Early soil development on Surtsey Island: insights from 20 profile descriptions

SUSANNE CLAUDIA MÖCKEL[1*] AND BJARNI D. SIGURDSSON[1]

[1]Faculty of Environmental and Forest Sciences, Agricultural University of Iceland, Árleynir 22, 112 Reykjavík, Iceland
*Corresponding author: susanne@lbhi.is

ABSTRACT

Surtsey, a young volcanic island under strict protection from human activities, provides a unique natural laboratory to study soil formation on newly formed land. In July 2024, we examined 20 soil profiles across the island under varying influence of seabird activity and vegetation cover. Although all profiles reflected early-stage pedogenesis, seabird activity and vegetation clearly enhanced horizon development and organic matter accumulation, as reflected by frequent O and Bw horizons at vegetated sites within bird colonies. In contrast, sparsely vegetated or barren sites outside seabird colonies showed minimal organic matter accumulation, with no O-horizons and only occasional weakly developed Bw horizons. Our visual descriptions of soil profiles corroborate previous studies showing the strong role of ornithogenic inputs in organic matter and nutrient accumulation on the island. Future research should aim to better understand the influence of ornithogenic inputs and vegetation on weathering processes and the formation of secondary pedogenic minerals in soils of the island.

INTRODUCTION

Formed during a sub-oceanic volcanic eruption over the years 1963 to 1967, and protected since 1965, Surtsey island has for several decades served as a pristine natural laboratory for studying early succession of life on newly formed land without human interference (Einarsson 2009). Systematic monitoring of vegetation, birds, and other organisms is conducted on the island on a regular basis. Various other studies have been carried out more sporadically, including several on soil development and soil properties.

Surtsey offers a unique opportunity to follow the early stages of soil development on young land in real time – knowledge which becomes increasingly relevant as new land emerges, e.g. in front of receding glaciers (e.g. Vilmundardóttir *et al.* 2015). The majority of pedogenic studies on Surtsey so far have focused on the accumulation of soil organic carbon (SOC) and nitrogen (e.g. Leblans *et al.* 2014, Stefansdottir *et al.* 2014) and on the nutrient status of the island´s soils (e.g. Aerts *et al.* 2020, Sigurdsson & Leblans 2020). A few studies have also been conducted on soil organisms, first and foremost bacteria (Marteinsson *et al.* 2015) and nematodes (Ilieva-Makulec *et al.* 2015). The overriding and common narrative of these studies is the great importance of the seagull colony on the island for soil development and soil characteristics. For example, a study on soil nutritional parameters by Aerts *et al.* (2020) found higher N and P concentrations in soils from within the colony than outside, with higher N concentrations in shallow soils than in deep soils. By comparing the nitrogen isotopic fingerprints of bird faeces and pellets, soils and vegetation, the authors demonstrated that most of the N accumulation in soils in the bird colony was derived from the influx of ornithogenic organic material. At the northern spit of the island, seal colonies also contribute to the input of nutrients from the sea to the land (Magnusson *et al.* 2020).

The importance of birds for soil formation is also known elsewhere, for example in coastal areas of Antarctica, where the redistribution of nutrients from the ocean to land through birds positively influences soil organic carbon and nutrient levels (Bockheim 2015). Importantly, the influence of seabirds there is known to reach beyond the boundaries of their colonies, as wind erosion and water solutions can distribute nutrients to areas distant from the bird colonies. Seabirds can also play a role in shaping soil characteristics in warmer and drier climatic zones. For instance, in the gulf of California, Wait *et al.* (2005) demonstrated significantly higher soil moisture contents, soil respiration rates, higher N, P and K contents, and $\delta^{15}N$ enrichment in arid soils affected by ornithogenic organic influxes than in soils with similar climatic conditions not affected by seabirds.

In July 2024, descriptions of soil profiles were conducted across Surtsey to gain a general overview of the state of soil formation, the variety of soils found, and to form a foundation for further research on soil development on this young land. Below, we provide an overview of the field work approach, as well as the described soil profiles. Suggestions for future research are also discussed.

METHODS

Site selection and soil profile descriptions

Fieldwork for soil profile descriptions took place between 16. and 18. July 2024. All soil profiles were located near permanent vegetation survey plots of the island (≤ 5 m from each plot). A subsample of 20 plots was chosen (Fig. 1) based on the seabird influence, density and type of vegetation cover, topography and type or grain size of parent material.

Eight vegetated sites within a seagull colony (dominated by *Larus fuscus;* sites 1, 3, 4, 6, 7, 8, 9, 10), five sparsely vegetated sites under some influence of seabirds (sites 12, 22, 23, 30, 37) and seven sparsely vegetated or unvegetated sites under little influence of birds (sites 13, 14, 15, 16, 18, 19, 21) were described (Fig. 1). Sites 30 and 37 additionally receive nutrients from seal colonies. By the time of fieldwork, the seagull colony had been established for nearly 40 years (since 1986) and had increased in area and number of birds since that time (Magnusson *et al.* 2020, Magnusson & Magnússon 2000). Amongst dominant vascular plants at permanent vegetation monitoring plots in the colony are *Leymus arenarius, Poa pratensis, Tripleurospermum maritimum, Stellaria media, Festuca richardsonii, Puccinelia coarctata* and *Honckenya peploides* subsp. *diffusa.* (Table 1).

At each site, a soil pit of ≤ 1 m was dug, which at many sites allowed for excavation of complete soil profiles. At some sites (particularly at slopes), the total soil depth exceeded 1 m. For each soil profile, horizon occurrence and depth were recorded. For each soil horizon, clearness and shape of horizon boundary, Munsell soil colour, structure, consistence, roots and texture were recorded following Schoeneberger *et al.* (2012). Soils ≥ 30 cm deep were defined as deep, soils < 30 cm were defined as shallow.

Soils at sites 1, 3, 4 are relatively deep, forming from tephra-sands deposited on sheet lava, and from organic remains from local vegetation. Soils at sites 6-10 are rather shallow, likewise forming from tephra-sands overlying sheet lava, and from vegetation remains. Soils at sites 22 and 23 are

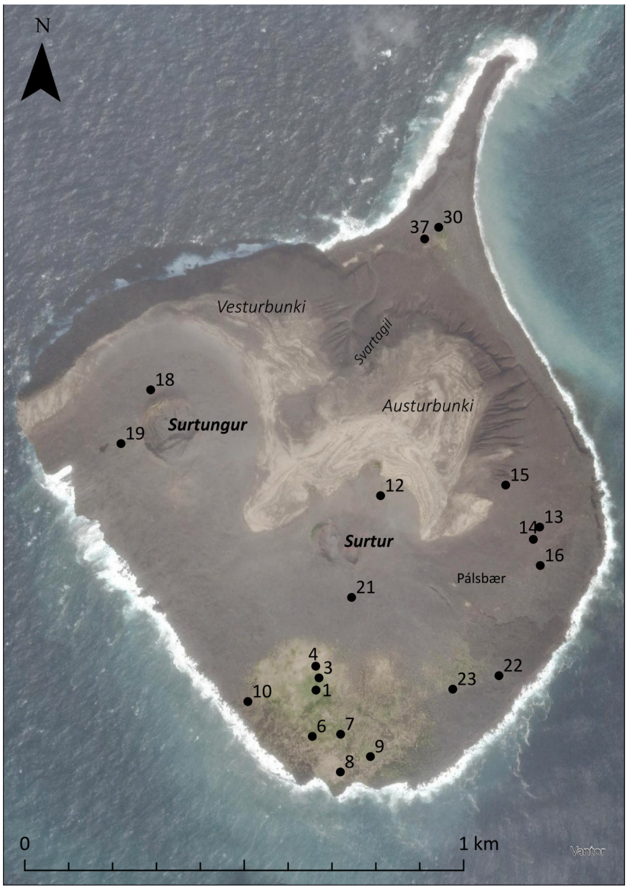

Figure 1. Aerial view of Surtsey showing the main place names on the island and the locations of the soil profiles described in this study (numbered dots). The numbers correspond to permanent vegetation survey plots. Basemap from Esri *et al.* (2023).

shallow, forming in rather fine-grained tephra on sheet lava. Soils at sites 30 and 37 are deep (> 1 m), forming in sand deposits; notably, the environment of these sites is very dynamic, with constant erosion and deposition of material by wave action. Soils at sites 12, 13, 14, 15 and 21 form in tephra sand of various grain size overlying sheet lava; soils of sites 12, 15 and 21 are deep soils, while soils at sites 13 and 14 are rather shallow. Finally, soils at sites 18 and 19 are shallow, forming in coarse-grained tephra on sheet lava, in close vicinity to the crater Surtungur (Fig. 1).

RESULTS AND DISCUSSION

Ornithogenic influence on soil development

Our profile descriptions reflect the strong ornithogenic influence on the island´s soils, as shown by earlier studies on SOC and nitrogen (Aerts *et al.* 2020, Leblans *et al.* 2014, Sigurdsson & Leblans 2020), but no such profile descriptions have been published before for the island.

All profiles showed soils at very early stages of soil formation, with soil colour ranging from dark brown to black (Tables 1 and 2). Colour mainly reflects the volcanic mineral parent material, though significant

Table 1. Selected soil morphological properties for vegetated sites within a seagull colony with deep and shallow soils. Profile descriptions followed Schoeneberger *et al.* (2012). Colour codes: 7.5YR 2.5/2 = very dark brown, N 2.5/0 = black, 7.5YR 4/2 = brown, 7.5YR 3/2 = dark brown, 10YR 2/2 = very dark brown, 7.5YR 3/1 = very dark gray, 10YR 3/2 = very dark grayish brown. Structure (grade, size, type): 1 = weak, f = fine, m = medium, co = coarse, gr = granular. Roots: 1 = few, 2 = common, 3 = many, vf = very fine, f = fine, m = medium.

Pedon no.	Horizon	Depth (cm)	Boundary	Colour	Structure	Consistence	Roots	Texture	Dominant vegetation
Vegetated sites, deep soils									
1	O	0 – 5	abrupt smooth	7.5YR 2.5/2	NA	NA	3 vf, 2 f	NA	*Leymus arenarius, Poa pratensis, Tripleurospermum maritimum, Stellaria media*
	OBw	5 – 12	abrupt smooth	O: 7.5YR 2.5/2; Bw: N 2.5/0	1, f, gr	NA	3 vf, 2 f	loamy sand	
	C	12 – 35		N 2.5/0	1, m-co, gr	loose	3 vf	sand	
3	O	0 – 4	abrupt smooth	7.5YR 2.5/2	NA	NA	3 vf, 3 f, 2 m	NA	*Leymus arenarius, Poa pratensis*
	OBw	4 – 12	abrupt smooth	O: 7.5YR 2.5/2; Bw: N 2.5/0	1, f, gr	NA	3 vf, 3 f, 2 m	loamy sand	
	C	12 – 32		N 2.5/0	1, m-co, gr	loose	3 vf, 1 f, 1 m	sand	
4	O	0 – 7	abrupt smooth	7.5YR 2.5/2	NA	NA	3 vf, 3 f, 2 m	NA	*Leymus arenarius, Poa pratensis*
	C	7 – 77		N 2.5/0	1, m-co, gr	loose	3 vf, 1 f, 1 m	sand	
Vegetated sites, shallow soils									
6	O	0 – 14	clear smooth	7.5YR 4/2	NA	NA	3 f	NA	*Festuca richardsonii, Stellaria media, Poa pratensis*
	OBw	14 – 20		7.5YR 3/2	1, f, gr	very friable	3 f	loamy sand	
7	O	0 – 10	clear smooth	7.5YR 4/2	NA	NA	3 f	NA	*Festuca richardsonii, Poa pratensis*
	OBw	10 – 19		7.5YR 3/2	1, f, gr	very friable	3 f	loamy sand	
8	O	0 – 4	abrupt smooth	7.5YR 2.5/2	NA	NA	3 f	NA	*Festuca richardsonii, Puccinellia coarctatas, Poa pratensis*
	Bw	4 – 22		10YR 2/2	1, f, gr	very friable	3 f	loamy sand	
9	O	0 – 10	abrupt smooth	7.5YR 2.5/2	NA	NA	3 f	NA	*Festuca richardsonii, Poa pratensis*
	Bw	10 – 28		10YR 2/2	1, f, gr	very friable	3 f	loamy sand	
10	OC	0 – 4	abrupt smooth	7.5YR 3/1	1, f, gr	NA	3 vf, 2 f	sand	*Festuca richardsonii, Honckenya peploides* subsp. *diffusa, Leymus arenarius*
	C	4 – 16		10YR 3/2	1, f, gr	loose	3 vf, 2 f, 1 m	sand	

vegetation cover adds organic influence at some sites. Soil structure is generally weakly developed, dominated by single-grain horizons; some vegetated sites show weak granular structure, typically with loamy sand texture, while other horizons are mostly sandy (Tables 1 and 2).

Despite the characteristics of early-stage soil formation in all profiles, clear differences emerge between the vegetated soils within the seagull colony and sparsely or unvegetated soils under lower seabird influence (Fig. 2 and 3, Tables 1 and 2). Profiles in the colony (1, 3, 4, 6–10) exhibit O or OC horizons at the surface, with high organic content sometimes mixed with mineral material. Many also have young Bw (or OBw) horizons, indicating early pedogenic mineral formation. Likely, ornithogenic inputs not only enhance vegetation establishment and contribute organic matter to the soils but also shape weathering processes and secondary mineral formation. While the glassy nature and high porosity of volcanic ejecta facilitates high weathering rates and rapid soil formation, not least in volcanic areas dominated by basaltic materials (Bonatotzky *et al.* 2021, Ugolini & Dahlgren 2002), abiotic and biotic factors play a regulating role. For example, the influence of seabirds on soil pH could be of importance for weathering rates (Oelkers and Gislason 2001) and the formation of some secondary minerals. Sigurdsson and Magnusson (2010) demonstrated an average pH of 6.7 in soils from vegetated sites within the seagull colony in contrast to a higher average soil pH of 7.6 in non- or sparsely vegetated soils outside the colony. This significantly lower pH of the bird influenced soils might promote the formation of allophane, which is favoured at pH 5-7 (Parfitt 2009). Haus *et al.* (2016) demonstrated that oxalic acid in guano enhanced weathering of tephra and precipitation of poorly crystalline minerals in young soils of Antarctica. The reduction of pH with increased vegetation colonisation and organic matter decomposition of parent material of basaltic origin may, however, not be solely a direct response to the seabird allochthonous inputs. Similar reductions in pH have also been found in young soils on nunataks

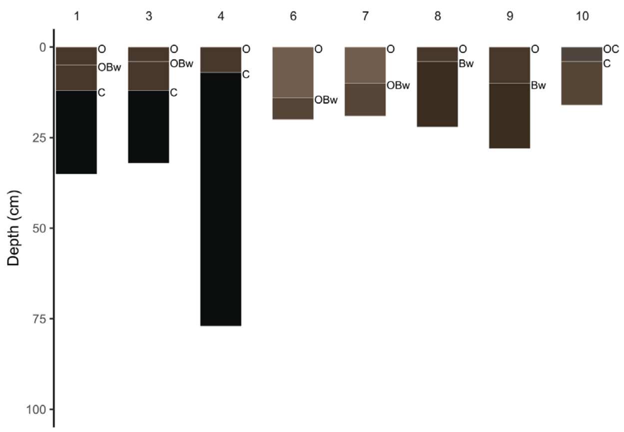

Figure 2. Schematic illustration of soil horizonation at vegetated sites on Surtsey island. Sites 1, 3 and 4 have relatively deep soils (≥ 30 cm), while sites 6 - 10 have shallow soils (< 30 cm).

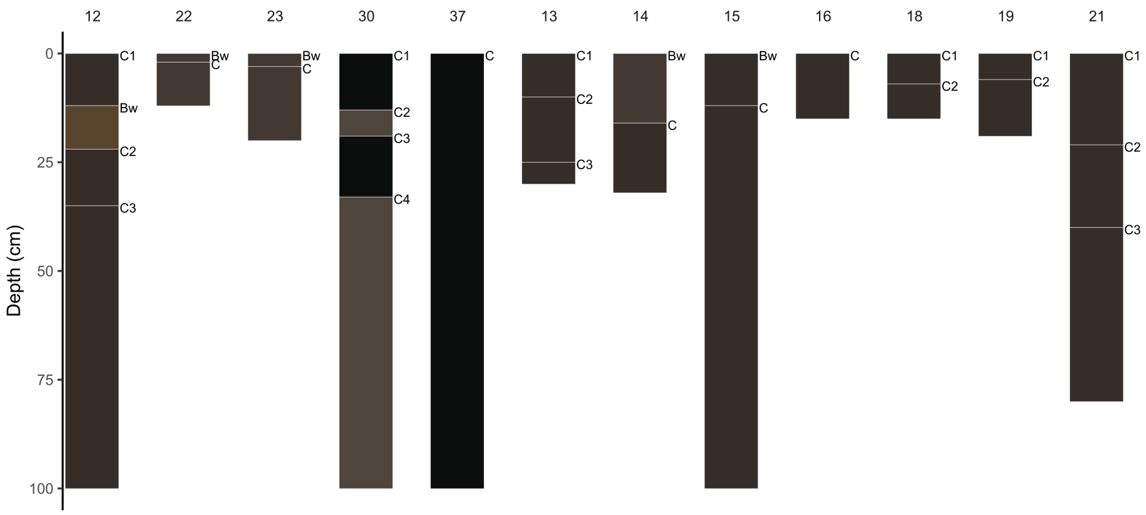

Figure 3. Schematic illustration of soil horizonation at sparsely vegetated or barren sites on Surtsey island. Sites 12, 15, 21, 30 and 37 have deep soils (≥ 30 cm), while sites 13, 14, 16-19, 22 and 23 have shallow soils (< 30 cm). The total soil depth of profiles reaching 100 cm exceeded 1 m. Some influence of seabirds is at sites 12, 22, 23, 30 and 37, while seabird influence is little at sites 13, 14, 15, 16, 18, 19 and 21.

Table 2. Selected soil morphological properties for sparsely vegetated or barren sites under some (12, 22, 23, 30, 37) or little influence of seabirds (13, 14, 15, 16, 18, 19, 21). Profile descriptions followed Schoeneberger *et al.* (2012). Colour codes: 10YR 2/1 = black, 10YR 3/3 = dark brown, N 2.5/0 = black, 10YR 3/1 = very dark gray; 7.5YR 2.5/1 = black. Structure (grade, size, type): 1 = weak, f = fine, m = medium, gr = granular, sg = single grain. Roots: 1 = few, 2 = common, 3 = many, vf = very fine, f = fine, m = medium.

Pedon no.	Horizon	Depth (cm)	Boundary	Colour	Structure	Consistence	Roots	Texture	Dominant vegetation
Sparsely vegetated or barren sites, deep soils									
12	C1	0 – 12	abrupt smooth	10YR 2/1	sg	loose	3 vf	sand	*Tripleurospermum maritimum, Silene uniflora, Leymus arenarius, Honckenya peploides* subsp. *diffusa, Rumex acetosella*
	Bw	12 – 22	clear smooth	10YR 3/3	sg	loose	3 vf	sand	
	C2	22 – 35	clear smooth	10YR 2/1	sg	loose	2 vf	sand	
	C3	35 – > 100		10YR 2/1	sg	loose	2 vf	sand	
15	Bw	0 – 12	clear smooth	10YR 2/1	sg	loose	2 vf	sand	*Honckenya peploides* subsp. *diffusa, Leymus arenarius*
	C	12 – > 100		10YR 2/1	sg	loose	2 vf, 1 f	sand	
21	C1	0 – 21	clear smooth	10YR 2/1	sg	loose	1 vf	sand	*Honckenya peploides* subsp. *diffusa, Silene uniflora*
	C2	21 – 40	clear smooth	10YR 2/1	sg	loose	very few vf	sand	
	C3	40 – 80		10YR 2/1	sg	loose	none	sand	
30	C1	0 – 13	abrupt smooth	N 2.5/0	sg	loose	2 vf, 1 f	sand	*Leymus arenarius, Honckenya peploides subsp. diffusa, Cakile maritima* subsp. *islandica*
	C2	13 – 19	abrupt smooth	10YR 3/1	sg	loose	2 vf	sand	
	C3	19 – 33	abrupt smooth	N 2.5/0	sg	loose	1 vf	sand	
	C4	33 – > 100		10YR 3/1	sg	loose	3 vf, 2 f	sand	
37	C	0 – > 100	NA	N 2.5/0	sg	loose	none	sand	*Leymus arenarius, Honckenya peploides* subsp. *diffusa, Cakile maritima* subsp. *islandica*
Sparsely vegetated or barren sites, shallow soils									
13	C1	0 – 10	clear smooth	10YR 2/1	sg	loose	1 vf	sand	*Leymus arenarius, Honckenya peploides* subsp. *diffusa, Silene uniflora*
	C2	10 – 25	abrupt smooth	10YR 2/1	sg	loose	1 vf	sand	
	C3	25 – 30		10YR 2/1	sg	loose	1 vf	sand	
14	Bw	0 – 16	abrupt smooth	7.5YR 2.5/1	sg	loose	2 vf	sand	*Honckenya peploides* subsp. *diffusa, Leymus arenarius, Silene uniflora*
	C	16 – 32		10YR 2/1	sg	loose	very few f	sand	
16	C	0 – 15		10YR 2/1	sg	loose	3 vf., 3 f, 1 m	sand	*Silene uniflora, Leymus arenarius, Honckenya peploides* subsp. *Diffusa*
18	C1	0 – 7	clear smooth	10YR 2/1	1, f, gr	loose	1 vf	sand	*Honckenya peploides* subsp. *diffusa, Silene uniflora, Armeria maritima* subsp. *maritima*
	C2	7 – 15		10YR 2/1	1, f, gr	loose	very few vf	sand	
19	C1	0 – 6	clear smooth	10YR 2/1	1, f, gr	loose	1 vf, 1 m	sand	*Honckenya peploides* subsp. *diffusa, Silene uniflora, Armeria maritima* subsp. *maritima*
	C2	6 – 19		10YR 2/1	1, f, gr	loose	very few vf	sand	
22	Bw	0 – 2	abrupt smooth	7.5YR 2.5/1	1, f, gr	very friable	3 vf	loamy sand	*Silene uniflora, Festuca richardsonii, Poa pratensis*
	C	2 – 12		7.5YR 2.5/1	1, f-m, gr	loose	2 vf, 2 f	sand	
23	Bw	0 – 3	abrupt smooth	7.5YR 2.5/1	1, f, gr	very friable	3 vf	loamy sand	*Silene uniflora, Festuca richardsonii, Poa pratensis*
	C	3 – 20		7.5YR 2.5/1	1, f-m, gr	very friable	3 vf	loamy sand	

(glacier islands) during primary vascular plant succession over longer time periods without bird allochthonous influences (Sigurdsson & Leblans 2020, Vilmundardóttir *et al.* 2014).

In sparsely and non-vegetated soils, organic accumulation is limited, yet profiles 12, 14, 15, 22, and 23 show early Bw horizons. At sites 12, 22 and 23 there is an increasing influence of seabirds in recent years, possibly enhancing weathering processes through addition of organic acids (Haus *et al.* 2016) and lowering of pH (Parfitt 2009, Sigurdsson & Magnusson 2010). Formation of Bw horizons at the less bird-influenced sites 14 and 15 may be influenced by the presence of deep-rooting plants *Leymus arenarius* and *Honckenya peploides* (Table 2). Work by Stefansdottir *et al.* (2014) identifies *Leymus arenarius* as a likely key factor for soil development on the island outside the seagull colony. They showed significantly increased N accumulation, and higher SOM levels in *Leymus arenarius* dunes, positively correlating with dune age.

Suggestions for future soil research on Surtsey island

We propose a timely investigation of weathering processes and the formation of clay-sized secondary minerals in the soils of Surtsey. Research on the amount and characteristics of pedogenic minerals has, to our knowledge, not yet been conducted on the island, despite the fundamental role these constituents play in soils. Clay-sized minerals are crucial for many soil properties and processes, including specific surface area, water holding capacity, nutrient retention, cation exchange capacity, pH buffering, organic matter accumulation, soil aeration, and more soil characteristics (Ito & Wagai 2017). Importantly, clay-sized minerals vary considerably in structure, composition, and chemical reactivity, which strongly influences the properties of individual soils.

A key characteristic of Andosols - soils formed from volcanic ejecta, such as in Iceland - is the formation of nanocrystalline clay-sized minerals allophane and imogolite, as well as ferrihydrite (Arnalds 2015). In warmer regions with xeric moisture regimes and sufficient Si in the soil solution, halloysite formation is favoured (Harsh 2012, Parfitt 2009). Allophane, the most common clay mineral in Icelandic Andosols, is closely linked to many characteristic properties of volcanic soils, including their high potential for organic matter stabilization, low bulk densities, great water holding capacities, poor cohesion and phosphorus fixation (Arnalds 2015). As this mineral, together with other nanocrystalline phases, profoundly shapes soil properties, its formation is a crucial indicator of pedogenesis in volcanic ejecta, and a fundamental component of the functioning of Andosols.

Thus, a timely question is whether seabirds not only influence organic matter accumulation in the soils of Surtsey but also influence weathering processes and the formation of pedogenic minerals. As discussed above, it is plausible that the island´s sea gull colony affects the formation of nanocrystalline mineral phases such as allophane, for instance through enhanced weathering and pH modification by ornithogenic material and vegetation (Haus *et al.* 2016, Parfitt 2009).

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