (i.e., 64% of all agricultural land worldwide) is polluted with pesticide residues, with at least one active substance exceeding its no-effect concentrations for one active substance[111]. The United Nations Food and Agriculture Organization (FAO) estimates that global pesticide applications doubled between 1990 and 2010[112], and the amount of pesticides used in agriculture is positively correlated to the mean annual temperature[113] (Fig. 4). In general, with rising temperature, pesticide applications are expected to increase together with growing crop pest pressures that are correlated with milder winters[7,114]. In the United States, future pesticide usage has been estimated to increase by 10-20% for corn, 5-15% for potatoes, 5-15% for soybeans, and 2-5% for cotton[114]. Taken together, these factors suggest that the pesticide application in Sweden could increase coincident with climate change, and one study that specifically included Sweden forecasts a higher runoff of insecticides over much of the country in 2090 compared to 1990[113] (Fig. 5).

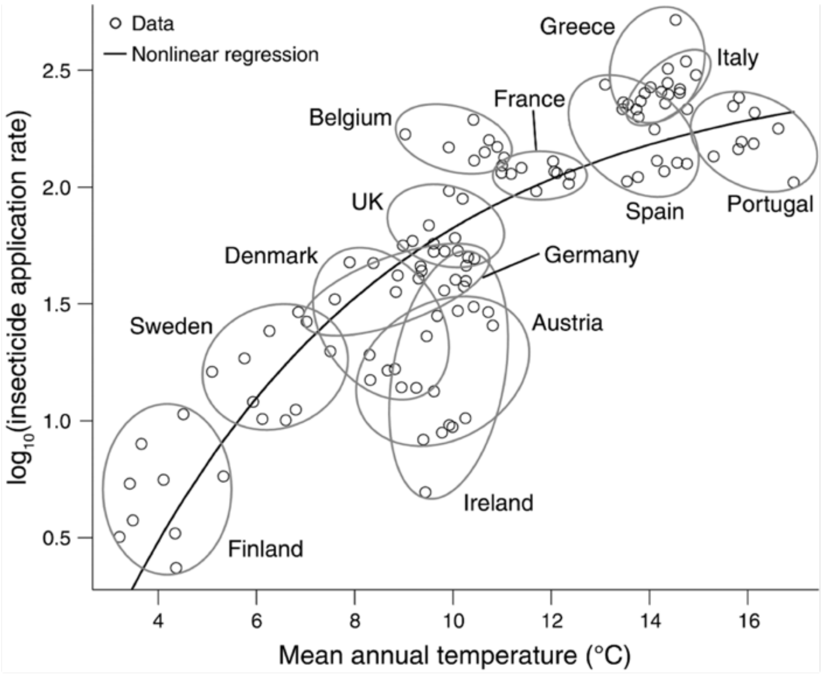


Figure 4 Insecticide application dependent on temperature. Relationship between mean annual temperature and rate of insecticide application per country for 1990–2000 is given as $\log_{10}(AR)=1/2\{[4.48(1-e^{-0.06((T-2.4)3)})-0.2] + [1-e^{-0.06((T-2.4)2)})-0.2]\}$ where AR is the rate of insecticide application of a country in grams per hectare per year, and T is mean annual temperature; $P < 2 \times 10^{-16}$, $R^2 = 0.067$. Figure and text adapted from Kattwinkel et al. (2011)[113].

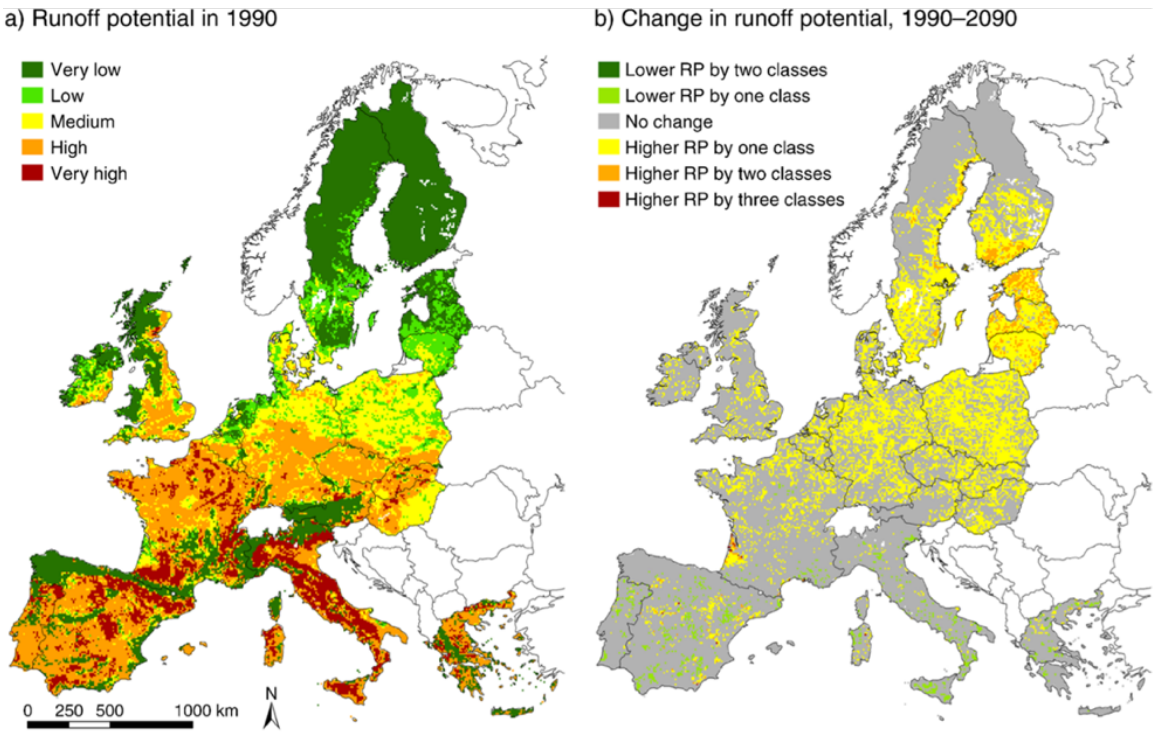


Figure 5 Runoff potential in Europe. **A** Runoff potential (RP) in 1990 and **B**. change in runoff potential from 1990 to 2090 for the A1B scenario given as the change in RP class. RP indicates a logarithmic decrease from class to class in the amount of insecticide runoff. The change in RP is given as the difference between the classes in 2090 and 1990. Hence, an increase in the RP by two classes could represent an increase from low to high (see Material and methods: GIS modelling). Figure adapted from Kattwinkel et al. (2011)[113].

A study focussing on pesticide application in the United Kingdom predicts that the impact of climate warming on pesticide exposure will mostly arise from indirect effects on land-use change[115]. In Europe, the changing climate was estimated to increase the arable land by 47% (from 1,925,265 km^2 in 2020 to 2,790,484 km^2 in 2100)[116]. Consequently, plant hosts and pests are likely to move north with the warming climate (Fig. 6)[116]. This global northward shift of agricultural climate zones is predicted to move by up to 1200 km by 2099, turning roughly 44% of the boreal region into arable land[117]. The general impact of higher temperatures is likely to be the application of higher volumes of pesticides as well as more frequent application[118] and use of different pesticide types[7]. Particularly in Scandinavia and the Baltic countries, future pesticide application is predicted to increase strongly, leading to increased exposure of insects to insecticides and plants to herbicides[113]. Additionally, the higher temperatures caused by climate change are likely to shift plant species in Europe towards those that cope better with the changing climate[119]. Whereas the southern European arable land is predicted to lose the ability to grow energy crops by 2050 due to a warming climate, the suitable arable land crops such as maize, sunflower and soybean[120] will be either shifted northwards[121] or to higher altitudes[120]. By the end of the 21st century, the amount of arable land to grow grain maize in northern Europe is predicted to increase by between 30 to 50 %, with much of southern Sweden becoming suitable[122,123]. Other mainly southern grown crops such as vine grapes are predicted to be cultivated in the south of Sweden in the near future, especially in coastal parts of Småland, and in Halland and Skåne[124,125]. Suitable crops for higher temperatures, such as maize and peas, have already increased in Sweden´s agriculture during the last years, while the total area of arable land in Sweden has slightly decreased (Tab. 9 + Fig. 7). Land-use changes in response to the warming climate are thus likely to affect all factors within agriculture in Sweden, with consequent effects on pesticide use and exposure that are difficult to fully predict[126].

Pesticides used in agriculture can be taken up via consumption by agricultural animals and, thus, transferred to humans. Soybeans produced in Brazil make up 95% of the diet of chickens raised in Sweden. and 66% of the diet of Swedish pigs. These Brazilian soybeans contain pesticide residues that are transferred to the meat-producing animals that feed on them[127]. Replacing imported soybeans with crops grown in Sweden could reduce the potential exposure to meat produced in Sweden by 90% (chicken fillet) and 70% (minced pork)[127]. Since the early 2000s, the cultivation of soybeans in Sweden has been increasing[128].

Pesticides can escape from agricultural areas into the environment via volatilisation, which is most relevant during the first 3-6 hours after application[129]. Persistent and mobile pesticides and their transformation products can also be transported to groundwater, which threatens the quality of drinking[130], and via runoff to surface water. The EU Water Framework Directive (WFD) requests monitoring of watercourses in Europe[131]. However, the poor health status of European water bodies due to the occurrence of pesticides or other pollutants can nevertheless remain undetected, as water sampling and analysis are often insufficiently undertaken[131].

Several pesticides, such as imidacloprid[132], clothianidin[133], and thiamethoxam[134], are banned within the EU for outdoor cultivation, but their application in greenhouses remains. Pesticides applied indoor can seep into the environment and, thus, contaminate surface and groundwater[135], soil, air, and plants[136]. Workers at greenhouses and consumers are at particular risk of exposure[135]. Despite its ban on outdoor application, imidacloprid was found to be one of the most frequently detected pesticides in Swedish rivers, often exceeding its predicted no-effect concentration (PNEC)[135,137].

A modelling study for Canada tried to predict pesticide usage and pollution in the future against the background of a warming climate[138]. It was estimated that pesticide application would occur earlier in the year under conditions with higher temperatures but would not necessarily imply higher pesticide usage by itself[138]. Across more than 20 climate simulations, future pesticide occurrence in the environment could not be clearly forecasted due to high variability in the climate change scenarios[138]. The study indicated that the effects of climate change on pesticide exposure need to be assessed locally, as they depend strongly on local weather and on factors such as whether pesticide applications occur directly before rain events[138].

In a study for the United States of America, an increase of up to 47% to the exposure of aquatic environments was estimated due to increasing usage of pesticides in agriculture under climate change[139]. Especially the cultivation of berries, fruiting vegetables, apples and other pomes, and stone fruits were identified as driving higher pesticide applications in the future[139], and thus this study has some relevance also for Sweden and is consistent with the higher runoff of insecticides forecasted by Kattwinkel et al. (2011)[113] (Fig. 5).

Climate change is likely to affect environmental fate pathways for pesticides that may lead to changes in exposure to pesticides in the future. Higher temperatures may increase the volatilisation of pesticides[7,140] and lead to faster degradation rates of pesticide residues[141]. Initial concerns that wetter soils affected by higher precipitation rates may enhance mobilisation of pesticide-rich waters through higher hydraulic conductivities were put aside as pesticide degradation was found to also increase in wetter soils[115]. Still, increased rainfall may transport more pesticides into surface waters and soil[142]. On the other hand, climate change and elevated temperatures also lead to periodic droughts during warmer and drier summers in Sweden. Drier soils may lessen the potential for biodegradation[143], and, thus, pesticide residues from spring application would be more effectively stored in soil throughout the summer. The biodegradation of pesticides is also influenced by the composition of pesticide degrading microbial communities[144], and the response of these communities to climate change is difficult to predict.

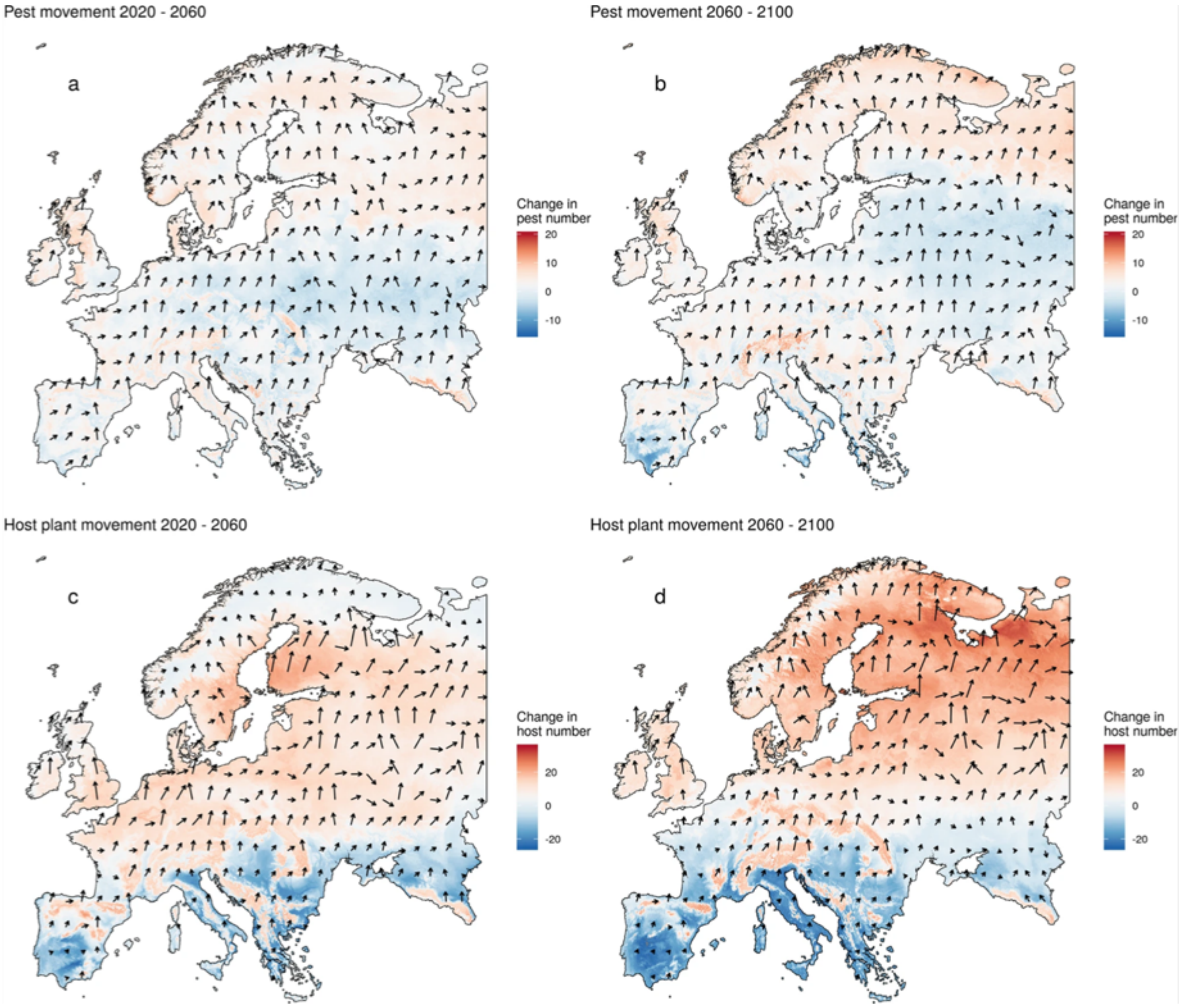


Figure 6 Pest and host plant shifts in Europe. Climatic suitability shift for pests and host plants. Arrows show for each grid cell the average direction of climatic suitability shift overall species. For each species, the direction from where each newly suitable grid cell can be reached from was calculated to its closest suitable grid cell in the previous time step. The length of the arrows is proportional to the number of colonisations of each grid cell. The coloured maps show the change in total number of pests (top) and host plants (bottom) with suitable conditions during the time steps of 2020–2060 (left) and 2060–2100 (right). Red shadings indicate an increase of the number of species with suitable climate; blue shadings indicate decreasing numbers. Climatic suitability shift and change in number of species are shown for the RCP8.5 scenario. Figure adapted from Grünig et al. 2020[116].

Table 9. Arable land in Sweden. Total arable land by crop in Sweden [hectares]. Data were taken from Jordbruksverket.se [accessed on 14 December 2021].

Year	Autumn wheat	Autumn barleys	Barley	Boil and fodder peas, vetch and field beans	Maise	Oats	Flax	Rye	Spring barley	Spring wheat	Sugar beet	Food potatoes	Total barley	Total rapeseed and turnip rape	Total field area
1981	157056	0	729276	18040	0	507806	0	52373	0	73700	52442	29727	0	0	2937878
1985	187712	0	710669	45517	0	474711	0	48323	0	98924	51884	28023	0	0	2921552
1989	252343	0	500925	37225	0	432651	0	70695	0	39463	50594	26651	0	0	2853116
1990	320120	0	492027	32725	0	387823	0	73460	0	29595	49951	27304	0	0	2844593
1991	225331	0	490896	23377	0	364272	0	43239	0	33387	38502	28269	0	0	2790027
1992	233678	0	454097	14084	0	360859	0	34597	0	36644	47963	30414	0	0	2767942
1993	271839	39024	0	8731	0	321980	0	46408	381451	32595	51288	27830	0	0	2779737
1994	212116	29555	0	6618	0	341436	0	38971	443499	39734	53357	25473	0	0	2780085
1995	222310	26228	0	11964	0	278319	0	39699	427167	39084	57523	27640	0	0	2766647
1999	209652	11889	0	30056	0	305674	34183	24516	470117	65788	59883	24433	0	0	2746940
2001	354497	9577	0	29936	0	278177	4441	34411	387924	44671	54836	23780	0	0	2694203
2002	285247	6384	0	31959	0	295000	3193	24395	410451	54358	54819	23147	0	0	2679947
2003	364055	6356	0	28938	0	279812	3734	24372	362126	47296	50099	21924	0	0	2668583
2005	295322	5352	0	31286	0	200114	9850	21394	373199	59435	49184	22088	0	0	2703338
2006	317602	5700	0	26186	0	206060	8764	23457	309444	43339	44184	20217	0	0	2660685
2007	323191	8274	0	19204	0	207910	4333	24715	318408	38372	40684	20338	0	0	2647976
2008	311249	9911	0	16949	12172	227300	2926	26982	395131	49247	36704	19527	0	0	2631303
2009	326318	17938	0	24092	15247	195744	8773	35950	351606	47856	39684	19669	0	0	2643165
2010	331801	17929	0	36078	16321	164380	19141	24231	300853	68183	37954	19829	0	0	2633454
2011	349801	14375	0	32509	15833	181163	14739	24093	313457	66988	39635	20054	0	0	2618887
2012	283574	9134	0	31359	16482	196239	8798	22025	364691	84804	39025	18702	0	0	2608277
2013	209868	13702	0	30061	15895	200572	4837	25130	378858	11634 9	36237	17801	0	0	2604530
2014	379910	13357	0	34219	16622	164892	6562	27134	321927	75284	34253	17632	0	0	2596525
2015	395243	15698	0	48373	16972	168060	7094	23651	311782	64702	19449	16649	0	0	2590057
2016	375008	19182	0	55842	17440	180868	8403	16650	308165	76196	30674	17335	0	0	2579607
2017	409104	19284	0	55899	17996	158174	4536	21598	298552	66761	31183	17079	0	0	2568354
2018	295120	14828	0	52530	18398	163887	3624	19663	382345	85944	30738	15985	0	0	2554350
2019	423435	20623	0	39393	22011	147879	2190	33323	279330	48750	27266	16282	0	0	2551505
2020	401385	20490	0	42325	21568	184508	2256	31253	278980	50096	29810	16134	0	0	2549529
2021	436858	22865	0	43209	20971	174427	3714	25906	255707	44749	28702	14933	1E+06	106123	2545949

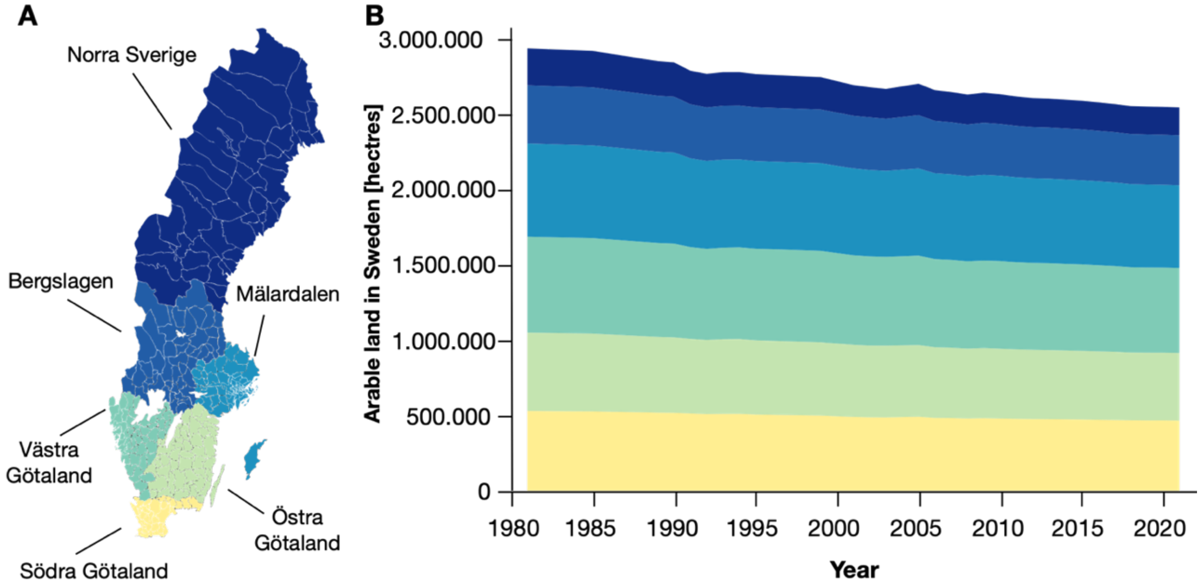


Figure 7. Arable land of Sweden. **A.** Map indicating the six major regions in Sweden. **B.** Area [in hectares] of arable land in Sweden per region. Regions are defined by the Ansvarskommittén for the Swedish government in 2007[145]. Data taken from Jordbruksverket.se [accessed on 14 December 2021].

As part of the Green Deal, the EU aims to apply at least 25% of its agricultural land to organic farming by 2030[146]. Sweden had already reached 20.4 % in 2019[147]. Hence, a dramatic decrease in pesticide use in Sweden is not to be expected in response to EU Green Deal initiatives, but further adoption of organic farming in Sweden could drive additional declines in pesticide use.

In summary, in the scope of climate change, more and different pests (i.e., insects and pathogens harmful to plants) will occur in Northern Europe and Sweden, which will increase the application of established pesticides and increase the introduction of new pesticides to the market (Tab. 10). Additionally, warmer temperatures will increase the pesticide application period. It is likely that due to unpredictable weather conditions, luxury and high-value crops might be moved indoors, leading to higher usage of pesticides that are banned to used otherwise. This amplified pesticide use will increase the risk of exposure due to the consumption of pesticide residuals on crops and directly on workers in greenhouses. Yet, increased temperatures and heavy rain events may change the environmental fate of pesticides after application, which, however, is not expected to change the exposure risk as any increase in mobility is countered by increases in degradation, and the magnitude of the changes are small, relative to what could happen due to changes in the application.

Table 10. Results pesticide use. Climate change-associated drivers, responses, and consequent influence on chemical exposure for pesticide use. Arrows pointing up (↑) indicate an increase and arrows pointing down (↓) indicate a decrease of the exposure risk; a pointy symbol (•) indicates no changes in the exposure.

Climate Change-associated driver	Response	Influence on chemical exposure in pesticide use
More and different pests	Increased application of (new) pesticides	↑ due to consumption of residuals from crops
Longer periods of higher temperatures	Longer application periods	↑ due to consumption of residuals from crops
Land use change to cultivate different crop types	More cultivation of soybean and maize in Sweden, potential introduction of pesticide intensive crops like grapes	↑ due to requirements for pest protection with different mixes of pesticides ↓ if soybeans from South America used as feed for Swedish livestock can be substituted with local soybeans with lower pesticide residues
Increased temperature and changes in rain fall rates	Change of environmental fate of pesticides after application	• No significant changes in exposure compared to other drivers such as increased pesticide use

3.6 Environmental contaminants in food

The relevance of food as a contaminant exposure pathway for humans depends on the properties of the chemical contaminant and the type of food. It is only water-soluble chemicals (log K_{OW} < 2), volatile (Log K_{OA} < 6) and very large (log K_{OW} > 11) chemicals that do not significantly bioaccumulate to humans if they are persistent[148]. However, persistence is the most important determinant of whether a chemical bioaccumulates through food to expose humans. Significant exposure to persistent chemicals can happen across a wide range of partitioning properties, including chemicals with log K_{OW} well below what is typically thought of as “hydrophobic”[148]. The persistent and hydrophobic chemicals PCBs are known to bioaccumulate. The populations in the world whose diet include carnivorous mammals, therefore, have the highest human exposure to such organic contaminants[149]. For polar substances, such as several perfluoroalkyl and polyfluoroalkyl substances (PFAS), drinking water is an important exposure pathway [150].

The Swedish Food Agency observes and informs about the contamination of food in Sweden. Currently, the listed categories of undesirable substances of concern in food on the Swedish food market are 1) “acrylamides”, 2) “metals”, and 3) “environmental pollutants”[151]. The general population in Sweden is mainly exposed to acrylamides and polyacrylamides via drinking water and consumption of specifically heated foods[152].

Metals (arsenic, cadmium, lead) are of concern in food products in Sweden. Consumption of heavy-metal polluted food such as fish during pregnancy may have adverse health effects on the child, with risk of, e.g., autoimmune diseases[153]. Inorganic arsenic is carcinogenic, causes adverse health effects [154], and is found in rice products on the Swedish food market, which is why the Swedish Food Agency recommends limiting the consumption of rice and rice products to four times (children) or six times per week (adults)[155]. On the Swedish food market, cadmium is mainly found in potatoes and cereal products and is estimated to originate from fertilizers, sewage sludge discharge on arable land, and farmland manure[156]. Lead is commonly found in low levels in most foods in Sweden. The most important exposure pathway for lead is through the consumption of cereals, vegetables, and drinking water[157].

As environmental pollutants of concern, the Swedish Food Agency highlights the bioaccumulative polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDDs and PCDFs; collectively termed "dioxins" in this report) and PCBs. Concentrations of dioxins and dioxin-like PCBs in fatty fish exceed the EU threshold for food and feed in some areas[158], which is why the Swedish Food Agency advises limited consumption of fish from polluted areas (Baltic Sea, Gulf of Bothnia, Lake Vänern, and Lake Vättern)[159].

A major pathway for dioxins to the Baltic Sea is via long-range transport from other parts of Europe, followed by atmospheric deposition[160]. European emissions of dioxins are currently the highest in Spain, Italy, Bulgaria, Slovenia, and the United Kingdom (iron and steel industry) and Cyprus and Portugal (public electricity generation)[161]. A changing climate, with more precipitation in the Baltic Sea region could impact the rate of deposition of pollutants transported from such source areas to the Baltic Sea. Heavier rain events will induce higher runoff from land to receiving water bodies and, consequently, mobilise contaminants (e.g., dioxins[162], PFAS[163]) from land to water that may contaminate both fish and drinking water[164]. Increased runoff may therefore lead to locally increased human exposure to chemicals due to the consumption of contaminated fish. An additional effect of increased runoff from land to the Baltic Sea is increased transport of terrestrial organic carbon to the sea[165,166]. A higher proportion of terrestrial organic carbon in sediment has been demonstrated to lower the capacity of the sediments to bind hydrophobic organic contaminants such as PCBs[167]. As a consequence, it is possible that sediment will release more bioaccumulative substances into water, leading to higher concentrations in fish and exposure to humans.

PFAS total concentration in fish from Swedish lakes generally decrease from south to north, while long chained (>10 carbon atoms) PFAS prevalence increase towards the north[168], although the relative contribution of various PFASs differs between regions in Sweden. Fish from southwestern Sweden show the highest relative abundance of PFOS concentrations, whereas fish from the North are higher in other perfluorocarbons[168].

Other PFAS substances are of concern in contaminated drinking water[150]. Frequently occurring PFAS in drinking water include the perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS)[150]. Other PFAS, such as fluorotelomer alcohols and polyfluoroalkyl phosphate esters, serve as water and grease protection in food-packaging materials and can be absorbed through the food[169,170]. Perfluoroalkyl acids (PFAA) and PFOA have been phased out in Europe, but due to their high persistence, they will remain in the environment[150] and continue to contaminate drinking water and foods[171] such as fish[172] or crops irrigated with contaminated water[173]. However, a recent study shows that although perfluorohexane sulfonate (PFHxS) and PFAS remain in the environment, the reduced emissions that have resulted from regulations have reduced the human exposure through contaminated drinking water in Sweden's Uppsala county[174]. With more occurring extreme heavy rain events at higher frequencies, the water balance might be changed in several locations in Sweden. This may facilitate an increased transport of PFAS from contaminated sources into the drinking water reservoirs.

A vegetarian diet has been highlighted as a key element to support the transition towards reduced emissions of greenhouse gases[175,176] and also to promote personal health[177]. Reducing the meat consumption in Sweden by 50% and replacing it with crops grown in Sweden can reduce the climate impact of the traditional Swedish meat-based diet by 20%[178]. Consequently, the cultivation of grain legumes in Sweden would have to be increased from currently 2.2% of Swedish arable land to 3.2%, which is considered to be feasible[178]. Meat from Swedish production, including cattle and swine, showed decreasing levels of persistent organic pollutants (POPs) such as PCBs, HCB, and p,p´-DDE during the years 1991 to 2004[179]. Still, a diet based on less meat and more vegetarian alternatives is likely to reduce the exposure to POPs, as they efficiently accumulate in food chains.
The extent that such a dietary shift would increase the exposure to pesticide residues depends on the type of farming products that are consumed, i.e., conventional versus organic farming. Conventionally farmed products in omnivore diets show less pesticide residues than conventionally farmed products consumed in vegetarian/vegan diets. Only a fully organic farmed vegetarian/vegan diet was found to result in less pesticide residues in the food products compared to a conventional omnivore diet [180].

Cultivating more crops in Sweden implicates a higher need for irrigation and the application of nutrients on arable soils. As part of the Circular Economy Action Plan, the EU plans to implement new approaches to facilitate water reuse in agriculture[181]. In areas in Sweden with low precipitation (e.g., the island of Gotland), wastewater is already applied for irrigation after storage for several months in large reservoirs[182]. Wastewater is used by other countries such as Spain[183], either as irrigation in areas where water is scarce or to reintroduce nutrients to arable land. However, using treated wastewater in agriculture may incur the risk of chemical pollutant transport[184] to arable land. The content of chemical contaminants found in wastewater may vary depending on the season, with, for instance, higher concentrations of diclofenac and clarithromycin during tourist seasons[185]. The Swedish EPA aims to publish a report in mid-2022 to provide an approach on how to implement the EU regulation on sewage water use into the Swedish legislation.

The option to reuse sewage sludge from wastewater treatment plants in Sweden is an ongoing discussion. The Royal Swedish Academy of Agriculture and Forestry (Kungliga Skogs- och Lantbruksakademin) reviewed the background and consequences of sewage sludge application on arable land, highlighting the advantages of nutrient reuse[186]. Svenskt Vatten argues that applying sludge on arable land may be an efficient possibility not only to recover nitrogen, phosphorus, and other nutrients in the soil but also to increase circularity and, thus, sustainability[187]. Sewage sludge amendment on arable land is also a considered strategy to reduce emissions of greenhouse gases[188].

Sewage sludge contains traces of heavy metals and organic chemical compounds[189]. Contaminants found in sludge produced in Sweden include BDE-209, dioxins, chlorinated paraffins, PAHs, PCBs, PFOS, pharmaceuticals, and other drugs[190,191]. Studies have shown that PAHs, when applied in sewage sludge on arable land in high concentrations (>150 mg/ha)[192], accumulate in soil and can be taken up by wheat and, consequently, pose a human health risk when consumed[193]. Additionally, microplastics can be found in sewage[194]. The certification system REVAQ was designed for sewage sludge in consultation with the Swedish EPA in 2008[187]. This system aims to reduce the amount of unwanted hazardous substances that are transported to treatment plants by managing possible chemical exposure risks during these processes[187,195]. An assembled consortium of environmental consultants and scientists from governmental agencies, the environmental ministry, and federal lawyers recommended banning the spread of sludge on arable land in Sweden[194], even though REVAQ has the ambition to introduce a quality control of high standards.

In summary, climate change might drive a decision to use sewage sludge and wastewater on agricultural fields in Sweden and to expand their use in other parts of Europe, leading to potential increased exposure to chemical residuals on crop foods and in water. Extreme weather events (e.g., droughts or heavy rain) might change the water balance in several locations in Sweden and require adaptations in the management of source water for drinking. In turn, this might affect the PFAS exposure, in particular, however, an increased exposure risk towards PFAS uptake through drinking water or food is not very likely. Runoff from land to water is expected to increase, which locally may lead to increased exposure through elevated concentrations of pollutants in fish as well as in drinking water. A shift in diet towards less meat is expected to reduce exposure to bioaccumulative contaminants such as many of the POPs, however, it is uncertain whether it will coincidently increase exposure to pesticide residues (Tab. 11).

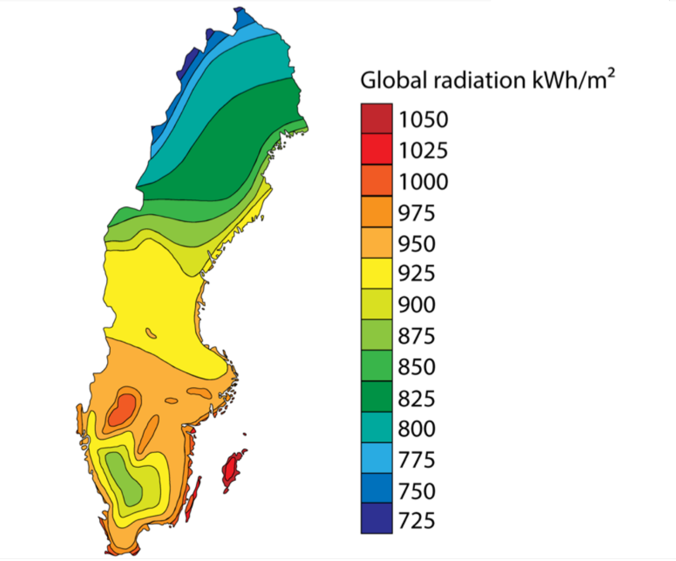
Table 11. Results chemical exposure in foods. Climate change-associated drivers, responses, and consequent influence on chemical exposure for environmental contaminants in food. Arrows pointing up (↑) indicate an increase and arrows pointing down (↓) indicate a decrease of the exposure risk; a pointy symbol (•) indicates no changes in the exposure.

Climate Change-associated driver	Response	Influence on chemical exposure in foods
Higher demand for nutrients and water to irrigate crop fields	Sewage sludge + water on crop fields	↑due to wastewater and sludge containing contaminants (metals and organics)
Higher run-off from land into receiving water bodies driven by increased incidences of extreme rain events	Higher episodic run-off of contaminants to surface water which may contaminate drinking water	↑ increase only local, due to consumption of drinking water
Higher run-off from land into receiving water bodies driven by increased incidences of extreme rain events	Higher episodic run-off of contaminants to surface water which may be taken up by fish	↑ increase only local, due to consumption of fish
Changes in the water balance at the national level	Changes in management of source water for drinking, which could affect PFAS exposure in particular	• No change in uptake of PFAS via drinking water and food (potential for decreases or increases depending on water level changes). We don't anticipate that this will be a strong effect.
Dietary transition to lower meat consumption	Less consumption of POP loaded meat (i.e., pigs and chicken fed with imported soybeans) **and** increased consumption of crops	↓lower exposure due to less meat consumption **and/or** ↑ higher exposure due to increased direct crop consumption

3.7 UV radiation

UV radiation in Sweden currently follows a slight upward trend. From the mid-1980s until 2018, there has been an increase of 8% in average solar radiation[246], and this trend is likely to continue in the future (Fig. 8A+B). Under this scenario of increasing UV radiation, the usage of sunscreens in Sweden is likely to increase, with corresponding increased human exposure to the chemicals contained in sunscreen formulations.

A



B

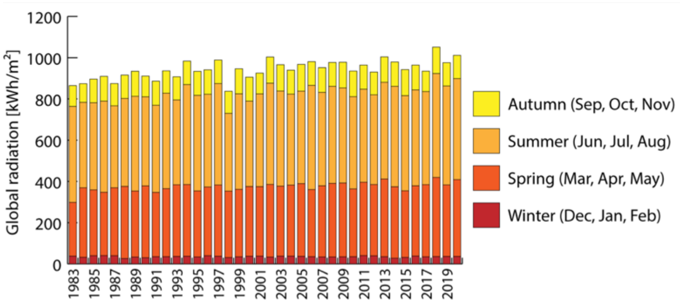


Figure 8 Global solar radiation in Sweden. **A.** Global solar radiation in Sweden in one year. Figure adapted from Lindahl and Stoltz (2018) by SMHI [196]. **B.** The development of global solar radiation in Sweden from eight weather stations. Figure adapted from Lindahl et al. (2018) [196].

Two types of sunscreens exist, physical and chemical. Physical or mineral sunscreens reflect UV radiation and act as a physical barrier. Active ingredients used in physical sunscreens contain titanium dioxide and/or zinc oxide[197]. Both titanium dioxide and zinc oxide are considered to be safe for the human skin[198]. On the contrary, chemical sunscreens absorb UV light and contain other active ingredients, such as avobenzone, ensulizole, homosalate, octinoxate, octisalate, octocrylene, or oxybenzone[197]. These substances can all be systemically absorbed by the human skin and exceed the safety threshold (plasma concentration > 0.05 ng/mL) set by the U.S Food & Drug Administratraion[199].

If the use of sunscreens increases, the concentration of their residuals will increase in freshwater systems when people spend time in the water for recreational purposes[200]. For example, commonly used UV filters in sunscreens, such as avobenzone (CAS No. 70356-09-1) and octocrylene (CAS No. 6197-30-4)[201,202] have been found in the environment and have been shown to bioaccumulate in marine life, be transported through the food chain, and expose humans who consume recreationally caught fish[203–205].

Exposure to chemical ingredients contained in sunscreens occurs via dermal uptake[206]. A recent study confirmed the dermal uptake of avobenzone and octocrylene via sunscreen use in human skin[207]. Dermal uptake of chemical compounds from sunscreen products may cause allergies and other potential adverse health effects. For example, the dermal uptake of oxybenzone-based (oxybenzone and benzophenone-2) sunscreen can have adverse effects in animals causing mortality, feeding, and motion behaviour[208]. Other sunscreens, e.g., non-nano-titanium dioxide (TiO_2) products, show less severe effects in animal studies (i.e., only temporary disrupted motion behaviour) and may function as a suitable replacement [208].

The absorption of sunscreen chemicals may be enhanced when concurrently applied with insect repellent spray[206]. With rising temperatures, the European geographical distribution of mosquitoes and other pathogens will expand and, concurrently, increase its population and lifespan, therefore, feeding on humans is likely to increase, too[6,209]. Consequently, it is likely that the usage and application of insect repellent may increase and, with it, induce higher dermal allergy rates[210,211] in the Swedish population and potentially higher dermal absorption of sunscreen chemicals.

In summary, with the changing climate, UV radiation is slightly increasing in Sweden, which is likely to lead to higher usage of sunscreen[212], which will increase the exposure to sunscreens through dermal absorption[202]. Additionally, mosquitoes and other human feeding parasites are becoming more abundant due to the warmer climate, which likely will increase the application of insect repellent on the skin. (Tab. 12). However, the magnitude and pace of climate change impacts on UV radiation and insect abundance in Sweden is not expected to be large. It seems likely that public attitudes and regulations related to the use of sunscreen and insect repellents, will be a more important driver of trends in their use among the Swedish population than climate change (e.g.,[213]).

Table 12. Results UV radiation. Climate change-associated drivers, responses, and consequent influence on chemical exposure for UV radiation. Arrows pointing up (↑) indicate an increase in the exposure.

Climate Change-associated driver	Response	Influence on chemical exposure in UV radiation
Gradual increase in UV radiation	Increase in sunscreen application	↑ exposure to chemical sunscreens through dermal uptake
Increase in abundance of mosquitoes and other pathogens feeding on human	Increase in application/usage of insect repellents	↑ exposure to insect repellents, particularly when applied with sunscreen simultaneously

4. RESULTS

4.1 Scenarios

The outcomes of the literature review of potential drivers of change in chemical exposure related to climate change (section 3) were used to identify the most relevant exposure pathways for the Swedish population, i.e., exposure through indoor air, drinking water, food and consumption and the use of sunscreen products. For each of these pathways, three possible scenarios for human exposure to chemicals in Sweden have been elaborated. The scenarios are based on the Shared Socioeconomic Pathways (SSPs), a scenario framework used for global change research[214]. The SSPs were defined as reference pathways to depict plausible alternative situations in the development of ecosystems and society over the period of a century[214]. The first scenario (SSP1) *Taking the Green Road*, simulates a global community that has developed into a sustainable society with sustainable and equal use of common resources. SSP1 comprises low challenges to mitigation and adaptation due to climate change. The second scenario (SSP2) describes medium challenges to mitigation and adaption and relays to *Taking the Middle of the Road*, the third scenario (SSP3) compares to *Taking the Highway* in a fossil-fuel development with high challenges to mitigation and high challenges to adaptation[215]. The scenarios are dependent upon and defined by the measures that the world takes to reduce greenhouse gas emissions.

4.1.1 Drinking water

The drinking water in Sweden is obtained from both surface water and groundwater[216]. Approximately 2000 municipal and 3000 private waterworks supply the public and commercial facilities with drinking water[216]. Various authorities, companies, and producers are required to facilitate a safe drinking water supply to Sweden´s population[216].

With the changing climate, Sweden is likely to suffer from more floods and droughts in the future. Floods may transport chemical contaminants into groundwater and surface water. More frequently occurring droughts raise the mobilisation of heavy metals and leakage to groundwater. Depending on the extent of the changing climate, the consequences of human exposure to chemicals in the environment may vary.

4.1.1.1 SSP 1: Sustainability – Taking the Green Road

In a scenario of sustainable development, measures to manage waste and potential leakage of hazardous materials from industrial sites and densely populated areas during flooding events have been adopted. At the same time, measures to increase the percentage of treated surface runoff would have been implemented, as well as solutions to avoid wastewater overflow events in urban areas. Measures to protect surface water from pulsed contaminant transport during, e.g., pesticide application, have been implemented. Under this scenario, a shift towards a higher percentage of organic farming would have taken place, reducing the risk of exposure to pesticides potentially mobilised to surface and groundwater. Even if the effects of the changing climate would have been attenuated under this scenario, occasional droughts and floods will occur and events of remobilization of chemical pollutants into the surface, and groundwater will need to be managed.

4.1.1.2 SSP 2: Taking the Middle of the Road

Climate change will gradually cause more and stronger rain events and droughts in Sweden than estimated for the mild scenario, leading to the mobilisation of various chemicals and exposure to contaminants, particularly through drinking water. Development towards sustainable use of resources is slow. The effects of climate change on human exposure to chemicals through drinking water may be more unpredictable and variable in time and space due to the higher prevalence of droughts and rainfall but overall is not likely to change considerably compared to today, as measures toward more sustainable systems would be under adoption, however, at a slower pace than needed. Exposure would neither be reduced nor drastically increased either.

4.1.1.3 SSP 3: Fossil-fuelled Development – Taking the Highway

In the event of extensive impact of climate change with prolonged heavy rain and drought events in Sweden, the risk of producing drinking water with poorer quality will increase. No mitigation measures have been adopted, such as increasing the capacity of wastewater treatment plants or adaptation of organic farming. Overflow of wastewater will occur more frequently during heavy rain events if the capacity of treatment plants has not increased. To address the higher need for water, reuse of wastewater will be implemented, leading to the distribution of chemicals on arable land. Extensive rain incidents may transport more chemical pollutants from urban, agricultural and industrialised areas to surface and groundwater. Also, droughts that occur more frequently are more likely to mobilise metals from soil to surface water. Waterworks need to manage increased loads of potentially harmful chemicals (i.e., pesticides, heavy metals) in water used for the production of drinking water. In the case of heavy precipitation incidents, more and greater landslides may occur in areas in which landslides have not yet been predicted. In the case of a landslide in an area of an idled landfill, the risk of even higher surface water contamination will increase.

4.1.2 Food

Food produced in Sweden covers a wide range from locally grown crops, animals held for meat and milk production, and luxury food production (e.g., chocolates, cookies). Pesticide usage is forecast to increase due to climate change, leading to higher human exposure through consumption of contaminated crops. Chemical uptake via food can be influenced by pesticide treatment of crops and is foreseen to increase with climate change. With increasing pesticide application in the future, it can be expected that human exposure to pesticides will increase.

4.1.2.1 SSP 1: Sustainability – Taking the Green Road

In this scenario, the Swedish and international community manage common resources in a sustainable and equitable manner. Measures to minimize food waste have been implemented, putting less pressure on agriculture and reducing the need for pesticides and veterinary drugs. The Swedish population has shifted towards a more plant-based diet, thereby reducing exposure to chemicals from the imported feed. Upstream measures to reduce chemicals entering wastewater treatment plants have been enforced. Sewage sludge can thereby be applied to arable land as part of the development of a circular economy without increasing human exposure to chemicals. Measures that were implemented to protect drinking water from contamination due to runoff events will also prevent contaminants from entering aquatic food webs during heavy rainfall.

4.1.2.2 SSP 2: Taking the Middle of the Road

Climate change will gradually cause more and stronger rain events in Sweden. These will lead to higher exposure to chemicals transported from land to drinking water, and to aquatic food webs and eventually fish. The higher demand for agriculture, in combination with poor development of sustainable solutions for chemical use and management, will lead to chemical exposure through the reuse of sludge on arable land.

4.1.2.3 SSP 3: Fossil-fuelled Development – Taking the Highway

Climate change will have an extensive impact in Sweden, with prolonged heavy rain and drought events as consequences. This will lead to increased transport of chemicals by runoff to surface water and aquatic food webs. Pesticide use in agriculture will continue to increase. Reuse of sewage sludge and wastewater on agricultural land will need to be implemented to meet the demands of agriculture in a changing climate.

This will lead to higher exposure to chemicals through food when no mechanisms, e.g., adding additional treatment steps in wastewater treatment plants, are in place to reduce chemicals to enter these facilities plants.

4.1.3 The indoor environment

As described in section 3.1, with the warming climate an increasing demand for energy efficient buildings is expected and the number of air-conditionings in private households is likely to increase[217]. This may translate into lower ventilation rates in buildings in the future. With poorer ventilation practices in buildings, indoor emissions and concentrations of chemicals are likely to increase. Additionally, extreme weather events such as wildfires or coldwaves will drive the population (particularly vulnerable sub-groups such as elderly and children) to spend more time indoors, which will increase their exposure to contaminants indoor.

4.1.3.1 SSP 1: Sustainability – Taking the Green Road

Under this scenario more sustainable construction materials and furnishings will be adopted, avoiding hazardous substances such as VOCs or flame-retardants, resulting in reduced exposure indoor. At the same time, under this scenario the world would have adopted measures to prevent temperature rising further and therefore extreme weather events, for example, elevated temperatures during the summer periods, will not be as extreme and/or will be lasting for shorter time periods. In these circumstances, buildings will be more likely to be sufficiently ventilated, rendering indoor air safer.

4.1.3.2 SSP 2: Taking the Middle of the Road

In a medium case scenario, slow progress is made to achieve changes regarding the usage and production patterns of construction materials. The transition to more sustainable construction materials and furnishing is undergoing. This transition in itself limits the exposure to hazardous substances in the indoor environment, but it is still not sufficient to improve the average indoor air quality in buildings. Regarding temperatures, the rising trend is slowly stabilised but not sufficient to avoid occasional heatwaves or coldwaves, which slightly will increase the time spent indoors and, therefore, the exposure to potential chemicals present in the indoor environment. Trends in the installation of air-conditioning devices in people's homes increase slightly, and consequently, ventilation with open windows is reduced.

4.1.3.3 SSP 3: Fossil-fuelled Development – Taking the Highway

In the case of extreme heat events, the risk of indoor chemical exposure elevates drastically. No change toward sustainability and extreme weather events has been implemented. Forest fires will increase in frequency and intensity, consequently leading to an urban air quality decline, and more time will be spent indoors, which will lead to a higher exposure.

4.1.4 Usage of sunscreen and insect repellent products

With a warming climate, the population is likely to spend more time during the summer outside in the direct sunlight. The usage of sunscreen and sun blockers will increase, leading to an increase in dermal uptake of its ingredients. Additionally, the geographic distribution of mosquitos occurring in Sweden has changed due to the warming climate, introducing more disease-carrying mosquito[218] and tick[219] species to Sweden. With the rising temperatures, the areas suitable for mosquitoes will expand up to the North of Sweden by 2050 and, thus, will facilitate the expansion of insects and other disease-carrying vector species further[220].

One of the most important protections against mosquitoes- or tick-borne diseases is the use of repellents[221]. Even though natural repellents (essential oils) are available on the market, synthetic repellents (Ethyl Butylacetylaminopropionate, Icaridin) are preferred by the user, as they are longer lasting and more effective[221]. The most effective and mostly used repellent is N,N-dimethyl-3-methylbenzamide (DEET), which is also the most toxic component for the user[221]. For protection, the application of dermal repellent products in Sweden will increase, leading to higher dermal uptake of sunscreen ingredients when applied simultaneously. Yet, mitigation options regarding sunscreen usage are low for the society and depend on regulatory decisions.

Human exposure to chemicals in sunscreen and insect repellents in Sweden could change in response to climate change, but changes in exposure are likely to be dominated by trends in public attitudes towards the use of these products. Public health information campaigns aimed at increasing sunscreen use, or regulation of insect repellent chemicals of concern are more likely to determine changes in exposure in the future than climate change-related drivers.

4.2 Population groups at risk

The evaluated risks refer to the general population but minor groups of the population, e.g., children or socio-economically disadvantaged groups, are especially susceptible to some of those risks as summarised and explained in Tab. 13.

Table 13. Some of the chemicals and chemical groups the Swedish population may be exposed to in the future. The chemicals were selected to illustrate changes in future exposure due to climate change. Note that this is not a comprehensive list of chemicals the population will be exposed to in the future.

Chemical (group)	Exposure pathway	Population groups at risk	Reason
Heavy metals	Drinking water	Population living near closed landfills	Mobilization by floodwaters or landslides and insufficient treatment capacity of local waste water treatment plants
Heavy metals	Consumption of cereals, potatoes	Socio-economically disadvantaged sub-populations; general population	Lower access to organic and locally produced foods of higher price
Dioxins	Consumption of lipid-rich fish caught in the Baltic Sea or the larger lakes in the south	Consumers of lipid-rich fish (e.g., herring) caught in the Baltic Sea	Higher consumption of lipid-rich fish caught in the Baltic Sea
Pesticides (residues)	Cereal, vegetables, fruit, meat (animals fed with contaminated food)	Socio-economically disadvantaged sub-populations; general population	Lower access to organic and locally produced foods of higher price
SVOCs	Indoor air, ingestion of dust	Children	Higher access to the source
VOCs	Indoor air	General population	Spending time indoors
Sunscreen chemicals	Dermal uptake via sunscreen/contaminated water bodies	General population; particularly children	Increased use of sunscreens and of surface water in recreational areas

5. CONCLUDING REMARKS AND RECOMMENDATIONS

The impact of climate change on the exposure of chemicals in the environment is likely to be non-linear, which stresses the importance of identifying thresholds in the particular areas of concern[7]. Banning particular chemicals (e.g., the pesticide DDT at the beginning of the 1970s) can be an effective measure to lower contamination levels in humans, but for persistent chemicals the time-scale for reversing exposure is decades or longer[222]. Thus, exposure to some chemicals can commit the population to a long period of exposure that is poorly reversible.

The number of chemicals available on the global market exceeds the capacity for risk assessment worldwide, and the production volume and diversity of chemicals has been increasing exponentially for decades[223]. In Europe, there is an initiative to transition to a circular economy by 2050[181], which requires that products can be efficiently recycled. The trends of exponentially increasing chemical production and diversity of chemicals in commerce are not compatible with transitioning to a circular economy[224].

Ultimately, population-level exposure to chemicals is determined by the amounts of chemicals that are used and released by society. The challenge of transitioning to a circular economy requires a transformational change in how chemicals are used in Europe. If such a change is realized through aggressive regulatory action before 2050, it will have a much more dramatic effect on human exposure to chemicals than any of the impacts of climate change on chemical exposure that are described in this report. However, in reality it is likely that neither transformational actions that fully address climate change nor that fully address the requirements for chemical production and use to achieve circular economy will be realized before 2050. Therefore, we recommend further development of scenarios that consider alternative policy and societal development pathways for both climate change mitigation and regulation of chemicals production and use to achieve circular economy. Such an analysis would provide a more quantitative assessment of policy alternatives to address the two "Grand Challenges of Environmental Sciences"[225] posed by climate change and unsustainable use of materials.

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