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Mercury in Soils of Seabird Nesting Islands in West Iceland

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ABSTRACT. Seabirds are globally recognized vectors of marine-derived materials, which get deposited on land at their breeding colonies, potentially altering local soil chemistry. We studied mercury (Hg) in soil cores on two islands in west Iceland that host thousands of nesting seabirds, predicting that Hg subsidies from nesting birds would result in elevated Hg in local soils. However, despite clear evidence from nitrogen isotopes of marine influence (seabird faeces) on coastal soil cores, O horizon Hg concentrations averaged 223 nanograms per gram (ng/g), were similar between reference and seabird-nesting sites, and were within the range of soils elsewhere in Europe and the Arctic. The concentration of Hg declined for samples deeper in the core, mirroring declines in organic content and concomitant increases in stable isotopes of nitrogen. A more detailed analysis of local pedogenic processes is required to determine the relative contribution of lithogenic, atmospheric, and anthropogenic Hg, but our data do not suggest that seabirds are markedly increasing local soil Hg through ornithogenic subsidies.

Key words: core; loss on ignition; isotope; Arctic; ornithogenic

RÉSUMÉ. À l'échelle mondiale, les oiseaux de mer sont reconnus en tant que vecteurs de matières d'origine marine, celles-ci étant déposées à leurs colonies de nidification de la terre ferme, ce qui peut avoir pour effet de modifier la chimie du sol local. Nous avons étudié le mercure (Hg) se trouvant dans des carottes de sol de deux îles de l'ouest de l'Islande où nichent des milliers d'oiseaux de mer, prédisant que les bonifications en Hg des oiseaux nicheurs donneraient lieu à des taux de Hg élevés dans les sols locaux. Cependant, malgré la preuve évidente d'isotopes d'azote d'influence marine (déjections d'oiseaux de mer) dans les carottes de sol côtier, les concentrations de mercure de l'horizon O atteignaient en moyenne 223 nanogrammes par gramme (ng/g), étaient semblables entre le point de référence et les sites de nidification des oiseaux de mer, et se situaient dans la même gamme de sols que ceux se trouvant ailleurs en Europe et dans l'Arctique. La concentration de Hg diminuait dans le cas des échantillons prélevés plus en profondeur dans les carottes, reflétant des diminutions du contenu organique et des augmentations concomitantes des isotopes stables d'azote. Bien qu'une analyse plus détaillée des processus pédogénétiques locaux s'avère nécessaire dans le but de déterminer la contribution relative du mercure lithogénétique, atmosphérique et anthropique, nos données ne suggèrent pas que les oiseaux de mer fassent augmenter considérablement la teneur en Hg du sol local au moyen de leurs bonifications ornithogéniques.

Mots clés : carotte; perte par calcination; isotope; Arctique, ornithogénique

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INTRODUCTION

Many animals are considered important biovectors (Doughty et al., 2016) influencing the distribution of various elements and chemicals at local to global scales (Blais et al., 2007; Gallant et al., 2020). Seabirds are perhaps the best-known biovectors because they are globally distributed, feed in the ocean, and return to terrestrial colonies where they release nutrients and chemicals through defecation, regurgitation, and mortality (Otero et al., 2018; De La Peña-Lastra, 2021). Compared to areas remote from seabirds and without chemical subsidies (e.g., Ellis, 2005), soils in colony areas are altered and fertilized by seabirds moving marine-derived material from ocean to land (e.g., Ellis, 2005). The effects of ornithogenic biotransport of chemicals are especially prominent at high latitudes, where terrestrial nutrient availability in soils (especially nitrogen) is often low (e.g., Hartley et al., 2010). While it has been known for some time that the redistribution of nutrients by seabirds (and, in some areas, the increase in soil fertility) can be considered a form of ecosystem engineering (Smith et al., 2011; Mosbech et al., 2018), the likelihood of biotransport of contaminants by seabirds was not systematically considered until late in the twentieth century (Bargagli et al., 1998; Klekowski et al., 1999; Sun et al., 2000; Blais et al., 2005; Evenset et al., 2007). With the growth of biotransport studies, this phenomenon has now been documented for seabird colonies from the Arctic (Michelutti et al., 2009) to

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temperate regions (Mallory et al., 2015) to tropical regions (Zhu et al., 2014) to the Antarctic (Huang et al., 2014).

One biotransported contaminant that has received considerable attention is mercury (Hg). Mercury is a non-essential element and neurotoxin that is mobile through complex food chains, now often deemed food webs (especially in its methylated form; O'Connor et al., 2019) and can have negative effects on wildlife, even at sublethal concentrations (e.g., Fort et al., 2014). Environmental levels of Hg have increased over the past two centuries due to anthropogenic activities (Pacyna et al., 2016), leading Hg to be listed as one of the World Health Organization's main chemicals of concern (O'Connor et al., 2019). As well, many countries are parties or signatories to the Minamata Convention (https://www.mercuryconvention.org/en; UNEP, 2019), a global initiative to monitor and reduce Hg levels in the environment. This agreement has highlighted the need for additional studies on storage and movement of Hg among environmental compartments in order to help understand discrepancies between atmospheric and biotic trends (e.g., Wang et al., 2019).

Iceland, a member party in the Minamata Convention, is a subarctic nation where millions of seabirds nest, largely in colonies along the extensive coastline and numerous nearshore islands (Petersen, 2006), and forage in the surrounding North Atlantic Ocean (e.g., Davies et al., 2021). Research has demonstrated that seabirds feeding in marine food webs in the North Atlantic are exposed to Hg, which can become elevated in upper–trophic level predators (Thompson et al., 1992; Bond and Diamond, 2009; Fort et al., 2014; Albert et al., 2021; Dietz et al., 2021). As well, recent studies have established that marine-derived Hg can move from seabird faeces into soils around breeding colonies, and then into terrestrial vegetation and food webs (e.g., Choy et al., 2010; Cipro et al., 2019; Shoji et al., 2019). Consequently, our goal in this project was to examine the concentrations of Hg in soils on islands supporting seabird colonies in order to determine current Hg concentrations, evaluate whether levels were elevated by seabird presence, and assess whether levels may have changed over time. We predicted, first, that sites within and below seabird nesting areas would have higher Hg concentrations than sites remote from nesting seabirds, and second, that Hg would decline with increasing soil depth due to recent guano and atmospheric deposition inputs accumulating in the organic soil surface only, combined with incomplete retention at depth, over time, of Hg from ornithogenic subsidies.

MATERIALS AND METHODS

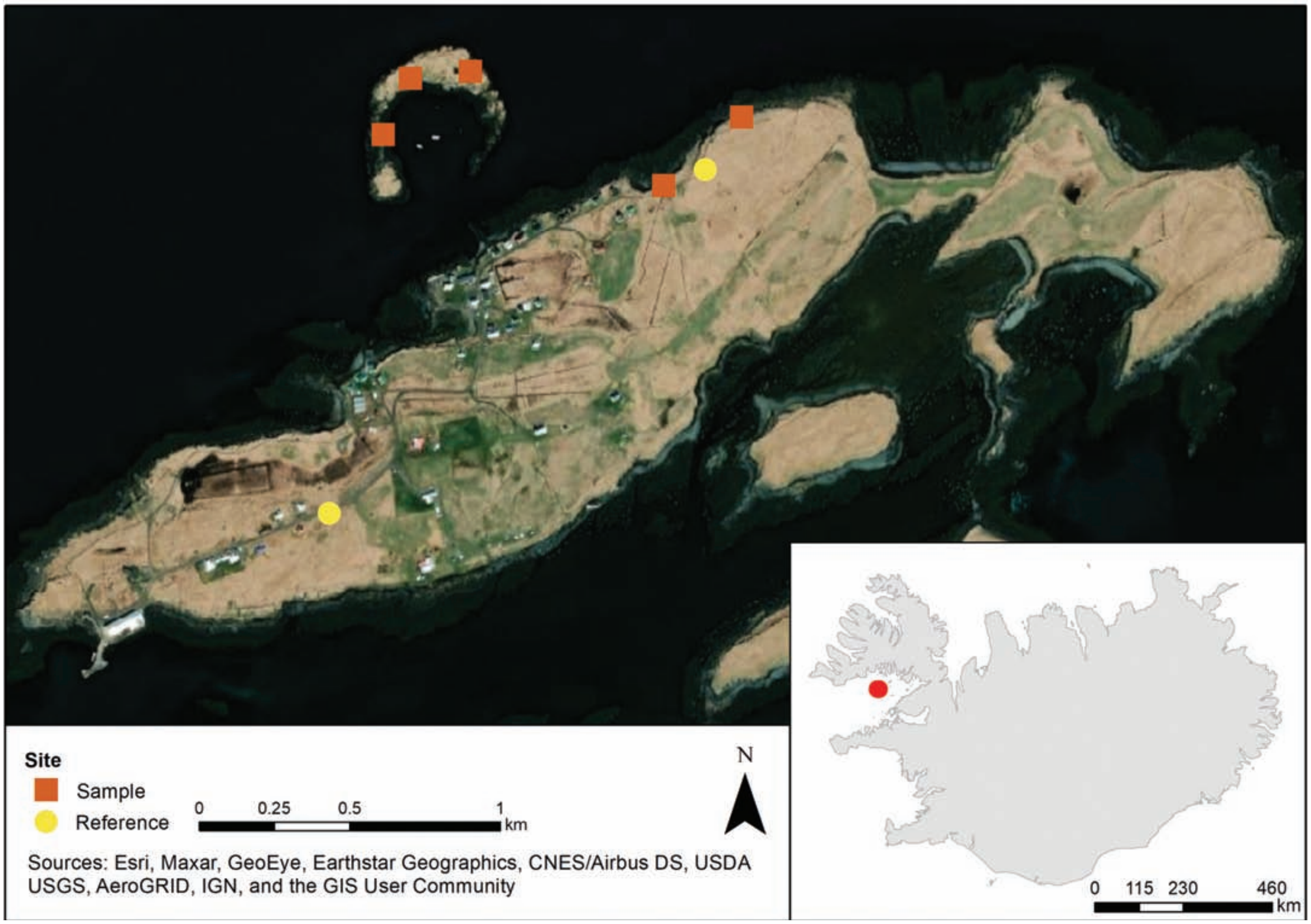
Study Site Description

We sampled soils on two small islands in Breiðafjörður Bay, western Iceland: Flatey and Hafnarey (Fig. 1; 65˚22′ N, 22˚55′ W). Both are subarctic, basaltic islands covered in grasses. Flatey is about 50 ha in size, with a maximum elevation of ~16 m, while Hafnarey covers approximately 2 ha and rises 25 m. Hafnarey is uninhabited. On Flatey, two families live on the island year-round; they farm some areas for hay and access other islands by boat (in the past, to move livestock) to harvest seabirds, the most important of which, economically speaking, is the Common Eider (*Somateria mollissima*). The two islands, part of the ~3200 in the bay (of which 54 comprise the Flatey farms), support thousands of nesting birds. The principal seabird species at the sites are: Black Guillemot (*Cepphus grylle*), Northern Fulmar (*Fulmarus glacialis*), Black-legged Kittiwake (*Rissa tridactyla*), Atlantic Puffin (*Fratercula arctica*), Arctic Tern (*Sterna paradisaea*), European Shag (*Phalacrocorax aristotelis*), and the Common Eider, although 20 bird species may nest regularly in the sites (Petersen 1979). Seabird research has taken place at these sites for >40 years (e.g., Petersen, 1981; Petersen et al., 2020; Wood et al., 2021).

Icelandic soils are relatively young, and their composition is strongly influenced by volcanogenic source rocks (Arnalds, 2004, 2015) and ash, the latter of which may contribute some Hg (~20–70 ng/g; Baturin et al., 2012). In the northwest, the coast and islands are covered principally in histosols (>20% carbon), with aeolian contributions of andic materials (Arnalds and Gretarsson, 2001). In July 2017 we sampled soils by taking cores using a 3 cm-diameter stainless steel corer at three sites on Hafnarey and four sites on Flatey. On the former, all cores were collected in grassy areas ~200 m from each other and among seabird nest sites. On Flatey we collected soils at two sites below seabird nesting ledges, on small cliffs (~200 m apart), and two "reference" sites: one above the nesting cliffs with no nesting seabirds, at the edge of a small field, and one in the middle of the island at the undisturbed edge of a meadow (~1.5 km away; Fig. 1). We tried to take cores at five other seabird-influenced sites, but substrate was not suitable (basically coarse gravel) or cores could not be obtained (vegetation was effectively on bedrock). We carefully removed the surface vegetation, then pushed the corer into the ground until we encountered bedrock (generally ~ 8 cm) or could not extend the core any farther (~ 30 cm; one reference site). We extruded the soil cores, carefully sectioned each into 1 cm slices (which we separated out using a plastic spoon), placed the slices in a sealed plastic bag, and labelled the bags. All sites appeared to contain O and A horizon soil layers. We kept samples cool in the initial period, then shipped them to Canada, where we froze them within seven days of sampling. All soil samples remained frozen at ~ −20°C until we prepared them for analysis, thus minimizing Hg(0) formation and loss from soil (Pannu et al., 2014). We thawed and air dried soil samples, removed major rocks or pebbles, and manually homogenized the samples into a fine powder with a mortar and pestle.

Soil Analysis

In the Mercury Lab at Acadia University we measured total Hg (hereafter "Hg") in dried, homogenized 50 mg



Sources: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA USGS, AeroGRID, IGN, and the GIS User Community

FIG. 1. The Flatey and Hafnarey study sites in Breiðafjörður Bay, western Iceland. Seabird-influenced soil sampling sites are shown with an orange square; reference sites are shown with a yellow circle.

subsamples using a Nippon Instruments MA-3000 Direct Mercury Analyzer that uses thermal pyrolysis, with gold amalgamation atomic absorption (USEPA method 7473). During analysis we concurrently analyzed certified reference materials for quality reference; these were within acceptable limits: marine sediment standard (MESS-3; recovery: 110.1 ± 4.8% n = 15), dogfish muscle (DORM-4; recovery: 102.0 ± 2.3% n = 15), and dogfish liver tissue (DOLT-5; recovery: 94.6 ± 0.4%; n = 3). Triplicates (n = 4) yielded an average of 2.2 % RSD, and we calculated the method detection limit (MDL = 3.97 ng/g) as 3x the standard deviation of the blanks, assuming a 50 mg sample size. We report all values in dry weight.

The organic composition and content in soils strongly influences Hg concentrations in soils (Qiu et al., 2005; Liang et al., 2009). To estimate organic content in soil, in the Mercury Lab we measured the loss on ignition (LOI) of samples. We placed dry, homogenized (100–500 mg) subsamples on tin weigh boats, weighed them, combusted them at 550˚C for 2 h in a muffle furnace, cooled them and weighed the remaining soil contents. We measured triplicates (n = 5) every 15 samples, which yielded an average of 4.78% RSD.

The influence of seabird guano on receiving environmental matrices can be elucidated by measuring stable isotopes of nitrogen, where greater nitrogen-heavy isotope signatures are indicative of inputs from higher trophic levels (e.g., Hobson and Clark, 1992; Post, 2002; Blais et al., 2005). We sent ~5 g of each homogenized soil sample to the Stable Isotopes in Nature Laboratory (University of New Brunswick, Canada) for analysis. That lab combusted samples in an elemental analyzer and sent gases to the isotope-ratio mass spectrometer using a continuous flow interface. We report data as differences in isotopic ratios (in parts per thousand or per mil; ‰) compared against standards of atmospheric nitrogen (AIR) for nitrogen, according to the following equation:

$$\delta X = \left(\frac{R_{sample}}{R_{std}} - 1 \right)$$

where δX is $\delta^{15}N$, in ‰; R is the ratio of the abundance of the heavy to the light isotope ($^{15}N/^{14}N$); R_{sample} is the ratio within the sample; and R_{std} is the ratio of heavy to light isotope within the international standard (Hobson and Clark, 1992). In our analyses, we normalized isotope values using in-house standards (USGS61, bovine liver, muskellunge muscle) calibrated against International Atomic Energy Agency standards. To assess accuracy, we tested against standards for nicotinamide, N_2, and CH_7. Collectively, the precision on laboratory standards was 1.0% for $\delta^{15}N$. For nine samples, which we analyzed twice each, analytical precision was good, at 1.0% for $\delta^{15}N$.

We conducted all statistical analyses and data visualization in RStudio (version 1.1.463). For each statistical test we examined normality and homogeneity of variance, and we visually inspected residuals from tests for deviations from normality. We used Pearson correlation to describe trends in parameters with depth, and linear mixed models to test effects of independent factors (depth, $\delta^{15}N$, and LOI) on Hg concentrations, retaining site as a random factor.

RESULTS

The mean concentration of Hg across seven O horizon, surface soil samples from cores was 222.9 ± 28.6 ng/g; counter to predictions, the five seabird-influenced surface samples had a slightly lower value (214.4 ng/g) to that of the reference sites (244.2; small sample size precluded statistical comparison). Mean $\delta^{15}N$ was 12.33 ± 2.88‰, 47% higher in seabird-influenced sites (mean 13.58‰) than reference sites (mean 9.21‰). Loss on ignition averaged 79 ± 11% for all seven sites and was similar for those near seabird (78%) and reference locations (82%).

Visual examination of the chemical markers in the cores (Fig. 2) suggested different patterns depending on sampling location. When we pooled data from the five cores at seabird sites for descriptive purposes, they generally had high $\delta^{15}N$ throughout the core, which increased slightly with depth ($r_{38} = 0.41, p = 0.01$), while Hg ($r_{38} = -0.74, p < 0.001$) and LOI ($r_{38} = -0.64, p < 0.001$) declined with depth. LOI, Hg, and $\delta^{15}N$ exhibited no trend throughout the reference core taken in the middle of Flatey (filled symbols in Fig.2; all $p > 0.5$). The reference core closer to and above the seabird cliffs had consistent $\delta^{15}N$ and LOI with depth (both $p > 0.07$), but Hg declined rapidly deeper in the soil ($r_6 = -0.88, p = 0.02$).

Across all seabird sites, Hg significantly declined with increasing depth (linear mixed effects model, $\chi^2_1 = 8.275$, $p = 0.004$) and with increasing $\delta^{15}N$ ($\chi^2_2 = 40.5, p < 0.001$), but did not change with changes in LOI ($\chi^2_1 = 0.005, p = 0.94$).

DISCUSSION

Our main goals were to determine the concentration of Hg in surface soils near seabird colonies in western Iceland and to assess whether biotransport by seabirds may be contributing to elevated levels of Hg that could assimilate into local food webs. These same processes have been observed to varying degrees farther north in the Arctic (e.g., Choy et al., 2010; Kristiansen et al., 2019). Thus, with our sites having very high numbers of seabirds (Lilliendahl and Sólmundsson, 1997), similar marine food webs supporting elevated Hg in prey (e.g., McMeans et al., 2010), and analogous, rocky coastlines apt to receive elemental subsidies, we expected similar effects of biovector colonies in Iceland. However, our predictions were not supported; there was little evidence of elevated Hg in soils closer to seabird colonies than at reference sites, despite nitrogen isotopic signatures that clearly suggested a strong seabird influence (i.e., nitrogen derived from higher trophic–level subsidies through faeces; Blais et al., 2005) near seabird areas. In general, soil Hg at these sites was not markedly different from that noted in limited information from elsewhere in Iceland.

To date, our knowledge of Hg in many Arctic soils is quite poor (Gamberg et al., 2015; Kristiansen et al., 2019), a lack influenced in part by the high costs and logistical challenges of working in this part of the world (Mallory et al., 2018). However, as a subarctic region with large geomorphological diversity and active volcanism, soils of Iceland are perhaps better studied (Arnalds, 2004). Volcanic and aeolian contributions figure prominently in the formation of Icelandic soils, although like other Arctic regions, cryoturbation and other periglacial processes may also be very important (Arnalds, 2015). In terms of soil Hg concentrations, information from Iceland is limited but current. For example, Kolon et al. (2020) reported soil Hg concentrations ranging from 10–300 ng/g, and Mutia et al. (2021) found similar concentrations (50–150 ng/g) near and distant from Icelandic power plants.

In a study of Hg content in volcanic soils across Europe, Peña-Rodríguez et al. (2012) found Hg concentrations ranging from 3–640 ng/g. They noted that Hg accumulation is strongly influenced by the degree of evolution of the volcanic soils and the presence of metal-humus complexes, organic matter, and inorganic Al and Fe compounds. They also noted that the degree of pedogenetic soil evolution strongly influenced total Hg soil content and that lithogenic Hg could account for up to 320 ng/g in a soil sample (Peña-Rodríguez et al., 2012). Lithogenic Hg appeared to be most strongly correlated to Al–humus complexes and clay content, suggesting that soil-forming processes are an important factor in the total Hg content of volcanogenic soils.

The mean Hg concentrations we observed in surface soils (~220 ng/g) fell in the range reported in these earlier studies, despite the fact that thousands of seabirds nest on and fly around our study islands, defecating at sites and resulting in the delivery of Hg subsidies to receiving soils (e.g., Signa et al., 2013; Geizer et al., 2021). In a study of Hg in lambs (*Ovis aries*; that ate plants growing in Icelandic soil), Reykdal and Thorlacius (2001) found generally low Hg concentrations across Iceland compared to other countries, with the northwest region showing similar or lower levels of Hg than elsewhere in Iceland, suggesting that the risk of ingestion of Hg under these conditions were very low, at least for herbivorous livestock at that time.

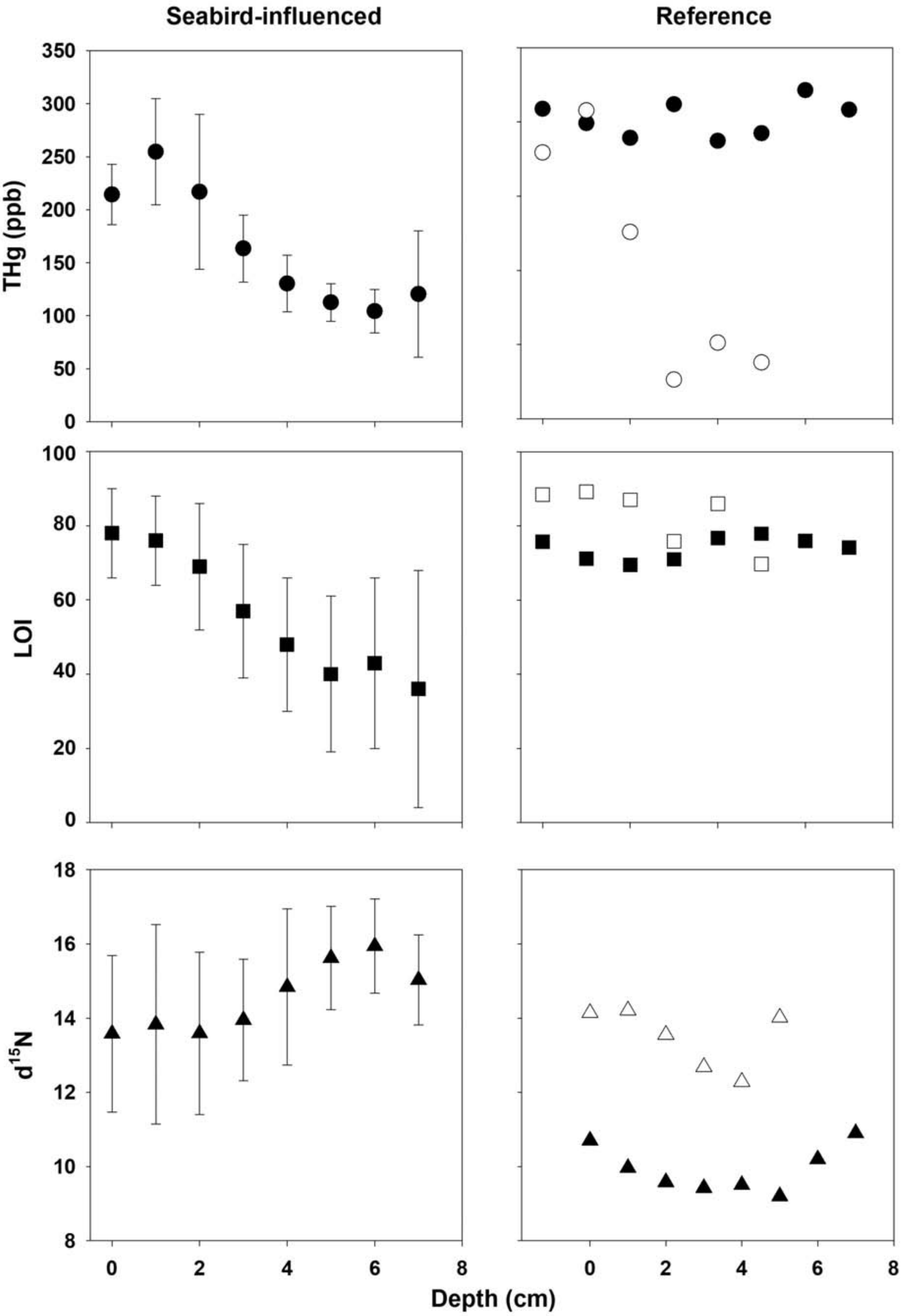


FIG. 2. Mean ± SD patterns of THg (ng/g; top panels), loss on ignition (LOI, %; middle panels), and d^{15}N (‰; bottom panels) in seabird-influenced (left panels; n = 5) and reference (right panels; n = 2) soil samples. On the right hand panels, the filled symbols are values from the reference site in the middle of the island, while open symbols are the clifftop reference site.

From an environmental health perspective, these soil Hg values are very low compared to soil Hg concentrations typical of Hg-contaminated sites, and well below international risk thresholds, which vary from 500 – 10,000 ng/g, depending on the location and activity (CCME, 1999; Panagos et al., 2021). For example, at a contaminated site in Poland, surface Hg soil concentrations ranged from 122,000 – 393,000 ng/g (Boszke et al., 2008), and there are numerous sites in North America and Asia where the target concentrations to reduce Hg in soils is 1500 ng/g (Ma et al., 2015), approximately 10 times higher than the typical concentrations we found.

While these Hg values provide coarse measures for comparison, the complexities of chemical reactions in soils that might affect Hg concentrations are numerous (Evans, 2007; Gamberg et al., 2015; O'Connor et al., 2019), as are issues of atmospheric Hg flux to, and Hg(0) loss from, soils (e.g., O'Connor et al., 2019; Pannu et al., 2014). It is therefore difficult to compare among sites and processes, especially when we did not measure other soil chemistries that can affect mercury retention and loss (e.g., soil texture, pH, water content, temperature flux, and microbiology; Schuster, 1991; O'Connor et al., 2019). For example, our mean soil Hg concentrations were at the higher end of the range of studies that have reported Hg at seabird colonies (Table 1). Although some of these studies found significantly lower Hg in reference site soils compared to colony soils (e.g., McIntyre et al., 2022), other studies failed to find significant differences in concentration (e.g., Kristiansen et al., 2019; Shoji et al., 2019). Even when we consider Hg in Arctic soils without seabird influence, study results suggest the presence of a broad range of concentrations, possibly resulting from a number of different influences. Loseto et al. (2004), for example, found concentrations of Hg in Canadian Arctic soils averaging 46 ng/g, approximately 25% of the concentrations at our study sites. At first glance, this would suggest our findings showed high Hg. Yet, in Loseto et al. (2004), the range of concentrations (10 – 250 ng/g) was wide enough to cover most of the concentrations we found in our Icelandic cores. Other samples from the central and western Canadian Arctic measured Hg values of 26 – 303 ng/g (Gamberg et al., 2015), again with median values lower than what we found, but also with a broad range of concentrations. Collectively, all of these values fall within the typical range of Hg concentrations of surface soils, generally considered 50 – 300 ng/g (Kabata-Pendias, 2000; Panagos et al., 2021).

TABLE 1. Mean (range or ± standard deviation) Hg in soils from seabird colonies in this and previous studies.

Seabird type	Location	Hg (ng/g)
Various[1]	Breiðafjörður, Iceland	214 (± 28)
Gull[2]	Nova Scotia, Canada	76 – 373 (55 – 638)
Gull[3]	New Brunswick, Canada	151 – 240 (25 – 425)
Gull[4]	Cíes Islands, Spain	198 (± 49)
Gull[5]	Atlantic Islands National Park, Spain	120 (± 40)
Penguin[6]	South Shetland Islands, Antarctica	28 – 247
Auklet[7]	Hokkaido, Japan	60 (± 10)
Various[8]	Svalbard, Norway	46 (± 29)
Various[9]	Global	20 – 200

[1] This study; [2] McIntyre et al., 2022; [3] Otorowski, 2006; [4] Otero and Fernández-Sanjurjo, 2000; [5] De La Peña-Lastra et al., 2019; [6] Cipro et al., 2019; [7] Shoji et al., 2019; [8] Kristiansen et al., 2019; [9] De La Peña-Lastra, 2021

Our short soil cores did exhibit some interesting patterns. For example, even with only ~7 cm depth, there were declines in LOI (a proxy for organic content) and increases in $\delta^{15}N$ with increasing depth. The decline in organic content was predictable (e.g., Wang et al., 2004), certainly for short cores, as the boundary of organic (upper) and inorganic (lower) layers is not far apart, and many Icelandic lithologies weather rapidly (Arnalds, 2015). Moreover, ammonia volatilization in guano-influenced soils can impact $\delta^{15}N$ concentrations (Mizutani and Wada, 1988), and nitrogen transformation processes at depth typically lead to increasing $\delta^{15}N$ (e.g., Evans, 2007; Hobbie and Ouimette, 2009), so this pattern was also consistent with previous work. We did not analyze the factors that might influence the decline in Hg with depth. However, Hg binds to organic material, the concentration of which was reduced at greater depth, so this may be a major contributor. Peña-Rodríguez et al. (2012) also noted a decline, with depth, in soil Hg, and attributed this, in part, to reduced concentrations of metal-humus deeper in soils. As well, Icelandic soils are noted for their high ability to hold moisture (Arnalds, 2015). We suspect that soils under the seabird nesting sites, which are largely shallow, underlain by bedrock, and near the coastline, were very regularly wet at depth (with more exposure to fog, sea spray, waves, and runoff due to proximity to the ocean; Fig. 3), which influenced Hg movement (Pannu et al., 2014). McIntyre et al. (2022) sampled soils at four seabird nesting colonies, showing that soils at the waterlogged site held far less Hg despite having much higher densities of nesting gulls (although water at those sites had higher MeHg; Kickbush et al., 2018). As such, moisture content and site-specific dynamics may also influence Hg in these soils. Interestingly, the main reference core taken near a field in the centre of the island showed no consistent change in LOI or Hg with increasing depth (all the way to 1 m; not shown in Fig. 2). It was a much deeper core and much less affected by high waves or other local water movement, and with the bedrock much deeper, water likely drained better through soil, creating less influence on Hg.

Irrespective of the variation in Hg with depth, what is notable is that the Hg concentrations in soil at the reference sites were similar to the seabird cores and to those on the higher part of the range noted elsewhere in Iceland (Kolon et al., 2020; Mutia et al., 2021). Clearly seabird faeces are providing Hg subsidies at the islands (e.g., Shoji et al., 2019; Geizer et al., 2021), at least at the nesting sites. Perhaps through local transportation processes (wind, fog, spray), seabird faeces may also affect inland sites, presumably close to the coast (e.g., Hargan et al., 2017), but in our case we

FIG. 3. View from one of the sampling locations on Hafnarey looking towards a kittiwake colony (researcher with net trying to catch birds), showing proximity to ocean and potential to receive sea spray, high waves, and fog. Flatey is in the background. (Photo: Mark Mallory)

would have expected higher $\delta^{15}N$ at the main reference site and we did not see that. Nevertheless, marine-derived Hg may be distributed to much of the island, and true reference sites would need to be found farther from the nesting area, perhaps along the coastal mainland. Alternatively, lithogenic Hg may be a significant source of the total Hg measured; in that case, analysis of pedogenic processes at all sites may be required to accurately determine the seabird contribution. Cores of additional island and coastal soil would help resolve the degree to which the Hg levels found in all cores at Flatey and Hafnarey were seabird-influenced.

Given that the Hg concentrations were within a normal range in soils (Kabata-Pendias, 2000), does this mean that the pattern of measured Hg concentrations changing with soil depth are not an issue at seabird colonies? At this point, we suggest that additional work is clearly required. Our focus was on total Hg, and we did not examine other aspects of soil chemistry or mercury speciation. Many researchers are linking warming climates, increasing soil decomposition rates, and consequent increased nutrient availability to potential enhancements of MeHg availability (e.g., Paranjape and Hall, 2017; Obrist et al., 2018), notably in wet soils like those in the Arctic (Gamberg et al., 2015) and Iceland (Arnalds, 2015). In earlier work in a bog system we showed that avian biovector nesting locations had little spatial relation to concentrations of total Hg in pore water in soils, but nesting density matched well with MeHg and phosphate concentrations, presumably due to enhanced chemical responses in the bog to excess phosphate from bird guano (Kickbush et al., 2018).

There is much we still do not understand about Hg, biotransport and the role that other chemical reactions and pedogenic processes may play in Hg mobilization in food webs. At our field site in particular, we suspect that the volcanogenic parent material for the soils may complicate the interpretation of our data. However, our survey of soils at seabird-colony islands in west Iceland did not find markedly higher Hg near nesting sites, nor substantially higher Hg in soils compared to elsewhere in the subarctic and Arctic, despite nesting and ornithogenic subsidies from thousands of seabirds that have high Hg in their guano (e.g., Albert et al., 2021; Geizer et al., 2021). The fate of this ornithogenic Hg at these sites remains unclear but does not currently appear to pose a risk for enhanced Hg accumulation in local terrestrial food webs. However, a key next step is to determine how much of this Hg is methylated to MeHg; seabird-influenced soils may have typical total Hg concentrations, but MeHg could be increased by fertilization (Kickbush et al., 2018), enhancing uptake into coastal food webs.

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