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3 **A spatial assessment of current and future foliar Hg**
4 **uptake fluxes across European forests**

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10 **Key Points:**

- 11 • Extreme hot and dry atmospheric conditions have the potential to reduce stom-
- 12 atal uptake of ambient mercury by pine trees in Europe
- 13 • Atmospheric drought controls on stomatal mercury uptake should be accounted
- 14 for in mercury transport models like GEOS-Chem
- 15 • Forest foliar mercury uptake fluxes to Europe from a bottom-up model generally
- 16 agree well with results derived from literature and GEOS-Chem

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Abstract

Atmospheric mercury (Hg) is deposited to land surfaces mainly through vegetation uptake. Foliage stomatal gas exchange plays an important role for net vegetation Hg uptake, because foliage assimilates Hg via the stomata. Here, we use empirical relationships of foliar Hg uptake by forest tree species to produce a spatially highly resolved (1 km²) map of foliar Hg fluxes to European forests over one growing season. The modelled forest foliar Hg uptake flux is 23 ± 12 Mg Hg season⁻¹, which agrees with previous estimates from literature.

We spatially compare forest Hg fluxes with modelled fluxes of the chemistry-transport model GEOS-Chem and find a good overall agreement. For European pine forests, stomatal Hg uptake was shown to be sensitive to prevailing conditions of relatively high ambient water vapor pressure deficit (VPD). We tested a stomatal uptake model for the total pine needle Hg uptake flux during four previous growing seasons (1994, 2003, 2015/2017, 2018) and two climate change scenarios (RCP 4.5 and RCP 8.5). The resulting modelled total European pine needle Hg uptake fluxes are in a range of 8.0 - 9.3 Mg Hg season⁻¹ (min - max). The lowest pine forest needle Hg uptake flux to Europe (8 Mg Hg season⁻¹) among all investigated growing seasons is associated with unusually hot and dry ambient conditions in the European summer 2018, highlighting the sensitivity of the investigated flux to prolonged high VPD. We conclude, that stomatal modelling is particularly useful to investigate changes in Hg deposition in the context of extreme climate events.

1 Introduction

Mercury (Hg) is a toxic pollutant that is transported globally through the atmosphere and deposited from air to land surfaces mainly through vegetation uptake of ambient gaseous elemental Hg(0) (Demers et al., 2013; Jiskra et al., 2015; Enrico et al., 2016; Obrist et al., 2017; Feinberg et al., 2022). Consequently, vegetation uptake has the potential to lower atmospheric Hg(0) transport and Hg deposition to oceans, where Hg can be methylated and bioaccumulated in marine seafood for human consumption (Zhou et al., 2021). In order to assess and improve the effectiveness of mitigation policies for human exposure, it is thus necessary to constrain environmental drivers of vegetation Hg(0) uptake. Furthermore, process understanding of vegetation Hg(0) uptake is essential for assessing future human Hg exposure in the context of global change (Sonke et al., 2023).

Global vegetation and soil uptake of Hg(0) has been estimated to amount to 2850 ± 500 Mg year⁻¹ (Obrist et al., 2021; Zhou et al., 2021; Feinberg et al., 2022), exceeding approximate direct anthropogenic emissions to the air of 2200 Mg Hg year⁻¹ (Sonke et al., 2023). Forests contain 80 % of the global plant biomass (Pan et al., 2013), therefore representing a major vector for Hg(0) drawdown from the atmosphere. In forests, half of the total Hg(0) net deposition is estimated to be stored in tree foliage, while the other half is estimated to be transferred to vascular tissues (e.g. stem, branches, roots), or taken up by understory vegetation (e.g. shrubs, grasses) or nonvascular plants (lichen and mosses) (Zhou et al., 2021; Obrist et al., 2021; Zhou & Obrist, 2021). In tree foliage, Hg concentrations increase linearly between foliage emergence and senescence (Rea et al., 2002; Laacouri et al., 2013; Blackwell et al., 2014; Wohlgemuth et al., 2020; Pleijel et al., 2021) implying a net foliar Hg deposition flux, albeit Hg re-emission from foliar surfaces of up to 30% of gross foliage Hg(0) deposition had been observed in a subtropical forest in China (W. Yuan, Sommar, et al., 2019). The bulk (90-96%) of Hg is stored in foliage tissues as opposed to leaf surfaces and correlates with leaf stomatal density (Laacouri et al., 2013). Studies on Hg stable isotopes in foliage (Demers et al., 2013; Zhou et al., 2021), enriched isotope tracer experiments (Rutter et al., 2011) and the vertical variation of net foliar Hg uptake in forest canopies (Wohlgemuth et al., 2020) strongly suggest a diffusive uptake pathway of atmospheric Hg(0) to foliage interiors via the stomata (Liu et al., 2021). In this way, foliar Hg(0) uptake is linked to foliage stomatal aperture for atmospheric gas exchange (Wohlgemuth et al., 2022).

69 Trees regulate foliage stomatal aperture to balance the inward diffusion of CO₂ for
70 photosynthesis with the risk of desiccation caused by excessive outward diffusion of wa-
71 ter vapor (Körner, 2013). The degree of stomatal aperture depends on atmospheric CO₂
72 levels and hydrological conditions (soil water availability and atmospheric evaporative
73 demand) and varies among foliage-specific traits (age, tree species-specific evolutionary
74 metabolic strategy and water use efficiency) (Körner, 2013). Pine, for instance, is an iso-
75 hydric tree species capable of closing foliage stomata under warm and dry atmospheric
76 conditions relatively early compared to tree species like oak and spruce (Lagergren & Lin-
77 droth, 2002; Zweifel et al., 2007, 2009), resulting in a reduced stomatal conductance for
78 pine needle diffusive gas exchange (Panek & Goldstein, 2001). Consistently, Hg(0) up-
79 take rates by pine needles in Europe were found to be lower at forest sites across Europe,
80 where prolonged warm and dry atmospheric conditions prevailed over a given growing
81 season during daytime (Wohlgemuth et al., 2022).

82 Species-specific stomatal response strategies to meteorological conditions are par-
83 ticularly relevant for projections of future foliar Hg uptake under climate change. Increas-
84 ing global atmospheric temperatures driven by rising levels of greenhouse gases will re-
85 sult in an increased frequency of droughts (Grossiord et al., 2020) and higher soil mois-
86 ture deficits (Berg & Sheffield, 2018; Stocker et al., 2019) in various regions of the world.
87 These climatic conditions may decrease foliar Hg(0) uptake fluxes due to lower stomatal
88 conductance (Wohlgemuth et al., 2022). A reduced plant Hg sink could further be am-
89 plified by deforestation and forest diebacks, particularly in the tropics (Allen et al., 2015;
90 Brando et al., 2019; Feinberg et al., 2023). Other regions of the world are projected to
91 become wetter through an increase in precipitation rates under climate change (IPCC,
92 2021a), which might lead to higher foliage stomatal conductance relative to the present
93 and thus higher foliar Hg uptake. With continuing anthropogenic carbon emissions, an
94 elevated atmospheric CO₂ level might have an antagonizing effect on the foliar stomatal
95 Hg(0) uptake flux: foliar Hg(0) uptake could decline with decreasing stomatal conduc-
96 tance under CO₂ fertilization (Norby & Zak, 2011), or, the opposite, the vegetation sink
97 for Hg(0) could increase with intensified biomass growth and higher soil C contents (Hararuk
98 et al., 2013; Jiskra et al., 2018; H. Zhang et al., 2016). In order to make projections of
99 the foliar Hg uptake flux in the next decades, these climate change impacts need to be
100 further investigated and potentially implemented into global and regional Hg cycle mod-
101 els.

102 Current and future Hg fluxes are modelled in Global Chemical Transport Models
103 (CTMs). CTMs like GEOS-Chem (Selin et al., 2008) apply resistance-based algorithms
104 (Wesely, 2007) for modelling Hg(0) deposition fluxes from the atmosphere to vegetated
105 ecosystems and are often based on parameters like leaf area indices (LAIs), temperature
106 and wind speed. The resistance components for leaf stomata within CTMs commonly
107 represent consensus values optimized to fit observations of Hg deposition velocities over
108 vegetated surfaces (Selin et al., 2008; L. Zhang et al., 2009; Smith-Downey et al., 2010;
109 H. Zhang et al., 2016), without taking stomatal feedback to environmental conditions
110 into account (Wu et al., 2011; Khan et al., 2019). Consequently, forest tree species-specific
111 stomatal responses to climate change at foliage level are not parameterized in CTMs.
112 An additional problem related to CTMs is the uncertainty of modelled Hg(0) deposition
113 fluxes due to insufficient model evaluation against dry deposition measurements (Feinberg
114 et al., 2022). This issue of model validation was highlighted in a recent revision of GEOS-
115 Chem parameterization after matching the GEOS-Chem model design to various exper-
116 imental Hg(0) deposition measurements, which resulted in a doubling of the modelled
117 global flux of Hg(0) dry deposition to land compared to previous model outcomes (Feinberg
118 et al., 2022).

119 In this study, we assess the spatial variation of forest foliar Hg uptake fluxes across
120 Europe by producing a spatially highly resolved map of foliar Hg uptake fluxes to Eu-
121 ropean forests using a bottom-up model that incorporates pine tree stomatal responses
122 to climate conditions. We compare these spatially resolved fluxes to forest dry deposi-
123 tion fluxes modelled in GEOS-Chem in order to identify spatial discrepancies between

124 GEOS-Chem and the bottom-up model used here. We investigate the sensitivity of an
 125 empirical stomatal response model of pine to different climatic conditions during past
 126 growing seasons and for two climate change projections of the years 2068 - 2082 in or-
 127 der to outline the potential of incorporating a stomatal response function into CTMs.

128 2 Materials and Methods

129 2.1 Description of datasets

130 For creating maps of foliar and pine needle Hg uptake fluxes in Europe applying
 131 a bottom-up model (Sect. 2.2 and 2.3), we drew on multiple data sources:

- 132 • **Foliar Hg data.** A dataset of foliar Hg uptake rates was derived from Hg mea-
 133 surements in foliage of tree canopies at 272 forest sites of the UNECE International
 134 Co-operative Programme on Assessment and Monitoring of Air Pollution Effects
 135 on Forests (ICP Forests). Forest sites are mostly located in Central and North-
 136 ern Europe (+ 737 sites in Austria from the Austrian Bio-Indicator Grid) and har-
 137 monized foliage sampling methods were employed. All foliage samples within this
 138 dataset were harvested at the end of the growing seasons 2015 or 2017. Therefore,
 139 average foliage values of 2015/2017 constitute reference values of forest foliar Hg
 140 uptake fluxes relative to respective fluxes during investigated years of this study.
 141 The dataset is publicly available and contains 3569 foliar Hg concentrations of 23
 142 tree species and is described in detail in (Wohlgemuth et al., 2022).
- 143 • **Meteorological data.** Values on ambient temperature and relative humidity at
 144 surface air pressure (1000 hPa) in Europe (spatial resolution: 0.25° x 0.25°) ori-
 145 ginate from ERA5 hourly reanalysis data and were downloaded from the Coperni-
 146 cus Climate Data Store (Hersbach et al., 2018). The applied time frame includes
 147 hourly daytime (07:00 - 18:00 LT) values during the respective growing seasons
 148 (April - October) of 1994, 2003, 2015, 2017, and 2018.
- 149 • **Climate change data.** Regional climate simulation data of air temperature and
 150 relative humidity at 2 m above surface level for the years 2068 - 2082 and two dif-
 151 ferent climate change scenarios (Representative Concentration Pathway (RCP)
 152 4.5 and RCP 8.5 (IPCC, 2021b)) were obtained from the Coordinated Regional
 153 Climate Downscaling Experiment (CORDEX) (Jacob et al., 2020) framework for
 154 the European domain with a spatial resolution of 0.11° x 0.11° and a temporal res-
 155 olution of 3hourly daytime (09:00 - 18:00 LT) values. For representing a range of
 156 different climate model outputs, we calculated average values from multiple re-
 157 gional climate models (RCMs) downscaled from global climate models (GCMs)
 158 depending on availability for download from the Copernicus Climate Data Store
 159 (C3S, 2022). In total, we incorporated data of 15 combinations of 4 RCMs and
 160 6 GCMs for RCP 4.5 and of 13 combinations of 6 RCMs and 8 GCMs for RCP
 161 8.5 (see Table SI 3) for an overview of models and ensemble members).
- 162 • **European tree species distribution.** We used a map of spatial proportions of
 163 tree species groups per km² land area from (Brus et al., 2012). For use in calcu-
 164 lating pine foliar Hg uptake fluxes (see Sect. 2.3), we summed up spatial relative
 165 abundance values of *Pinus sylvestris*, *Pinus pinaster*, *Pinus nigra* and *Pinus halepen-*
 166 *sis* from European forest inventories (Mauri et al., 2017; Buras & Menzel, 2019)
 167 and multiplied these pine relative abundances with the respective total forest area
 168 per km² derived from (Brus et al., 2012) to obtain pine areal proportions. We per-
 169 formed the same calculation (sum of values of *Pinus sylvestris*, *Pinus pinaster*, *Pi-*
 170 *nus nigra* and *Pinus halepensis* and subsequent multiplication with respective to-
 171 tal forest area) to estimate the distribution of pine in Europe under climate change
 172 using relative abundance probabilities projected from climate analogues for the
 173 time period 2061 - 2090 and RCP 4.5 and RCP 8.5 by (Buras & Menzel, 2019).

174 • **Leaf Area Indices (LAIs) and Leaf Mass per Area (LMA) values.** We
 175 used the LAI satellite product (spatial resolution: 330 m) of PROBA-V (Dierckx
 176 et al., 2014; Fuster et al., 2020) to upscale foliar Hg uptake rates at each ICP Forests
 177 site to foliar Hg uptake fluxes (see Sect. 2.2), along with average LMA values per
 178 tree species from (Forrester et al., 2017).

179 2.2 Calculation of forest foliage Hg uptake fluxes

180 We determined forest foliar Hg uptake fluxes to European forests on a 1 km² spa-
 181 tial resolution applying three basic computational steps: 1) calculation of tree species-
 182 specific daily Hg uptake fluxes per m² ground area using a bottom-up model; 2) upscal-
 183 ing of respective foliar Hg fluxes per tree species to the European forested area using the
 184 areal distribution of corresponding tree species; 3) multiplication of daily forest foliar Hg
 185 uptake fluxes per latitude with latitude-dependent growing season length in order to ob-
 186 tain the forest foliar Hg uptake fluxes over one growing season.

187 Computational step 1) is based on the premise, that foliar Hg uptake rates are tree
 188 species-specific (Laacouri et al., 2013; Wohlgemuth et al., 2022; Pleijel et al., 2021). For
 189 this reason, we calculated median daily foliar Hg uptake fluxes per tree species group (see
 190 Table SI 2 for details) of all forest sites from the foliar Hg dataset (Sect. 2.1). The bottom-
 191 up modeling approach for calculating daily foliar Hg uptake fluxes from daily foliar Hg
 192 uptake rates is described in detail in Wohlgemuth et al., (2020) (Wohlgemuth et al., 2020).
 193 Briefly, daily foliar Hg uptake rates per gram foliage dry weight (units of ng Hg g_{d.w.}⁻¹ d⁻¹)
 194 were multiplied with tree species-specific LMA values (Sect. 2.1) to obtain daily foliar
 195 Hg uptake rates per foliage surface area (ng Hg m_{leaf}⁻² d⁻¹). Subsequently, values of daily
 196 foliar Hg uptake rates per foliage surface area are multiplied with values of LAI (m_{leaf}²
 197 m_{ground}⁻²; Sect. 2.1), resulting in daily foliar Hg fluxes per unit ground area (ng Hg m_{ground}⁻²
 198 d⁻¹). LAI values of coniferous forests are relatively constant during the active growing
 199 season after the initial growth phase of current-season needles (R. Wang et al., 2017),
 200 while LAI values of temperate deciduous forests increase rapidly at the beginning of the
 201 growing season (leaf flushing) and climax at peak season (June – August, northern hemi-
 202 sphere) (Q. Wang et al., 2005). For coniferous tree species, we used the maximum LAI
 203 value during the constant period at each forest site of the ICP Forests dataset to cal-
 204 culate needle foliar Hg uptake fluxes. For deciduous tree species, we calculated foliar Hg
 205 uptake fluxes as a temporal sequence at every LAI value available over the growing sea-
 206 son and subsequently used median foliar Hg uptake flux values of the growing season.
 207 For LAI values larger than 3, we applied a species-specific tree height correction factor,
 208 to account for lower foliar Hg uptake fluxes of shaded leaves in the lower canopy (Wohlgemuth
 209 et al., 2020) (refer to Table SI 1 for utilized tree height correction factors). For conifer-
 210 ous species, we multiplied Hg uptake fluxes of current-season needles with a species-specific
 211 needle age correction factor to account for lower Hg uptake rates of older needle age classes
 212 (Wohlgemuth et al., 2020) (refer to Table SI 1 for utilized needle age correction factors).

213 Computational step 2) involves the multiplication of the proportion of each tree
 214 species per km² land area with the respective species-specific median daily foliar Hg up-
 215 take fluxes. We matched tree species-specific Hg data with the areal forest distribution
 216 of the respective tree species (Brus et al., 2012). In the few cases of rare European tree
 217 species, where specific Hg data was lacking, we pooled Hg or forest distribution data by
 218 tree species group (see Table SI 2 for an overview of matched tree species groups between
 219 the two datasets). Subsequently, we added up all tree species-specific daily foliar Hg up-
 220 take fluxes within each km² and obtained one forest foliar daily Hg uptake flux per km².

221 In computational step 3) we calculated forest foliar Hg uptake fluxes per km² and
 222 one growing season by multiplying each daily foliar Hg uptake flux per km² with the grow-
 223 ing season length in days following a simple latitudinal model (CLRTAP, 2017). The lat-
 224 itudinal model of growing season determines a growing season length of 192 days at lat-
 225 itude 50° and decreases by 3.5 days per 1° of latitude moving north and increases by 3.5
 226 days per 1° of latitude moving south.

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2.3 Calculation of pine foliar Hg uptake fluxes

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Daily foliar Hg uptake rates of pine tree species were calculated taking into account the empirical dependence of needle Hg uptake fluxes to atmospheric VPD. Pine needle daily Hg uptake rates (upR_{pine} ; $\text{ng Hg g}_{\text{d.w.}}^{-1} \text{ d}^{-1}$) were found to be lower at forest sites, where the daytime fraction of water VPD > 1.2 kPa during the respective sample life period ($\text{proportion}_{\text{dayVPD}} > 1.2\text{kPa}$) was relatively high (Wohlgemuth et al., 2022). The negative correlation of pine needle Hg uptake with timespan of elevated atmospheric VPD was explained by a stomatal closure upon VPD threshold exceedance and thus a high stomatal resistance suppressing the diffusive uptake of Hg(0) from the atmosphere. The linear regression of daily foliar Hg uptake rates with $\text{proportion}_{\text{dayVPD}} > 1.2$ kPa is: $\text{upR}_{\text{pine}} = 0.116 - 0.13 \times (\text{proportion}_{\text{dayVPD}} > 1.2 \text{ kPa})$ (Wohlgemuth et al., 2022). We applied this linear relationship to calculate the pine foliar Hg uptake rates of the forest area of Europe during four different growing seasons in 1994, 2003, an average of 2015 and 2017, 2018, and projected for the time period 2068 - 2082 under RCP 4.5 and RCP 8.5 (IPCC, 2021b). We calculated hourly or 3hourly daytime VPD values from ERA5 (Hersbach et al., 2018) or CORDEX data (Sect. 2.1) on surface temperature and relative humidity using the Auguste-Roche-Magnus formula (W. Yuan, Zheng, et al., 2019) and subsequently determining the fraction of daytime hours when the VPD was above the threshold of 1.2 kPa over the respective latitudinal growing season length. Calculations with climate data were performed at sciCORE scientific computing center at University of Basel. We defined growing season length per latitude using a latitudinal model ((CLRTAP, 2017), see Sect. 2.2). In 2068 - 2082 we assumed the beginning of the growing season to be 3 days earlier and the end of the growing season to be 3 days later to take increases in growing season length under climate change into account (Jeong et al., 2011; Garonna et al., 2014). The underlying areal distribution of pine is based on European forest inventories and projections of pine abundances based on climate analogues under RCP 4.5 and RCP 8.5 by (Buras & Menzel, 2019) (see Sect. 2.1).

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2.4 GEOS-Chem forest deposition flux calculation

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GEOS-Chem is a global 3-D chemistry transport model, which includes a comprehensive Hg cycle (Selin et al., 2008). Table 1 gives an overview of the methodological approach and input parameters for calculating the respective Hg fluxes of GEOS-Chem and the bottom-up model (Sect. 2.2), which we compared spatially in this study.

Table 1. Caption

	bottom-up model	GEOS-Chem
model input parameters	spatial forest distribution (Brus et al., 2012); leaf area indices (LAIs) (Dierckx et al., 2014; Fuster et al., 2020); leaf mass per area (LMA) (Forrester et al., 2017); meteorological parameter: daytime VPD (Hersbach et al., 2018); foliar Hg uptake rates (Wohlgemuth et al., 2022)	spatial forest distribution (Gibbs, 2006); leaf area indices (LAIs) (H. Yuan et al., 2011); atmospheric Hg(0) levels (GEOS-Chem v12.8.1 simulation 2015); meteorological parameters: air temperature, pressure, solar radiation, cloud cover, wind speed (GEOS-FP) (Lucchesi, 2018)
spatial resolution	1 km x 1 km	0.25 x 0.3125°
basic methodological approach for Hg flux calculation	spatial upscaling of measured foliar Hg uptake rates (Wohlgemuth et al., 2020)	in-series calculation of Hg dry deposition velocity from parameterized resistance values (Wesely, 2007)
foliage stomatal Hg uptake flux component	calculated for pine based on daytime vapor pressure deficit (VPD) values (Sect. 2.3)	calculated within the canopy resistance component as a function of land type, leaf area indices (LAIs), and solar radiation
model output compared in this study	tree-species specific forest foliar Hg(0) uptake fluxes	Hg(0) dry deposition fluxes to coniferous and deciduous forest land cover

259 We used an offline version of the GEOS-Chem dry deposition code (Feinberg, 2022)
260 to be able to calculate dry deposition velocities at higher resolution and only for certain
261 land use types (i.e., forest areas). The offline dry deposition code computes deposition
262 velocities using a resistance-based approach (Y. Wang et al., 1998; Wesely, 2007). In-
263 put variables (Table 1) are gridded hourly GEOS-FP meteorological data for (e.g., air
264 temperature, wind speed, solar radiation, and cloud cover) and weekly LAI values based
265 on MODIS (H. Yuan et al., 2011) for the year 2015. The model calculates the Hg(0) dry
266 deposition velocity based on species-specific parameters including its biological reactiv-
267 ity ($f_0 = 10^{-5}$) and Henry's Law Constant ($H^* = 0.11 \text{ M atm}^{-1}$). To isolate the uptake
268 of Hg(0) to forests, we calculated the dry deposition velocity only over coniferous and
269 deciduous land cover types from the Olson land map (Gibbs, 2006). The offline calcu-
270 lations output hourly dry deposition velocities over the European domain at $0.25 \times 0.3125^\circ$
271 resolution. We converted the calculated Hg(0) deposition velocities to fluxes by multi-
272 plying with hourly surface Hg(0) concentrations from a GEOS-Chem v12.8.1 simulation
273 for 2015. For this study, we compared the GEOS-Chem Hg(0) dry deposition fluxes to
274 forests with foliar Hg(0) uptake fluxes calculated using the bottom-up model. For both
275 models, Hg fluxes were averaged over the latitude-dependent growing season length in
276 days and cropped to the same spatial extent. As GEOS-Chem and the bottom-up model
277 differ in their geographic resolution (GEOS-Chem: $0.25^\circ \times 0.31^\circ \sim 955 \text{ km}^2$ vs. bottom-
278 up: 1 km^2), we downsampled daily forest foliar Hg uptake fluxes from the bottom-up
279 model through bilinear interpolation.

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2.5 Uncertainty analysis of foliar Hg uptake fluxes

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The relative uncertainty value per tree species group depended on propagated uncertainties of calculation parameters used to derive the respective foliar Hg uptake flux per tree species group (see Table SI 4 for details and values). Subsequently, we calculated one relative uncertainty value per geographic tile of our European flux map (Fig. 1) by summarizing the relative uncertainty of each foliar Hg uptake flux per tree species group within each tile according to error propagation principles (Ku, 1966; Papula, 2003). We obtained the relative uncertainty for the total foliar Hg uptake flux to European forests (Fig. 1) by propagating all relative uncertainty values per tile. The final relative uncertainty value of total foliar Hg uptake flux to European forests and the reference growing seasons 2015/2017 is 0.52.

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3 Results and Discussion

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3.1 Spatial distribution of forest foliar Hg uptake fluxes across Europe

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Figure 1 visualizes forest foliar Hg uptake fluxes per growing season at a spatial resolution of 1 km^2 ($\text{g Hg km}^{-2} \text{ season}^{-1}$) in Europe. Forest foliar Hg uptake fluxes generally follow a spatial distribution of European forests, because this map (Fig. 1) is based on the proportion of forest tree species per land area (Brus et al., 2012). Consequently, the largest forest foliage Hg uptake fluxes in terms of area are on the Scandinavian Peninsula with dense forest land cover. Outside of Scandinavia, forest foliage Hg uptake fluxes fall along large contiguous forested areas, e.g. in the Carpathian Mountains, the South-Eastern Alps, the Balkans, or forested low mountain areas like the Black Forest.

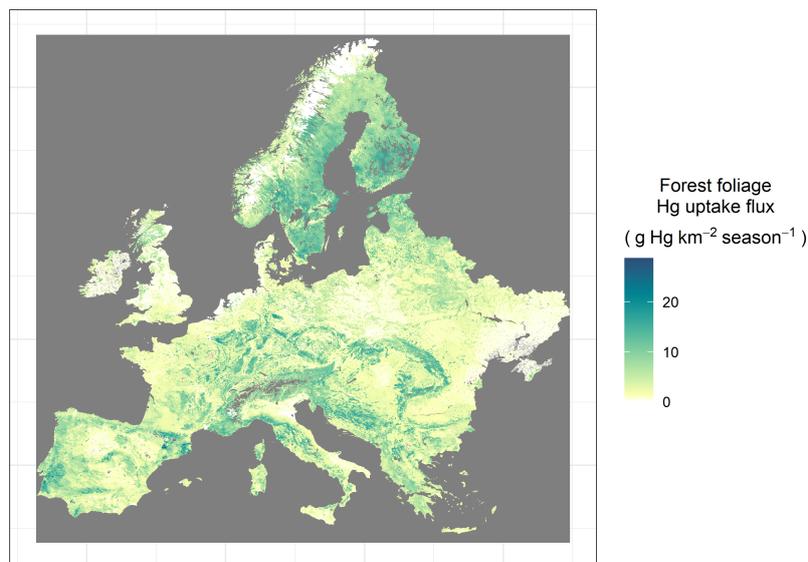


Figure 1. Spatial distribution of forest foliar Hg uptake fluxes ($\text{g Hg km}^2 \text{ growing season}^{-1}$) to Europe based on a bottom-up extrapolation of foliar Hg concentrations, that were measured and averaged over the 2015 and 2017 growing seasons. Dark grey areas represent excluded non-forested areas (e.g. surface waters or non-vegetated mountain areas).

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The sum of forest foliar Hg uptake fluxes over the land area of Europe as displayed in Figure 1 equals $23 \pm 12 \text{ Mg Hg season}^{-1}$. This total flux agrees within uncertainty

303 with a previous estimate for the total foliar Hg uptake flux to Europe of 20 ± 3 Mg Hg
304 over the 2018 growing season based on foliar Hg uptake fluxes at four forested sites (Wohlgemuth
305 et al., 2020). (Zhou & Obrist, 2021) evaluated a median global foliar Hg assimilation of
306 28 Mg yr^{-1} for deciduous broadleaf forests and 61 Mg yr^{-1} for evergreen needleleaf forests
307 by combining foliar Hg concentrations with annual net foliar biomass production data
308 of the respective forest types. From these global assimilation estimates by (Zhou & Obrist,
309 2021), we calculated a total foliar Hg assimilation of 29 Mg yr^{-1} to the deciduous and
310 coniferous forest land area of Europe (for details see SI, Text S1), which is slightly higher
311 but still within the uncertainty of the $23 \pm 12 \text{ Mg Hg season}^{-1}$ from this study. How-
312 ever, foliar Hg uptake fluxes based on net primary foliar biomass production by Zhou
313 and Obrist, (2021) (Zhou & Obrist, 2021) does not correct for lower foliar Hg uptake rates
314 by shade leaves and multiyear old needles (see Sect. 2.2) relative to sun leaves and younger
315 needles (Wohlgemuth et al., 2020), likely resulting in a systematic over-estimation. We
316 assume, that the different time reference (seasonal vs. annual) of the flux from this study
317 ($23 \pm 12 \text{ Mg Hg season}^{-1}$) and the flux derived from Zhou and Obrist, (2021) (Zhou &
318 Obrist, 2021) (29 Mg Hg yr^{-1}) only plays a minor role for explaining the difference be-
319 tween the two fluxes, since we expect a small net foliar biomass production in Europe
320 in winter outside of the growing season.

321 **3.2 Pine foliar Hg uptake fluxes under different VPD scenarios**

322 Figure 2 shows total pine forest foliar Hg uptake fluxes to Europe calculated un-
323 der different conditions of atmospheric surface-level water VPD during four past grow-
324 ing seasons (1994, 2003, 2015/2017, 2018) and simulated for the years 2068 - 2082 as an
325 average of multiple climate model outputs (see Sect. 2.2) under two different climate change
326 scenarios (RCP 4.5 and RCP 8.5). The leftmost bar (Fig. 2) represents a theoretical base-
327 line pine needle Hg uptake flux in absence of VPD induced stomatal control (potential
328 maximum transpiration rates) on the pine needle Hg uptake flux. The total pine nee-
329 dle Hg uptake flux to Europe during the reference growing season 2015/2017 (Sect. 2.2)
330 is $9.3 \pm 3.7 \text{ Mg Hg}$ representing 70% of the baseline flux of $13.3 \pm 5.3 \text{ Mg Hg season}^{-1}$.
331 Thus, based on the pine needle Hg uptake model used in this study (Sect. 2.3), the VPD
332 effect reduces the total pine needle Hg uptake flux to Europe by approximately 30%.

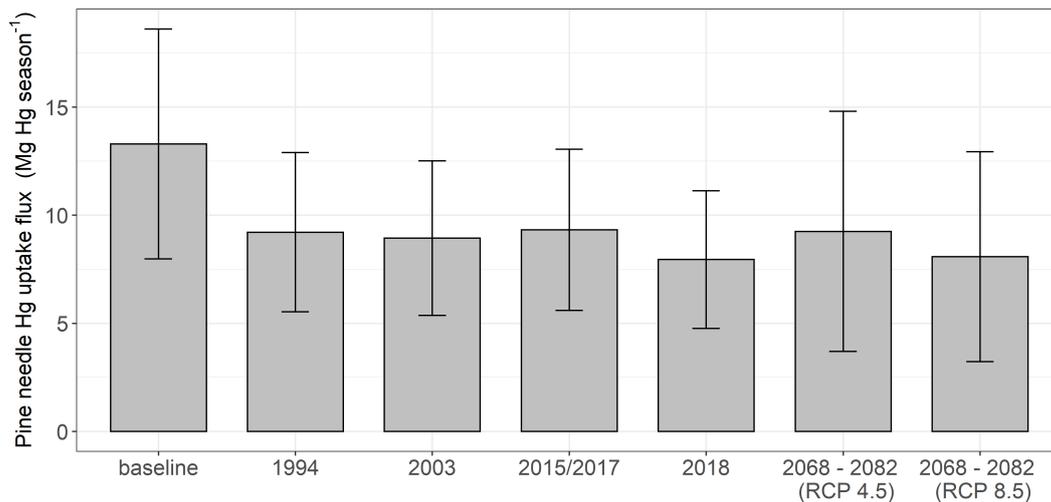


Figure 2. Pine needle Hg uptake flux to European pine forests (Mg Hg season^{-1}) calculated from atmospheric surface water vapor pressure deficit (VPD) conditions during the growing seasons 1994, 2003, 2015/2017, 2018 and projected for the years 2068 - 2082 under RCP 4.5 and RCP 8.5. Bar on the left represents a baseline pine forest needle Hg uptake flux with no VPD exceedance of 1.2 kPa throughout the growing season.

333 The relative standard deviation of modelled total pine needle Hg uptake fluxes for
 334 the investigated growing seasons (1994, 2003, 2015/2017, 2018, 2068 - 2082) was 0.07.
 335 Consequently, modelled total European pine needle Hg uptake fluxes hardly differed from
 336 each other among growing seasons. The total pine needle Hg uptake flux in Europe depend
 337 on VPD conditions in areas where pine forests prevail. Pine forests are primarily
 338 located in Northern Europe (SI Fig. 1), where hourly ambient VPD was > 1.2 kPa during
 339 30% or less of daytime in the growing seasons 1994, 2003 and 2015/2017 due to relatively
 340 cool and moist ambient conditions as compared to Central and Southern Europe
 341 (see e.g. VPD conditions during reference time period 2015/2017 Fig. 3a). In contrast
 342 to previous years, the European summer hydrological condition of 2018 has been described
 343 as an intense hot drought, during which pronounced stomatal closure of coniferous forests
 344 in response to high VPD were recorded in Switzerland (Gharun et al., 2020). In Southern
 345 Fennoscandia, conditions of ambient hourly VPD > 1.2 kPa prevailed over exceptionally
 346 long time proportions (around 40%) during the summer of 2018 (see Fig. 3b,
 347 (Buras et al., 2020)). As a result, the modelled total pine needle Hg uptake flux in Europe
 348 in 2015/2017 ($9.3 \text{ Mg Hg season}^{-1}$) was by a factor of 1.16 higher than the respective
 349 flux in 2018 ($8.0 \text{ Mg Hg season}^{-1}$). We conclude that hot and dry summer conditions
 350 (Fig. 2) in Fennoscandia crucially impact modelled past total pine needle Hg uptake
 351 fluxes in Europe. According to the model results, an average amount of 1.3 Mg Hg
 352 was not deposited via pine needle uptake in 2018 compared to 2015/17, potentially remaining
 353 in the atmosphere, where it can be long-range transported to the ocean (Zhou et al., 2021).
 354 These 1.3 Mg Hg are more than three times larger than the reported anthropogenic Hg emissions
 355 of Sweden in 2021 ??, highlighting the quantitative impact, that hot droughts can have on the
 356 pine needle Hg uptake flux.

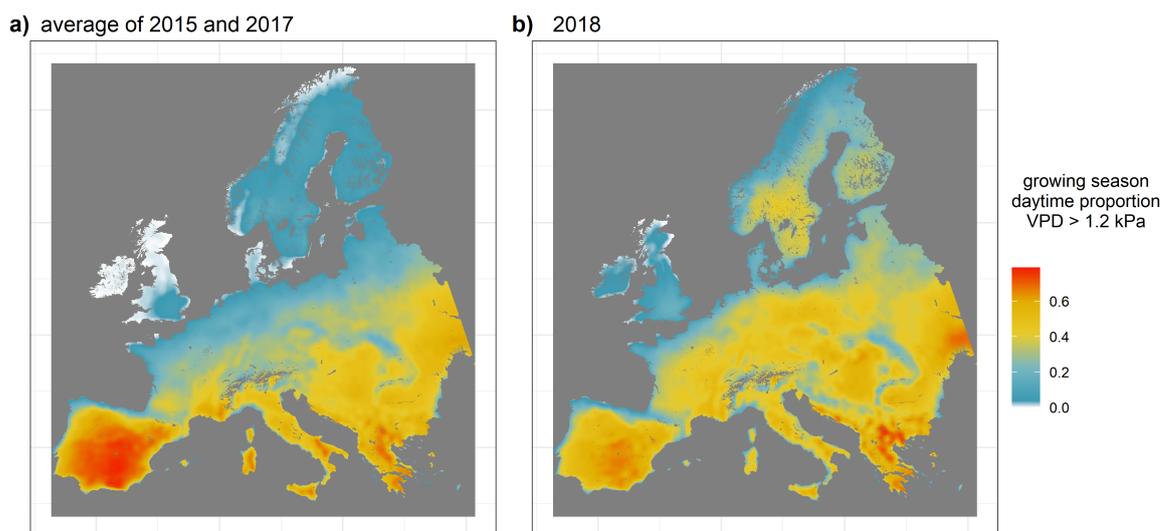


Figure 3. Average daytime proportion of surface level atmospheric water VPD > 1.2 kPa during a) the reference growing season 2015/2017, and b) the growing season 2018. All VPD values were calculated from hourly reanalysis data of ERA5 ambient air temperature and relative humidity (Sect. 2.1).

3.3 Projected pine forest needle Hg uptake fluxes under climate change scenarios

The projected total pine forest needle Hg uptake flux for 2068 - 2082 (RCP 4.5: 9.3 ± 5.5 Mg Hg season⁻¹; RCP 8.5: 8.1 ± 4.9 Mg Hg season⁻¹) was in the same range as the corresponding average flux for the years 1994, 2003, 2015 and 2017 of 9.1 ± 0.2 Mg Hg season⁻¹ (mean \pm sd), but slightly higher than the corresponding flux in the year of 2018 (8.0 ± 3.2 Mg Hg season⁻¹), during which Fennoscandia experienced a summer of relatively long hot and dry ambient conditions. Figure 4 maps the absolute deviation of the pine forest needle Hg uptake flux projected for 2068 - 2082 (simulated future flux) from the corresponding 2018 flux in Europe. Under RCP 4.5, the simulated future flux is higher (blue area in Fig. 4 a) than the 2018 flux in 65% of total area. Under RCP 8.5, the simulated future flux is higher (blue area in Fig. 4 b) than the 2018 flux in 43% of total area. In most area of Fennoscandia, where a majority of pine forests in Europe are located (SI Fig. 1a), the future flux is projected to be larger than in 2018. For both climate change scenarios, the projection predicts lower pine needle Hg fluxes to the Balkans and to the Southern Iberian Peninsula than in 2018 (Fig. 4).

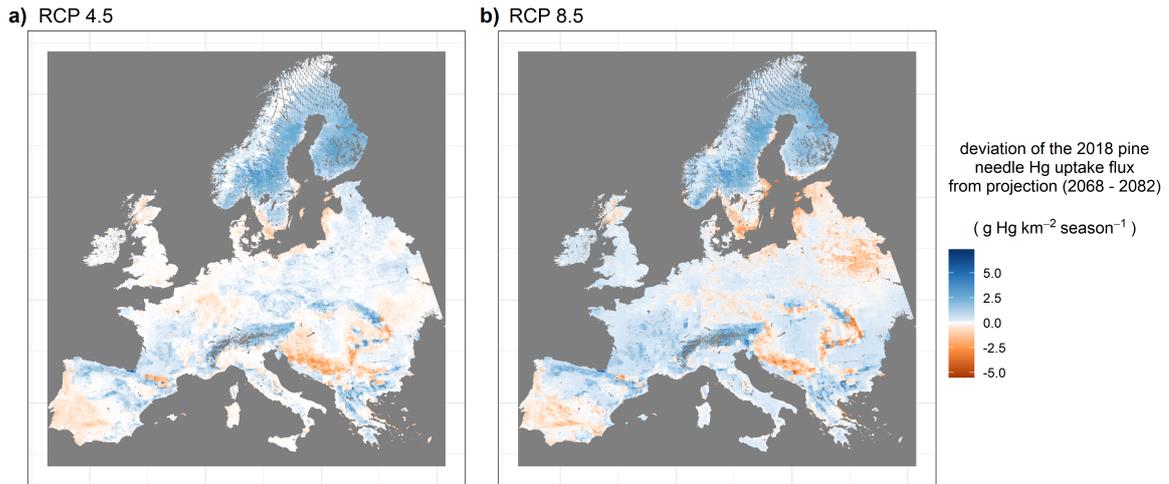


Figure 4. Absolute deviation of projected pine forest foliar Hg uptake fluxes for 2068 - 2082 (under RCP 4.5 (a) and RCP 8.5 (b)) from the corresponding flux modelled for 2018. In blue areas, the projected future flux under the two climate change scenarios is higher than the respective 2018 flux, in orange areas, this deviation is reversed.

373 The pine forest needle Hg uptake flux for 2068 - 2082 simulated here is a function
 374 of both modelled ambient VPD conditions during the growing season and the projected
 375 distribution of pine forests in Europe depending on climate analogs (Buras & Menzel,
 376 2019). While the pine forest cover in Southern Sweden is projected to decrease under
 377 the climate change scenarios RCP 4.5 and RCP 8.5 from around $50\% \text{ km}^{-2}$ to around
 378 $25\% \text{ km}^{-2}$, forest cover in Central and Northern Fennoscandia is projected to be relatively
 379 steady for climate analogs of both climate change scenarios (compare SI Fig. 1 a
 380 - c). Average long-term precipitation rates are projected to increase in Scandinavia, along
 381 with a decrease of meteorological drought in the coming decades under different climate
 382 change scenarios (Forzieri et al., 2014; Samaniego et al., 2018; Kellomäki et al., 2018),
 383 which could result in an increase of atmospheric humidity and a decrease of VPD in north-
 384 ern Europe (Oksanen et al., 2019). Under this scenario of wetter forest environments,
 385 the Hg sink of Scandinavian pine forest needles would not be significantly diminished.
 386 However, drought trends in Fennoscandia are still inconsistent and extreme drought events
 387 like in 2018 might occur more frequently under the current rate of climate change (IPCC,
 388 2021a). The summer of 2018 was a record hot drought in Europe (Buras et al., 2020),
 389 while climate simulations for 2068 - 2082 are averaged over multiple climate models (SI
 390 Table 3), possibly averaging out extreme events. In a scenario, where the maximum pro-
 391 portion of daytime VPD $> 1.2 \text{ kPa}$ per growing season averaged over 2068 - 2082 pre-
 392 vails at each spatial unit, the total pine forest needle Hg uptake flux to Europe reduces
 393 to $6.9 \text{ Mg Hg season}^{-1}$ for RCP 4.5 and $5.0 \text{ Mg Hg season}^{-1}$ for RCP 8.5, which cor-
 394 responds to 74% and 62% of the respective flux derived from an average VPD daytime
 395 proportion. We therefore suggest that extreme climate events of extended time periods
 396 of ambient daytime VPD $> 1.2 \text{ kPa}$ like during the growing season 2018 (Fig. 3b) could
 397 reduce the pine forest needle Hg uptake flux in Fennoscandia in future even compared
 398 to average long-term VPD projections (Fig. 4).

399 A source of model uncertainty of the future forest foliar Hg uptake flux under cli-
 400 mate change arises from atmospheric Hg(0) concentrations that depend on anthropogenic
 401 emissions, re-emissions of mobilized legacy Hg and future global deposition fluxes un-
 402 der climate and land use change (Sonke et al., 2023; Feinberg et al., 2023), which we could
 403 not account for in this study. However, our model outputs call attention to the sensi-

404 tivity of the pine needle Hg uptake flux to extreme hot and dry ambient conditions, which
 405 should be accounted for in chemistry-transport models under varying atmospheric Hg(0)
 406 levels. The impact of the hot and dry conditions on the pine Hg uptake fluxes might have
 407 implications for Hg inputs into aquatic ecosystems. In a recent review on Hg cycling in
 408 the context of global change, (Sonke et al., 2023) highlighted the potential of legacy Hg
 409 (i.e. actively cycling Hg that was mobilized in the past) to cause contamination by mobilization
 410 of Hg from soils to wetlands and coastal ecosystems via riverine systems. While
 411 most soil Hg enters riverine systems by soil erosion from agricultural lands, contaminated
 412 sites, and deforested woodland (Panagos et al., 2021; Sonke et al., 2023), a reduced forest
 413 foliar Hg uptake and subsequent deposition to forest soils may decrease the amount
 414 of runoff Hg from forest soils in the long-term, while long-range Hg transport to the open
 415 ocean via the atmosphere might be enhanced (Zhou et al., 2021).

416 3.4 Comparison of bottom-up model with GEOS-Chem

417 Figure 5 depicts spatial ratios of daily forest Hg uptake fluxes of the bottom-up model
 418 to GEOS-Chem. Absolute difference values of the two model outputs are shown in SI
 419 Fig. 2.

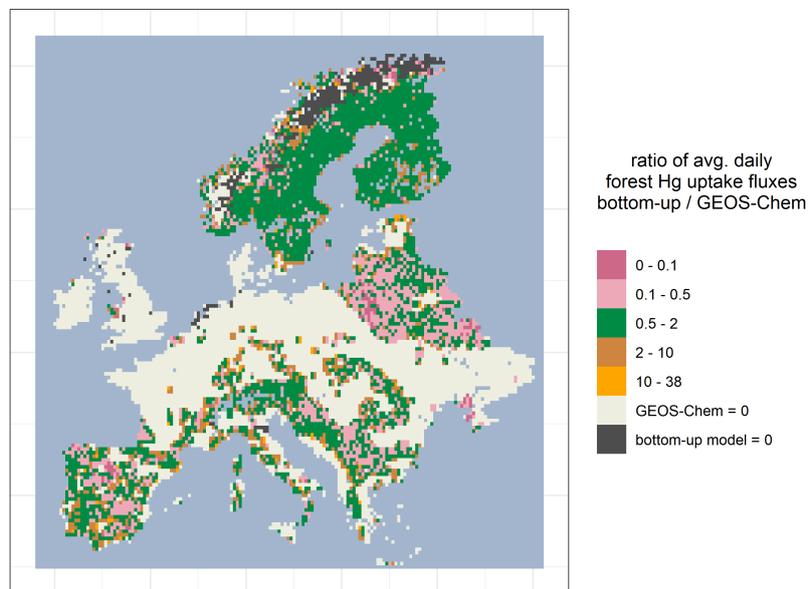


Figure 5. Ratios per spatial unit of daily forest Hg uptake fluxes averaged over the latitude-specific growing season length of the bottom-up model to GEOS-Chem.

420 Results of average daily foliar Hg uptake fluxes from GEOS-Chem and the bottom-
 421 up model were geographically comparable: In 59% of the spatial domain with values >
 422 0, average daily foliar Hg uptake fluxes from the two models differed by factor of 1 - 2
 423 from each other, in 37% of the domain, model values differed by a factor of 2 - 10 from
 424 each other, and in 4% of the domain respective values differed by a factor of > 10 from
 425 each other (Fig 5). We examined if differences in modelled average daily foliar Hg uptake
 426 fluxes at the same geographic location originate from differences in the underlying
 427 forest distribution maps of the two compared models. In 78% of spatial tiles with values
 428 > 0, the ratio of average daily foliar Hg uptake fluxes of the bottom-up model to GEOS-
 429 Chem agreed in range (Fig. 5) with the ratio of the forest fraction of the bottom-up model

430 to GEOS-Chem per respective spatial tile. We thus hypothesize that the bottom-up model
431 and GEOS-Chem generally produce similar foliar Hg flux values per spatial unit given
432 the same forest distribution. Reasons for minor differences in model outputs are chal-
433 lenging to identify, since the two models are based on different approaches, parameters
434 and underlying maps (Sect. 2.4). For future assessment of model accuracy, we therefore
435 suggest to compare model results to actual measurements of the forest foliar Hg uptake
436 flux (Obrist et al., 2021; Feinberg et al., 2022). The total foliar Hg uptake flux to the
437 European forested area (Fig. 1 and 5) was 22 Mg Hg season⁻¹ for GEOS-Chem which
438 almost equals the total flux of 23 ± 12 Mg Hg season⁻¹ for the bottom-up model (Sect.
439 3.1).

440 4 Conclusion

441 We created a highly resolved (1 km²) map (Fig. 1), which visualizes the spatial vari-
442 ation of foliar Hg uptake fluxes to European forests. The highest foliar Hg uptake fluxes
443 receive Fennoscandia, densely forested areas in Central and Southern Europe, e.g. the
444 Carpathian Mountains, the Balkans, or multiple low mountain areas. We suggest, that
445 this map (Fig. 1) can guide decisions on European background Hg monitoring of the ter-
446 restrial environment. The total forest foliar Hg uptake flux over the course of one grow-
447 ing season agrees well with Hg flux estimates derived from literature and from the chem-
448 ical transport model GEOS-Chem for the same land area of Europe (Fig. 5). This pre-
449 cision among modelling results on a European scale using different approaches gives us
450 confidence that the bottom-up model is overall able to represent the seasonal forest fo-
451 liar Hg uptake flux. We suggest that the accuracy of modelling results have to be fur-
452 ther determined using direct forest foliar Hg flux measurements.

453 Using an empirical relationship between Hg needle uptake rates of pine trees and
454 VPD threshold exceedance, we found a reduction in modelled pine forest needle Hg up-
455 take flux during the relatively hot and dry growing season in Fennoscandia in 2018 com-
456 pared to the growing seasons in 1994, 2003 and 2015/2017 (Fig. 2). The modelled av-
457 erage amount of Hg, that was not deposited via pine needle uptake in 2018 compared
458 to the reference time period of 2015/17 exceeded the reported anthropogenic Hg emis-
459 sions of Sweden in 2021, highlighting the quantitative significance of stomatal Hg up-
460 take. If these hot summer droughts occurred more frequently in Fennoscandia under cli-
461 mate change, the pine forest needle Hg uptake flux would be diminished while these ex-
462 treme conditions prevail, potentially increasing the Hg burden of the ocean via long-range
463 atmospheric transport. In order to better represent the impact of extreme climate events
464 on the pine forest needle Hg uptake flux, we therefore advise to incorporate a stomatal
465 component of the pine needle Hg uptake flux into chemical transport models like GEOS-
466 Chem.

467 5 Open Research

468 Calculated forest foliar Hg uptake fluxes to Europe (Fig. 1) and GEOS-Chem sim-
469 ulation data aggregated to seasonal values are publicly available for download from Zen-
470 do at <https://zenodo.org/record/7851718#.ZFUeLM5Bw2w> and <https://zenodo.org/record/7900753#.ZFUgqM5Bw2w> respectively. All input datasets to the bottom-up model
471 are described in detail in Section 2.1, along with their respective publications and databases,
472 from which the datasets can be accessed. The offline dry deposition code from GEOS-
473 Chem is accessible for download (Feinberg, 2022) and model output data from GEOS-
474 Chem can be obtained from the corresponding author upon request. All calculations and
475 visualizations were done in R, Version 4.0.3.
476

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References

- Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), art129. Retrieved 2021-10-22, from <https://onlinelibrary.wiley.com/doi/abs/10.1890/ES15-00203.1> doi: 10.1890/ES15-00203.1
- Berg, A., & Sheffield, J. (2018, June). Climate Change and Drought: the Soil Moisture Perspective. *Curr Clim Change Rep*, *4*(2), 180–191. Retrieved 2021-10-22, from <https://doi.org/10.1007/s40641-018-0095-0> doi: 10.1007/s40641-018-0095-0
- Blackwell, B. D., Driscoll, C. T., Maxwell, J. A., & Holsen, T. M. (2014, June). Changing climate alters inputs and pathways of mercury deposition to forested ecosystems. *Biogeochemistry*, *119*(1-3), 215–228. Retrieved 2020-03-10, from <http://link.springer.com/10.1007/s10533-014-9961-6> doi: 10.1007/s10533-014-9961-6
- Brando, P. M., Paolucci, L., Ummenhofer, C. C., Ordway, E. M., Hartmann, H., Cattau, M. E., ... Balch, J. (2019, May). Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis. *Annu. Rev. Earth Planet. Sci.*, *47*(1), 555–581. Retrieved 2021-10-22, from <https://www.annualreviews.org/doi/10.1146/annurev-earth-082517-010235> doi: 10.1146/annurev-earth-082517-010235
- Brus, D. J., Hengeveld, G. M., Walvoort, D. J. J., Goedhart, P. W., Heidema, A. H., Nabuurs, G. J., & Gunia, K. (2012, January). Statistical mapping of tree species over Europe. *European Journal of Forest Research*, *131*(1), 145–157. Retrieved 2019-08-26, from <http://link.springer.com/10.1007/s10342-011-0513-5> doi: 10.1007/s10342-011-0513-5
- Buras, A., & Menzel, A. (2019). Projecting Tree Species Composition Changes of European Forests for 2061–2090 Under RCP 4.5 and RCP 8.5 Scenarios. *Frontiers in Plant Science*, *9*, 1986. Retrieved 2021-09-22, from <https://www.frontiersin.org/article/10.3389/fpls.2018.01986> doi: 10.3389/fpls.2018.01986
- Buras, A., Rammig, A., & Zang, C. S. (2020, March). Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences*, *17*(6), 1655–1672. Retrieved 2021-12-07, from <https://bg.copernicus.org/articles/17/1655/2020/> doi: 10.5194/bg-17-1655-2020
- C3S. (2022). Copernicus Climate Change Service, Climate Data Store (CDS): CORDEX regional climate model data on single levels. Retrieved from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.bc91edc3?tab=overview> doi: 10.24381/cds.bc91edc3

- 530 CLRTAP. (2017). Revised Chapter 3 of the Manual on Methodologies and Cri-
 531 teria for Modelling and Mapping Critical Loads and Levels and Air Pol-
 532 lution Effects, Risks and Trends: Mapping Critical Levels for Vegetation.
 533 *Umweltbundesamt*. Retrieved from [https://www.umweltbundesamt.de/en/](https://www.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels)
 534 [manual-for-modelling-mapping-critical-loads-levels](https://www.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels) doi: [https://www](https://www.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels)
 535 [.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels](https://www.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels)
- 536 Demers, J. D., Blum, J. D., & Zak, D. R. (2013, March). Mercury isotopes in a
 537 forested ecosystem: Implications for air-surface exchange dynamics and the
 538 global mercury cycle. *Global Biochem. Cy.*, *27*(1), 222–238. Retrieved 2018-
 539 11-14, from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/gbc.20021)
 540 [gbc.20021](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/gbc.20021) doi: 10.1002/gbc.20021
- 541 Dierckx, W., Sterckx, S., Benhadj, I., Livens, S., Duhoux, G., Van Achteren, T.,
 542 ... Saint, G. (2014, April). PROBA-V mission for global vegetation
 543 monitoring: standard products and image quality. *Int. J. Remote Sens.*,
 544 *35*(7), 2589–2614. Retrieved 2021-08-30, from [https://doi.org/10.1080/](https://doi.org/10.1080/01431161.2014.883097)
 545 [01431161.2014.883097](https://doi.org/10.1080/01431161.2014.883097) doi: 10.1080/01431161.2014.883097
- 546 Enrico, M., Roux, G. L., Maruszczak, N., Heimbürger, L.-E., Claustres, A., Fu, X.,
 547 ... Sonke, J. E. (2016, March). Atmospheric mercury transfer to peat bogs
 548 dominated by gaseous elemental mercury dry deposition. *Environ. Sci. Tech-*
 549 *nol.*, *50*(5), 2405–2412. Retrieved 2019-06-20, from [http://pubs.acs.org/](http://pubs.acs.org/doi/10.1021/acs.est.5b06058)
 550 [doi/10.1021/acs.est.5b06058](http://pubs.acs.org/doi/10.1021/acs.est.5b06058) doi: 10.1021/acs.est.5b06058
- 551 Feinberg, A. (2022). Code reference: arifein/offline-drydep: Offline dry deposition
 552 model from GEOS-Chem v1.0 (v1.0).
 553 doi: <https://doi.org/10.5281/zenodo.6498126>
- 554 Feinberg, A., Dlamini, T., Jiskra, M., Shah, V., & E. Selin, N. (2022). Eval-
 555 uating atmospheric mercury (Hg) uptake by vegetation in a chemistry-
 556 transport model. *Environmental Science: Processes & Impacts*. Retrieved
 557 2022-07-25, from [https://pubs.rsc.org/en/content/articlelanding/](https://pubs.rsc.org/en/content/articlelanding/2022/em/d2em00032f)
 558 [2022/em/d2em00032f](https://pubs.rsc.org/en/content/articlelanding/2022/em/d2em00032f) (Publisher: Royal Society of Chemistry) doi:
 559 10.1039/D2EM00032F
- 560 Feinberg, A., Jiskra, M., Borrelli, P., Biswakarma, J., & Selin, N. E. (2023, Jan-
 561 uary). Land use change as an anthropogenic driver of mercury pollution. Re-
 562 trieved 2023-04-15, from <https://eartharxiv.org/repository/view/4963/>
 563 (Publisher: EarthArXiv)
- 564 Forrester, D. I., Tachauer, I. H. H., Annighoefer, P., Barbeito, I., Pretzsch, H., Ruiz-
 565 Peinado, R., ... Sileshi, G. W. (2017, July). Generalized biomass and leaf area
 566 allometric equations for European tree species incorporating stand structure,
 567 tree age and climate. *Forest Ecology and Management*, *396*, 160–175. Re-
 568 trieved 2020-06-10, from [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S0378112717301238)
 569 [pii/S0378112717301238](http://www.sciencedirect.com/science/article/pii/S0378112717301238) doi: 10.1016/j.foreco.2017.04.011
- 570 Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., & Bianchi, A. (2014,
 571 January). Ensemble projections of future streamflow droughts in Europe.
 572 *Hydrology and Earth System Sciences*, *18*(1), 85–108. Retrieved 2021-12-17,
 573 from <https://hess.copernicus.org/articles/18/85/2014/> (Publisher:
 574 Copernicus GmbH) doi: 10.5194/hess-18-85-2014
- 575 Fuster, B., Sánchez-Zapero, J., Camacho, F., García-Santos, V., Verger, A., La-
 576 caze, R., ... Smets, B. (2020, January). Quality assessment of PROBA-V
 577 LAI, fAPAR and fCOVER collection 300 m products of Copernicus Global
 578 Land Service. *Remote Sens.*, *12*(6), 1017. Retrieved 2021-03-17, from
 579 <https://www.mdpi.com/2072-4292/12/6/1017> doi: 10.3390/rs12061017
- 580 Garonna, I., Jong, R. d., Wit, A. J. W. d., Múcher, C. A., Schmid, B., & Schaep-
 581 man, M. E. (2014). Strong contribution of autumn phenology to changes in
 582 satellite-derived growing season length estimates across Europe (1982–2011).
 583 *Glob. Change Biol.*, *20*(11), 3457–3470. Retrieved 2019-10-17, from
 584 <https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.12625> doi:

- 585 10.1111/gcb.12625
- 586 Gharun, M., Hörtnagl, L., Paul-Limoges, E., Ghiassi, S., Feigenwinter, I., Burri,
587 S., ... Buchmann, N. (2020, September). Physiological response of Swiss
588 ecosystems to 2018 drought across plant types and elevation. *Philosophical
589 Transactions of the Royal Society B: Biological Sciences*, 375(1810), 20190521.
590 Retrieved 2023-04-16, from [https://royalsocietypublishing.org/
591 doi/full/10.1098/rstb.2019.0521](https://royalsocietypublishing.org/doi/full/10.1098/rstb.2019.0521) (Publisher: Royal Society) doi:
592 10.1098/rstb.2019.0521
- 593 Gibbs, H. K. (2006). Olson's Major World Ecosystem Complexes Ranked by Carbon
594 in Live Vegetation: an Updated Database Using the GLC2000 Land Cover
595 Product (NDP-017b).
596 doi: <https://www.osti.gov/biblio/1389498>
- 597 Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Sieg-
598 wolf, R. T. W., ... McDowell, N. G. (2020). Plant responses to rising vapor
599 pressure deficit. *New Phytol.*, 226(6), 1550–1566. Retrieved 2020-09-07, from
600 <https://nph.onlinelibrary.wiley.com/doi/abs/10.1111/nph.16485> doi:
601 10.1111/nph.16485
- 602 Hararuk, O., Obrist, D., & Luo, Y. (2013, April). Modelling the sensitivity of
603 soil mercury storage to climate-induced changes in soil carbon pools. *Bio-
604 geosciences*, 10(4), 2393–2407. Retrieved 2021-10-27, from [https://bg
605 .copernicus.org/articles/10/2393/2013/](https://bg.copernicus.org/articles/10/2393/2013/) doi: 10.5194/bg-10-2393-2013
- 606 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J.,
607 ... Thépaut, J.-N. (2018). ERA5 hourly data on pressure levels from 1979
608 to present. Copernicus Climate Change Service (C3S) Climate Data Store
609 (CDS).
610 doi: 10.24381/cds.bd0915c6
- 611 IPCC. (2021a). Climate change 2021. The physical science basis. Working group I
612 contribution to the Sixth Assessment Report of the Intergovernmental Panel
613 on Climate Change.
- 614 IPCC. (2021b). Summary for Policymakers. Climate Change 2021: The Physical
615 Science Basis. Contribution of Working Group I to the Sixth Assessment Re-
616 port of the Intergovernmental Panel on Climate Change. , *Cambride University
617 Press*.
- 618 Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M.,
619 ... Wulfmeyer, V. (2020, April). Regional climate downscaling over Eu-
620 rope: perspectives from the EURO-CORDEX community. *Reg Environ
621 Change*, 20(2), 51. Retrieved 2021-11-03, from [https://doi.org/10.1007/
622 s10113-020-01606-9](https://doi.org/10.1007/s10113-020-01606-9) doi: 10.1007/s10113-020-01606-9
- 623 Jeong, S.-J., Ho, C.-H., Gim, H.-J., & Brown, M. E. (2011). Phenology shifts at
624 start vs. end of growing season in temperate vegetation over the Northern
625 Hemisphere for the period 1982–2008. *Global Change Biology*, 17(7), 2385–
626 2399. Retrieved 2021-12-20, from [https://onlinelibrary.wiley.com/doi/
627 abs/10.1111/j.1365-2486.2011.02397.x](https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2486.2011.02397.x) doi: 10.1111/j.1365-2486.2011
628 .02397.x
- 629 Jiskra, M., Sonke, J. E., Obrist, D., Bieser, J., Ebinghaus, R., Myhre, C. L.,
630 ... Dommergue, A. (2018). A vegetation control on seasonal variations
631 in global atmospheric mercury concentrations. *Nat. Geosci.*, 1–7. Re-
632 trieved from [http:https://doi.org/10.1038/s41561-018-0078-8](http://https://doi.org/10.1038/s41561-018-0078-8) doi:
633 10.1038/s41561-018-0078-8
- 634 Jiskra, M., Wiederhold, J. G., Skyllberg, U., Kronberg, R.-M., Hajdas, I., & Kret-
635 zschmar, R. (2015). Mercury deposition and re-emission pathways in boreal
636 forest soils investigated with Hg isotope signatures. *Environ. Sci. Technol.*,
637 49(12), 7188–7196.
- 638 Kellomäki, S., Strandman, H., Heinonen, T., Asikainen, A., Venäläinen, A., & Pel-
639 tola, H. (2018, March). Temporal and Spatial Change in Diameter Growth

- 640 of Boreal Scots Pine, Norway Spruce, and Birch under Recent-Generation
641 (CMIP5) Global Climate Model Projections for the 21st Century. *Forests*,
642 *9*(3), 118. Retrieved 2021-12-16, from [https://www.mdpi.com/1999-4907/9/](https://www.mdpi.com/1999-4907/9/3/118)
643 [3/118](https://www.mdpi.com/1999-4907/9/3/118) doi: 10.3390/f9030118
- 644 Khan, T., Obrist, D., Agnan, Y., E. Selin, N., & A. Perlinger, J. (2019).
645 Atmosphere-terrestrial exchange of gaseous elemental mercury: parameteriza-
646 tion improvement through direct comparison with measured ecosystem fluxes.
647 *Environmental Science: Processes & Impacts*, *21*(10), 1699–1712. Retrieved
648 2021-10-20, from [https://pubs.rsc.org/en/content/articlelanding/](https://pubs.rsc.org/en/content/articlelanding/2019/em/c9em00341j)
649 [2019/em/c9em00341j](https://pubs.rsc.org/en/content/articlelanding/2019/em/c9em00341j) doi: 10.1039/C9EM00341J
- 650 Ku, H. (1966). Notes on the use of propagation of error formulas. *Journal of Re-*
651 *search of the National Bureau of Standards*, *70C*(4).
- 652 Körner, C. (2013). Plant–Environment Interactions. In A. Bresinsky, C. Körner,
653 J. W. Kadereit, G. Neuhaus, & U. Sonnewald (Eds.), *Strasburger’s Plant*
654 *Sciences: Including Prokaryotes and Fungi* (pp. 1065–1166). Berlin, Hei-
655 delberg: Springer. Retrieved 2019-11-25, from [https://doi.org/10.1007/](https://doi.org/10.1007/978-3-642-15518-5_12)
656 [978-3-642-15518-5_12](https://doi.org/10.1007/978-3-642-15518-5_12)
- 657 Laacouri, A., Nater, E. A., & Kolka, R. K. (2013, September). Distribution and
658 uptake dynamics of mercury in leaves of common deciduous tree species in
659 Minnesota, U.S.A. *Environ. Sci. Technol.*, *47*(18), 10462–10470. Retrieved
660 2019-06-20, from <http://pubs.acs.org/doi/abs/10.1021/es401357z> doi:
661 [10.1021/es401357z](https://doi.org/10.1021/es401357z)
- 662 Lagergren, F., & Lindroth, A. (2002, August). Transpiration response to soil mois-
663 ture in pine and spruce trees in Sweden. *Agr. Forest Meteorol.*, *112*(2), 67–85.
664 Retrieved 2021-08-31, from [https://www.sciencedirect.com/science/](https://www.sciencedirect.com/science/article/pii/S0168192302000606)
665 [article/pii/S0168192302000606](https://www.sciencedirect.com/science/article/pii/S0168192302000606) doi: 10.1016/S0168-1923(02)00060-6
- 666 Liu, Y., Liu, G., Wang, Z., Guo, Y., Yin, Y., Zhang, X., ... Jiang, G. (2021, Octo-
667 ber). Understanding foliar accumulation of atmospheric Hg in terrestrial veg-
668 etation: Progress and challenges. *Critical Reviews in Environmental Science*
669 *and Technology*, *0*(0), 1–22. Retrieved 2021-10-18, from [https://doi.org/10](https://doi.org/10.1080/10643389.2021.1989235)
670 [.1080/10643389.2021.1989235](https://doi.org/10.1080/10643389.2021.1989235) doi: 10.1080/10643389.2021.1989235
- 671 Lucchesi, R. (2018). File Specification for GEOS FP. GMAO Office Note No. 4 (Ver-
672 sion 1.2). Retrieved from http://gmao.gsfc.nasa.gov/pubs/office_notes
- 673 Mauri, A., Strona, G., & San-Miguel-Ayanz, J. (2017, January). EU-Forest, a high-
674 resolution tree occurrence dataset for Europe. *Sci Data*, *4*. Retrieved 2020-01-
675 29, from <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5215058/> doi:
676 [10.1038/sdata.2016.123](https://doi.org/10.1038/sdata.2016.123)
- 677 Norby, R. J., & Zak, D. R. (2011). Ecological Lessons from Free-Air CO₂
678 Enrichment (FACE) Experiments. *Annual Review of Ecology, Evo-*
679 *lution, and Systematics*, *42*(1), 181–203. Retrieved 2021-10-22, from
680 <https://doi.org/10.1146/annurev-ecolsys-102209-144647> doi:
681 [10.1146/annurev-ecolsys-102209-144647](https://doi.org/10.1146/annurev-ecolsys-102209-144647)
- 682 Obrist, D., Agnan, Y., Jiskra, M., Olson, C. L., Colegrove, D. P., Hueber, J., ...
683 Helmig, D. (2017, July). Tundra uptake of atmospheric elemental mercury
684 drives Arctic mercury pollution. *Nature*, *547*(7662), 201–204. Retrieved
685 2019-06-24, from <http://www.nature.com/articles/nature22997> doi:
686 [10.1038/nature22997](https://doi.org/10.1038/nature22997)
- 687 Obrist, D., Roy, E. M., Harrison, J. L., Kwong, C. F., Munger, J. W., Moosmüller,
688 H., ... Commane, R. (2021, July). Previously unaccounted atmospheric mer-
689 cury deposition in a midlatitude deciduous forest. *PNAS*, *118*(29). Retrieved
690 2021-07-26, from <https://www.pnas.org/content/118/29/e2105477118> doi:
691 [10.1073/pnas.2105477118](https://doi.org/10.1073/pnas.2105477118)
- 692 Oksanen, E., Lihavainen, J., Keinänen, M., Keski-Saari, S., Kontunen-Soppela, S.,
693 Sellin, A., & Söber, A. (2019). Northern Forest Trees Under Increasing Atmo-
694 spheric Humidity. In F. M. Cánovas, U. Lüttge, R. Matyssek, & H. Pretzsch

- 695 (Eds.), *Progress in Botany Vol. 80* (pp. 317–336). Cham: Springer Interna-
 696 tional Publishing. Retrieved 2021-12-17, from [https://doi.org/10.1007/](https://doi.org/10.1007/124_2017_15)
 697 [124_2017_15](https://doi.org/10.1007/124_2017_15)
- 698 Pan, Y., Birdsey, R. A., Phillips, O. L., & Jackson, R. B. (2013, November). The
 699 Structure, Distribution, and Biomass of the World’s Forests. *Annu. Rev.*
 700 *Ecol. Evol. Syst.*, *44*(1), 593–622. Retrieved 2022-01-10, from [https://](https://www.annualreviews.org/doi/10.1146/annurev-ecolsys-110512-135914)
 701 www.annualreviews.org/doi/10.1146/annurev-ecolsys-110512-135914
 702 doi: 10.1146/annurev-ecolsys-110512-135914
- 703 Panagos, P., Jiskra, M., Borrelli, P., Liakos, L., & Ballabio, C. (2021, October).
 704 Mercury in European topsoils: Anthropogenic sources, stocks and fluxes. *En-*
 705 *vironmental Research*, *201*, 111556. Retrieved 2021-07-29, from [https://](https://www.sciencedirect.com/science/article/pii/S0013935121008501)
 706 www.sciencedirect.com/science/article/pii/S0013935121008501 doi:
 707 10.1016/j.envres.2021.111556
- 708 Panek, J. A., & Goldstein, A. H. (2001, March). Response of stomatal conduc-
 709 tance to drought in ponderosa pine: implications for carbon and ozone uptake.
 710 *Tree Physiol.*, *21*(5), 337–344. Retrieved 2021-07-22, from [https://doi.org/](https://doi.org/10.1093/treephys/21.5.337)
 711 [10.1093/treephys/21.5.337](https://doi.org/10.1093/treephys/21.5.337) doi: 10.1093/treephys/21.5.337
- 712 Papula, L. (2003). *Mathematische Formelsammlung für Ingenieure und Naturwis-*
 713 *senschaftler* (8th ed.). Vieweg.
- 714 Pleijel, H., Klingberg, J., Nerentorp, M., Broberg, M. C., Nyirambangutse, B.,
 715 Munthe, J., & Wallin, G. (2021, December). Mercury accumulation
 716 in leaves of different plant types – the significance of tissue age and spe-
 717 cific leaf area. *Biogeosciences*, *18*(23), 6313–6328. Retrieved 2021-12-
 718 23, from <https://bg.copernicus.org/articles/18/6313/2021/> doi:
 719 10.5194/bg-18-6313-2021
- 720 Rea, A. W., Lindberg, S. E., Scherbatskoy, T., & Keeler, G. J. (2002). Mercury ac-
 721 cumulation in foliage over time in two northern mixed-hardwood forests. *Wa-*
 722 *ter Air Soil Poll.*, *133*, 49–67.
- 723 Rutter, A. P., Schauer, J. J., Shafer, M. M., Creswell, J. E., Olson, M. R., Robinson,
 724 M., ... Mallek, J. L. (2011, February). Dry deposition of gaseous elemen-
 725 tal mercury to plants and soils using mercury stable isotopes in a controlled
 726 environment. *Atmos. Environ.*, *45*(4), 848–855. Retrieved 2019-09-24, from
 727 <http://www.sciencedirect.com/science/article/pii/S1352231010009805>
 728 doi: 10.1016/j.atmosenv.2010.11.025
- 729 Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., ...
 730 Marx, A. (2018, May). Anthropogenic warming exacerbates European soil
 731 moisture droughts. *Nature Clim Change*, *8*(5), 421–426. Retrieved 2021-
 732 12-17, from <https://www.nature.com/articles/s41558-018-0138-5> doi:
 733 10.1038/s41558-018-0138-5
- 734 Selin, N. E., Jacob, D. J., Yantosca, R. M., Strode, S., Jaeglé, L., & Sunderland,
 735 E. M. (2008). Global 3-D land-ocean-atmosphere model for mercury:
 736 Present-day versus preindustrial cycles and anthropogenic enrichment fac-
 737 tors for deposition. *Global Biogeochemical Cycles*, *22*(2). Retrieved 2020-09-
 738 22, from [https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007GB003040)
 739 [2007GB003040](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007GB003040) doi: 10.1029/2007GB003040
- 740 Smith-Downey, N. V., Sunderland, E. M., & Jacob, D. J. (2010). Anthro-
 741 pogenic impacts on global storage and emissions of mercury from terres-
 742 trial soils: Insights from a new global model. *Journal of Geophysical Re-*
 743 *search: Biogeosciences*, *115*(G3). Retrieved 2019-06-20, from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JG001124)
 744 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JG001124 doi:
 745 10.1029/2009JG001124
- 746 Sonke, J. E., Angot, H., Zhang, Y., Poulain, A., Björn, E., & Schartup, A. (2023,
 747 May). Global change effects on biogeochemical mercury cycling. *Ambio*,
 748 *52*(5), 853–876. Retrieved 2023-04-15, from [https://doi.org/10.1007/](https://doi.org/10.1007/s13280-023-01855-y)
 749 [s13280-023-01855-y](https://doi.org/10.1007/s13280-023-01855-y) doi: 10.1007/s13280-023-01855-y

- 750 Stocker, B. D., Zscheischler, J., Keenan, T. F., Prentice, I. C., Seneviratne, S. I.,
751 & Peñuelas, J. (2019, April). Drought impacts on terrestrial primary pro-
752 duction underestimated by satellite monitoring. *Nat. Geosci.*, *12*(4), 264–
753 270. Retrieved 2021-10-22, from [https://www.nature.com/articles/](https://www.nature.com/articles/s41561-019-0318-6)
754 [s41561-019-0318-6](https://www.nature.com/articles/s41561-019-0318-6) doi: 10.1038/s41561-019-0318-6
- 755 Wang, Q., Tenhunen, J., Dinh, N., Reichstein, M., Otieno, D., Granier, A., & Pile-
756 garrd, K. (2005, June). Evaluation of seasonal variation of MODIS derived
757 leaf area index at two European deciduous broadleaf forest sites. *Remote*
758 *Sensing of Environment*, *96*(3-4), 475–484. Retrieved 2019-05-15, from
759 <https://linkinghub.elsevier.com/retrieve/pii/S0034425705001252>
760 doi: 10.1016/j.rse.2005.04.003
- 761 Wang, R., Chen, J. M., Liu, Z., & Arain, A. (2017, August). Evaluation of seasonal
762 variations of remotely sensed leaf area index over five evergreen coniferous
763 forests. *ISPRS Journal of Photogrammetry and Remote Sensing*, *130*, 187–
764 201. Retrieved 2020-10-13, from [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S0924271616305998)
765 [article/pii/S0924271616305998](http://www.sciencedirect.com/science/article/pii/S0924271616305998) doi: 10.1016/j.isprsjprs.2017.05.017
- 766 Wang, Y., Jacob, D. J., & Logan, J. A. (1998). Global simulation of tropospheric
767 O₃-NO_x-hydrocarbon chemistry: 1. Model formulation. *Journal of Geophys-*
768 *ical Research: Atmospheres*, *103*(D9), 10713–10725. Retrieved 2022-05-25,
769 from <https://onlinelibrary.wiley.com/doi/abs/10.1029/98JD00158>
770 (_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/98JD00158>) doi:
771 10.1029/98JD00158
- 772 Wesely, M. L. (2007, January). Parameterization of surface resistances
773 to gaseous dry deposition in regional-scale numerical models. *Atmo-*
774 *spheric Environment*, *41*, 52–63. Retrieved 2021-10-21, from [https://](https://www.sciencedirect.com/science/article/pii/S1352231007009740)
775 www.sciencedirect.com/science/article/pii/S1352231007009740 doi:
776 10.1016/j.atmosenv.2007.10.058
- 777 Wohlgemuth, L., Osterwalder, S., Joseph, C., Kahmen, A., Hoch, G., Alewell, C., &
778 Jiskra, M. (2020, December). A bottom-up quantification of foliar mercury
779 uptake fluxes across Europe. *Biogeosciences*, *17*(24), 6441–6456. Retrieved
780 2021-01-14, from <https://bg.copernicus.org/articles/17/6441/2020/>
781 doi: <https://doi.org/10.5194/bg-17-6441-2020>
- 782 Wohlgemuth, L., Rautio, P., Ahrends, B., Russ, A., Vesterdal, L., Waldner, P., ...
783 Jiskra, M. (2022, March). Physiological and climate controls on foliar mercury
784 uptake by European tree species. *Biogeosciences*, *19*(5), 1335–1353. Retrieved
785 2022-03-14, from <https://bg.copernicus.org/articles/19/1335/2022/>
786 (Publisher: Copernicus GmbH) doi: 10.5194/bg-19-1335-2022
- 787 Wu, Z., Wang, X., Chen, F., Turnipseed, A. A., Guenther, A. B., Niyogi, D., ...
788 Alapaty, K. (2011, May). Evaluating the calculated dry deposition velocities of
789 reactive nitrogen oxides and ozone from two community models over a temper-
790 ate deciduous forest. *Atmospheric Environment*, *45*(16), 2663–2674. Retrieved
791 2021-10-21, from [https://www.sciencedirect.com/science/article/pii/](https://www.sciencedirect.com/science/article/pii/S1352231011002275)
792 [S1352231011002275](https://www.sciencedirect.com/science/article/pii/S1352231011002275) doi: 10.1016/j.atmosenv.2011.02.063
- 793 Yuan, H., Dai, Y., Xiao, Z., Ji, D., & Shangguan, W. (2011, May). Reprocessing
794 the MODIS Leaf Area Index products for land surface and climate mod-
795 elling. *Remote Sensing of Environment*, *115*(5), 1171–1187. Retrieved
796 2023-04-16, from [https://www.sciencedirect.com/science/article/pii/](https://www.sciencedirect.com/science/article/pii/S0034425711000149)
797 [S0034425711000149](https://www.sciencedirect.com/science/article/pii/S0034425711000149) doi: 10.1016/j.rse.2011.01.001
- 798 Yuan, W., Sommar, J., Lin, C.-J., Wang, X., Li, K., Liu, Y., ... Feng, X. (2019,
799 January). Stable isotope evidence shows re-emission of elemental mercury
800 vapor occurring after reductive loss from foliage. *Environ. Sci. Technol.*,
801 *53*(2), 651–660. Retrieved 2019-11-29, from [https://doi.org/10.1021/](https://doi.org/10.1021/acs.est.8b04865)
802 [acs.est.8b04865](https://doi.org/10.1021/acs.est.8b04865) doi: 10.1021/acs.est.8b04865
- 803 Yuan, W., Zheng, Y., Piao, S., Ciais, P., Lombardozzi, D., Wang, Y., ... Yang,
804 S. (2019, August). Increased atmospheric vapor pressure deficit re-

- 805 duces global vegetation growth. *Sci. Adv.*, 5(8). Retrieved 2019-09-06,
806 from <https://advances.sciencemag.org/content/5/8/eaax1396> doi:
807 10.1126/sciadv.aax1396
- 808 Zhang, H., Holmes, C., & Wu, S. (2016, September). Impacts of changes
809 in climate, land use and land cover on atmospheric mercury. *Atmo-*
810 *spheric Environment*, 141, 230–244. Retrieved 2021-10-21, from [https://](https://linkinghub.elsevier.com/retrieve/pii/S1352231016304897)
811 linkinghub.elsevier.com/retrieve/pii/S1352231016304897 doi:
812 10.1016/j.atmosenv.2016.06.056
- 813 Zhang, L., Wright, L. P., & Blanchard, P. (2009, December). A review of cur-
814 rent knowledge concerning dry deposition of atmospheric mercury. *At-*
815 *mos. Environ.*, 43(37), 5853–5864. Retrieved 2019-10-03, from [http://](http://www.sciencedirect.com/science/article/pii/S1352231009007407)
816 www.sciencedirect.com/science/article/pii/S1352231009007407 doi:
817 10.1016/j.atmosenv.2009.08.019
- 818 Zhou, J., & Obrist, D. (2021). Global mercury assimilation by vegetation. *Environ.*
819 *Sci. Technol.*. Retrieved 2021-10-08, from [https://doi.org/10.1021/acs.est](https://doi.org/10.1021/acs.est.1c03530)
820 .1c03530 doi: 10.1021/acs.est.1c03530
- 821 Zhou, J., Obrist, D., Dastoor, A., Jiskra, M., & Ryjkov, A. (2021, March). Vege-
822 tation uptake of mercury and impacts on global cycling. *Nat. Rev. Earth Env-*
823 *iron.*, 1–16. Retrieved 2021-03-16, from [https://www.nature.com/articles/](https://www.nature.com/articles/s43017-021-00146-y)
824 [s43017-021-00146-y](https://www.nature.com/articles/s43017-021-00146-y) doi: 10.1038/s43017-021-00146-y
- 825 Zweifel, R., Rigling, A., & Dobbertin, M. (2009). Species-specific stomatal response
826 of trees to drought – a link to vegetation dynamics? *J. Veg. Sci.*, 20(3), 442–
827 454. Retrieved 2021-09-08, from [https://onlinelibrary.wiley.com/doi/](https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1654-1103.2009.05701.x)
828 [abs/10.1111/j.1654-1103.2009.05701.x](https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1654-1103.2009.05701.x) doi: 10.1111/j.1654-1103.2009
829 .05701.x
- 830 Zweifel, R., Steppe, K., & Sterck, F. J. (2007, June). Stomatal regulation by micro-
831 climate and tree water relations: interpreting ecophysiological field data with a
832 hydraulic plant model. *J. Exp. Bot.*, 58(8), 2113–2131. Retrieved 2021-04-19,
833 from <https://doi.org/10.1093/jxb/erm050> doi: 10.1093/jxb/erm050