Chapter 7
Mercury Emissions from Natural Sources and their Importance in the Global Mercury Cycle

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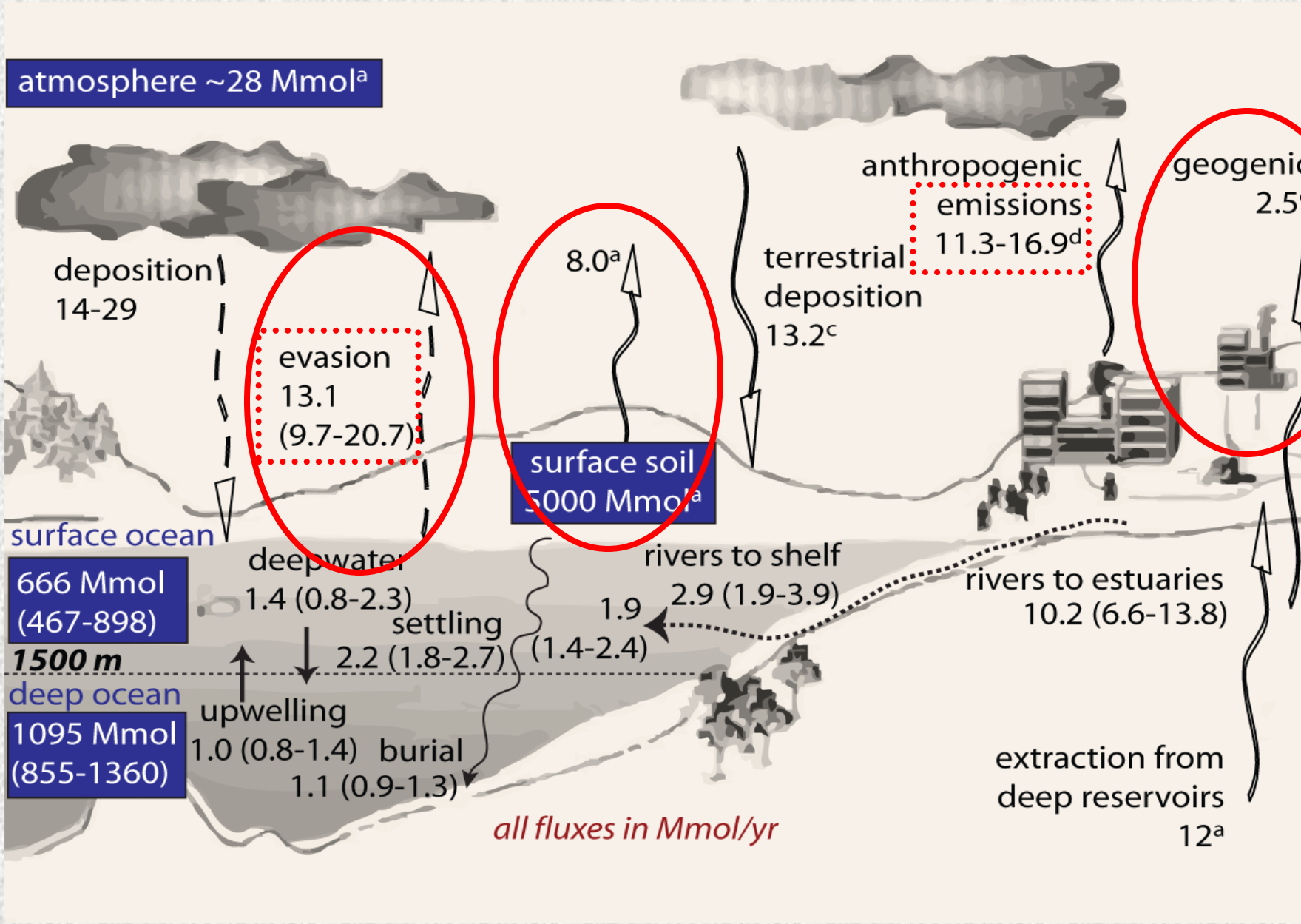


Source: Sunderland & Mason, 2007

Emissions from Natural Sources

- Importance of re-emission of deposited Hg from anthropogenic deposition
- Based on our current versus pre-industrial emission estimates, extent of re-emission is 50% of total for ocean; 50% for the terrestrial environment (Sunderland and Mason, 2007)
- Pre-industrial natural emissions estimates:

  1360 Mg/yr for ocean, 8 Mg/yr for terrestrial
- Definition of “natural” – e.g. biomass burning is primarily (>50%) a human-generated activity
- Forest fire emissions were not estimated as done so in Chapt 8
- Urban landscapes are not included in estimates
- Arctic depletion events and their impact not specifically focused on

Observed seawater Hg data (mean±stdev) reported in the literature

Ocean Basin	Hg (pM)	Hg(0) pM	Evasion Hg(0) (nmol/m^2/day)
North Atlantic	2.4±1.6[a]	0.41±0.31[a]	1.9±1.3[a]
	1.57±0.44[b]		0.156[d]
	2.1±0.6[c]		
Deep North Atlantic	2.3±0.8[e]	n/a	n/a
South and Equatorial	1.68±0.74[f]	1.2±0.8[f]	0.323[i]
Atlantic	2.9±1.7[g]	0.08-0.16[h]	9.6[j]
		0.11[i]	
Deep Atlantic/Bottom	1.7±0.7[k]	n/a	n/a
Water	0.96±0.41[l]		
	0.9±0.4[m]		
Mediterranean	2.2±0.4[n]	0.15±0.12[p]	0.14[r]
	2.54±1.25[o]	0.08-0.21[i,q]	0.23-0.48[q]
	1.46±0.41[p]		0.28-0.94[i]
North Pacific	0.64±0.26[s]	0.06±0.03[r]	0.88±0.11[r]
South & Equatorial	1-2[t,d]	0.13±0.07[r]	0.29±0.26[v]
Pacific		0.04-0.32[d]	0.40[d]
		0.06-0.14[v]	
Deep Pacific/Indian	1.2±0.3[s]	n/a	n/a
Antarctic	0.7-1.1[u]	no data	no data

Flux Estimates Based on Measurement and Constraints Imposed by Box and Global Modeling of Mercury Cycling

Table 2:Estimated fluxes from the ocean to the atmosphere for the various ocean basins. Adapted from (Sunderland 2007) and (Mason 2005).

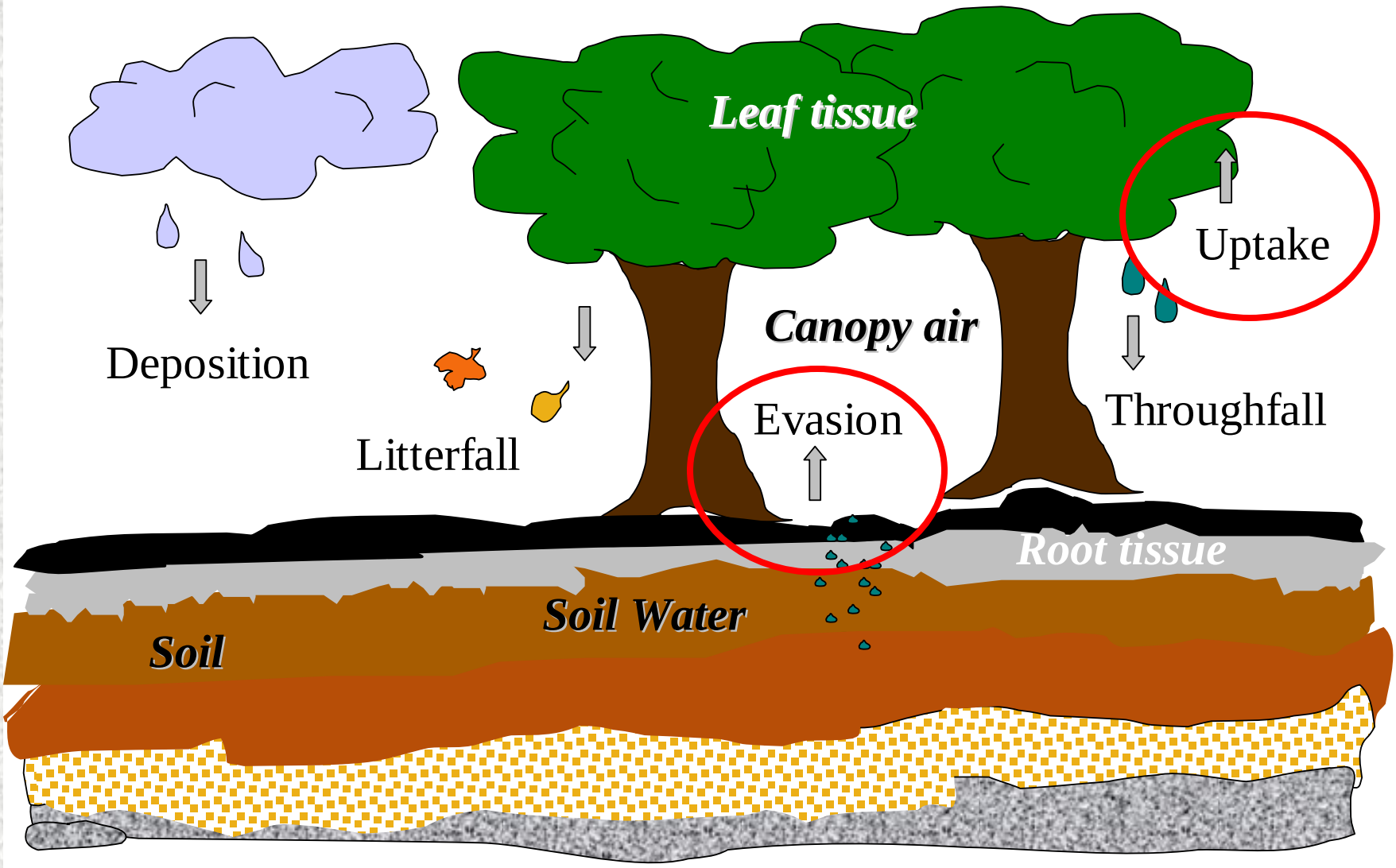
Basin	**Latitude Range**	**Area ($\times 10^{14}$ m^2)**	**Flux ($Mmol\ yr^{-1}$)**
North Atlantic	>55°N	0.20	0.6 (0.2-1.1)
Surface Atlantic	35°S - 55°N	0.62	3.2 (0.8-6.5)
Intermediate Atlantic	65°S - 35°S	0.20	0.4 (0.1-0.8)
Surface Mediterranean	30 - 35°N	0.025	0.2 (0.04-0.4)
North Pacific	> 30°N	0.27	1.0 (0.4-1.8)
Surface Pacific & Indian	40°S - 30°N	1.48	6.4 (1.9-13)
Intermediate Pacific & Indian	65°S – 40°S	0.50	1.1 (0.3-2.2)
Surface Antarctic	>65°S	0.12	0.06 (0.02-0.11)
Coastal Waters	10% of total area	0.035	0.30 (0.15 - 0.5)
Total		**3.45**	**13.3 (3.9 – 26.3)**

In Mg/yr (tons/yr)
2660 (790-5260

Comments on Ocean Emissions

- Major regions of the ocean have been little studied. More data required on evasion from Southern Hemispheric oceans, and from the Indian and North Pacific.
- Models suggest that there should be seasonal differences and perhaps diurnal cycling. Some data from the Mediterranean support these model results, There is little seasonal data for the open ocean.
- New methods now allow continuous measurement of dissolved gaseous Hg and also atmospheric Hg(0) so more detailed information is being rapidly gathered. This data will allow further constraint and refinement of emission fluxes

Schematic Indicating the Main Mechanisms of Mercury Exchange at the Terrestrial-Air Interface



Average fluxes, or in some cases the range of fluxes, for various ecosystems measured by a number of investigators (nmol m^{-2} $month^{-1}$). In the table, negative values indicate uptake of mercury rather than release..

Location	Flux (nmol m^{-2} $mnth^{-1}$)	Ref.	Location	Flux (nmol m^{-2} $mnth^{-1}$)	Ref.
Vegetation			**Ground Level**		
Forest			**Forest Floor**		
Hardwood	29 -238	1	Sweden	1.4 – 7.2	1
Pine	3.6 – 126	1	Oak Ridge, TN	7.2 - 25	8
Maple	20	2	Michigan	5.0	9
Spruce	6.1	2	Brazil	<1	7
Poplar	9.7	2	“Deforested” site	50	7
Oak	16.4	2	Desert Soils	-3.6-10.8	6
Other			**Mineral. Areas**		
Sagebush	-5.0	3	Av. for Nevada	13.3	10
Prairie grass	12.5	5	High Hg regions	max 1500	11
Cattail	60	6			
Model Estimates			**Model Estimates**		
Hardwood forest	max 16	4	Forest Soil	5.4	4
Agricultural crops	max 11	4	Agricultural soil	8.3	4
“Plant-related emissions”	3.2	12	“Av global soil”	1.5	12

Table 4: Estimates of the uptake of mercury by vegetation, primarily trees as estimated from the concentration of Hg in litterfall collected at the end of the growing season, or from measurements of leaf concentration over time.

Location	**Flux (nmol m^{-2} $mnth^{-1}$)**	**Ref.**
Various studies	6.6 – 16.5	1, 2
Temperate forest	5.4	3
Temperate forest	5.0	4
Model: NE USA	0.8 - 3	5

References 1: Lindberg et al. (2004); 2: (Gustin 2005); 3: (Rea, Keeler et al. 1996; Rea, Lindberg et al. 2002); 4: (St Louis, Rudd et al. 2001); 5: (Miller, Mason et al. 2007).

Approach to Estimation of fluxes

Evasion fluxes scaled by region with higher fluxes in warmer regions

And by vegetation type: e.g. forest>grassland>agricultural

Estimation of uptake

Different for different vegetation types and regions

Section of the Excel Spreadsheet used to Estimate Fluxes from Terrestrial Landscape

Terrestrial Environ	**Region**	**Area (x10^14 m2)**	**Evasion (ug m-2 yr-1)**	**Yearly Evasion Flux**	**Est Uptake (ug/m2/yr)**	**Total Uptake**	**Net evasion**
Forest	Polar	0.12	10.00	0.60	7.50	0.45	0.15
Tundra		0.08	8.00	0.32	2.00	0.08	0.24
Lakes		0.00	10.00	0.02	0.00	0.00	0.02
Ice		0.08	5.00	0.20	0.00	0.00	0.20
Total		**0.28**	**9.33**	**1.14**	**9.50**	**0.53**	**0.61**
Forest	Temper	0.12	17.50	1.05	12.00	0.72	0.33
Prairie/grassland	30-70	0.08	15.00	0.61	4.00	0.16	0.45
Chap/Wood/Scrub		0.08	15.00	0.60	4.00	0.16	0.44
Agriculture		0.09	12.00	0.55	4.00	0.18	0.36
Desert/Metalliferous		0.18	15.00	1.34	0.00	0.00	1.34
Lakes		0.03	20.00	0.29	0.00	0.00	0.29
Total		**0.58**	**15.75**	**4.44**		**1.22**	**3.21**

Table 5: Estimates of net evasion of mercury from terrestrial ecosystems which were calculated from the information provided in Tables 3 and 4, as discussed in the text.

Region	**Estimated Area (x 10^{14} m^2)**	**Av. Net Evasion (Mmol/yr)**	**%total evasion**
Polar/Boreal (>70^0)			
Boreal Forests	0.12	0.15 (0.06-0.30)	2.8
Tundra	0.08	0.24 (0.08-0.48)	2.9
Boreal Lakes	0.005	0.02 (0.01-0.05)	0.2
Ice Covered Polar Regions*	0.08	0.20 (0.12-0.40)	2.4
Temperate (30-70^0)			
Temperate Forest	0.12	0.33 (0.15-0.60)	4.0
Grassland/Prairie	0.08	0.45 (0.28-0.89)	5.4
Chaparral/Scrub	0.08	0.44 (0.28-0.88)	5.3
Temperate Agriculture	0.09	0.36 (0.18-0.73)	4.3
Desert/Metalliferrous Zones	0.18	1.34 (0.72-3.58)	16.1
Temperate Lakes	0.03	0.29 (0.18-0.59)	3.4
Tropical/Subtropical (0-30^0)			
Tropical Forests	0.25	1.23 (0.31-0.61)	14.8
Tropical Prairie/Grassland	0.009	0.06 (0.03-0.13)	0.7
Tropical Agriculture	0.063	0.28 (0.16-0.57)	3.3
Desert/Metalliferrous Zones	0.16	1.19 (0.8-3.18))	14.3
Savannah	0.15	1.05 (0.56-2.10	12.7
Tropical Lakes	0.011	0.17 (0.10-0.34)	2.0
Volcanoes/Geothermal	**NA**	0.45 (0.30-3.00)	5.4
Total	**1.5**	**8.3 (4.3-18.4)**	

Comments on Terrestrial Emissions

- Little information on emission estimates from tropical/sub-tropical locations
- Little information on seasonal changes
- Need more details on non-forested but vegetated locations
- Studies examining both uptake and emissions of Hg from the same location or methods of estimating net fluxes improved
- More data needed to further constrain estimates

Overall summary of fluxes by vegetation type and for aquatic systems.

Region	**Estimated Area ($\times 10^{14}$ m^2)**	**Av. Net Evasion (Mmol/yr)**
Oceans	**3.6**	**13.0**
Atlantic Ocean	1.02	4.2
Pacific and Indian Ocean	2.25	8.5
Antarctic Ocean	0.12	0.06
Mediterranean	0.025	0.2
Coastal waters	0.035	0.3
Terrestrial	**1.5**	**9.25**
Forest	0.49	1.71
Tundra/Grassland/Savannah/Prairie/Chaparral	0.40	2.24
Desert/Metalliferrous/ Non-vegetated Zones	0.42	2.73
Agricultural areas	0.15	0.64
Lakes	0.046	0.48
Evasion after Mercury Depletion Events	NA	1.0
Volcanoes/Geothermal	NA	0.45
Total		**22.3**

Table 6: Overall summary of fluxes by vegetation type and for aquatic systems. Compiled from the data in Tables 2 and 5.

Region	**Estimated Area (x 10^{14} m^2)**	**Av. Net Evasion (Mmol/yr)**
Oceans	**3.6**	**13.0**
Atlantic Ocean	1.02	4.2
Pacific and Indian Ocean	2.25	8.5
Antarctic Ocean	0.12	0.06
Mediterranean	0.025	0.2
Coastal waters	0.035	0.3
Terrestrial	**1.5**	**9.25**
Forest	0.49	1.71
Tundra/Grassland/Savannah/Prairie/Chaparral	0.40	2.24
Desert/Metalliferrous/ Non-vegetated Zones	0.42	2.73
Agricultural areas	0.15	0.64
Lakes	0.046	0.48
Evasion after Mercury Depletion Events	NA	1.0
Volcanoes/Geothermal	NA	0.45
Total		**22.3**

Terrestrial Environ	Region	Fraction of Region's Land	Area (x10^14 m2)	Evasion Flux (ug m-2 yr-1)	Yearly Evasion Flux	Est Uptake (ug/m2/yr)	Total Uptake	Net evasion
Forest	Polar	0.42	0.12	10.00	0.60	7.50	0.45	0.15
Tundra		0.28	0.08	8.00	0.32	2.00	0.08	0.24
Lakes		0.02	0.00	10.00	0.02	0.00	0.00	0.02
Ice		0.28	0.08	5.00	0.20	0.00	0.00	0.20
Total		1.00	0.28	9.33	1.14	9.50	0.53	0.61
Forest	Temper	0.21	0.12	17.50	1.05	12.00	0.72	0.33
Prairie/grassland	30-70	0.14	0.08	15.00	0.61	4.00	0.16	0.45
Chap/Wood/Scrub		0.14	0.08	15.00	0.60	4.00	0.16	0.44
Agriculture		0.16	0.09	12.00	0.55	4.00	0.18	0.36
Desert/Metalliferous		0.31	0.18	15.00	1.34	0.00	0.00	1.34
Lakes		0.05	0.03	20.00	0.29	0.00	0.00	0.29
Total		**1.00**	**0.58**	**15.75**	**4.44**		**1.22**	**3.21**
Forest	Tropical	0.38	0.25	25.00	3.06	15.00	1.84	1.23
Prairie/grassland	0 to 30	0.01	0.01	20.00	0.09	6.00	0.03	0.06
Agriculture		0.10	0.06	15.00	0.47	6.00	0.19	0.28
Desert/Metalliferous		0.25	0.16	15.00	1.19	0.00	0.00	1.19
Savanah		0.24	0.15	20.00	1.50	6.00	0.45	1.05
Lakes		0.02	0.01	30.00	0.17	0.00	0.00	0.17
Total		**1.00**	**0.64**	**20.83**	**6.49**		**2.50**	**3.98**
Volcanoes					**0.45**			**0.45**
Total			**1.50**		**12.52**		**4.26**	**8.26**

Table 2. Observed seawater Hg data (mean±stdev) reported in the literature

Ocean Basin	Hg (pM)	Hg(0) pM	Evasion Hg(0) (nmol/m^2/day)
North Atlantic	2.4±1.6[a]	0.41±0.31[a]	1.9±1.3[a]
	1.57±0.44[b]		0.156[d]
	2.1±0.6[c]		
Deep North Atlantic	2.3±0.8[e]	n/a	n/a
South and Equatorial	1.68±0.74[f]	1.2±0.8[f]	0.323[i]
Atlantic	2.9±1.7[g]	0.08-0.16[h]	9.6[j]
		0.11[i]	
Deep Atlantic/Bottom Water	1.7±0.7[k]	n/a	n/a
	0.96±0.41[l]		
	0.9±0.4[m]		
Mediterranean	2.2±0.4[n]	0.15±0.12[p]	0.14[r]
	2.54±1.25[o]	0.08-0.21[i,q]	0.23-0.48[q]
	1.46±0.41[p]		0.28-0.94[i]
North Pacific	0.64±0.26[s]	0.06±0.03[r]	0.88±0.11[r]
South & Equatorial Pacific	1-2[t,d]	0.13±0.07[r]	0.29±0.26[v]
		0.04-0.32[d]	0.40[d]
		0.06-0.14[v]	
Deep Pacific/Indian	1.2±0.3[s]	n/a	n/a
Antarctic	0.7-1.1[u]	no data	no data

n/a = not applicable. [a]Profile averages for samples taken between 50-70°N from *Mason et al.* [1998a]. [b]North Atlantic Surface Water flowing into the Mediterranean Sea measured by *Cossa et al*. [1997]. [c]European continental shelf margin from *Cossa et al.* [2004]; [d]*Mason and Fitzgerald* [1991; 1993]. [e]Water depths >1500 m, >50°N from *Mason et al.* [1998a]. [f]Subsurface water from the South and Equatorial Atlantic from *Mason and Sullivan* [1999]. [g]Surface water samples from the South and Equatorial Atlantic from *Mason and Sullivan* [1999]. [h]*Mason et al.* [2001]. [i]*Gardfelt et al.* [2003]. [j]*Lamborg et al.* [1999]. [k]Seawater below 1500 m in the Deep Atlantic from *Mason and Sullivan* [1999]. [l]Below 1500 m average from *Dalziel* [1995]. [m]Below 3300 m from *Dalziel* [1995]. [n]Seawater exiting the Strait of Gibraltar from *Cossa et al.* [1997] and also in the [o]Western Mediterranean. [p]*Horvat et al.* [2003]. [q]*Ferrara et al.* [2003]. [r]*Laurier et al.* [2003]. [s]*Laurier et al.* [2004].[t]*Gill and Fitzgerald* [1988]. [u]*Dalziel* [1995]; *Laurier et al.* [2004], *Mason and Sullivan* [1999] detected Antarctic Bottom Water and Antarctic Intermediate Waters in the Atlantic and Pacific Oceans. [v]*Kim and Fitzgerald* [1986].

Table 3: Average fluxes, or in some cases the range of fluxes, for various ecosystems measured by a number of investigators. Values have all been converted to a common flux unit of nmol m^{-2} $month^{-1}$. In the table, negative values indicate uptake of mercury rather than release. Results from the older literature are combined in estimates given in various review papers.

Location	Flux (nmol m^{-2} $mnth^{-1}$)	Ref.	Location	Flux (nmol m^{-2} $mnth^{-1}$)	Ref.
Vegetation			**Ground Level**		
Forest			**Forest Floor**		
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Maple	20	2	Michigan	5.0	9
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Poplar	9.7	2	"Deforested" site	50	7
Oak	16.4	2	Desert Soils	-3.6 to 10.8	6
Other			**Mineralized Areas**		
Sagebush	-5.0	3	Av. for Nevada	13.3	10
Prairie grass	12.5	5	High Hg regions	max 1500	11
Cattail	60	6			
Model Estimates			**Model Estimates**		
Hardwood forest	max 16	4	Forest Soil	5.4	4
Agricultural crops	max 11	4	Agricultural soil	8.3	4
"Plant-related emissions"	3.2	12	"Average global soil"	1.5	12

References: 1: (Hanson, Lindberg et al. 1995; Lindberg, Hanson et al. 1998); 2:(Hanson, Lindberg et al. 1995); 3: (Fay and Gustin 2007); 4: (Bash, Miller et al. 2004); 5: (Obrist, Gustin et al. 2005); 6: (Gustin, Engle et al. 2006) and references therein; 7: (Magarelli and Fostier 2005); 8: (Carpi and Lindberg 1997); 9: (Zhang, Lindberg et al. 2003); 10: (Gustin 2003) and references therein; 11: (Gustin 2005); 12: (Selin 2008).