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Pellets of *Stercorarius* spp. (skua) as plant dispersers in the Antarctic Peninsula

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Abstract: The Antarctic Peninsula has experienced some of the most accelerated warming worldwide, resulting in the retreat of glaciers and creation of new areas for plant development. Information regarding the plant dispersal processes to these new niches is scarce in Antarctica, despite birds being important vectors elsewhere. Many bird pellets (with feed remains such as bones and feathers) are generated annually in Antarctica, which are light and easily transported by the wind and include vegetation that is accidentally or purposely swallowed. The aim of this study was to analyze the presence of plant fragments within skua (*Stercorarius*/*Catharacta* spp.) pellets collected from two sampling areas in the Maritime Antarctic: Stinker Point (Elephant Island, 17 samples) and Byers Peninsula (Livingston Island, 60 samples), in the South Shetland Archipelago, during the austral summers of 2018 and 2020. In both study areas, five species of Bryophyta were found that were associated with the pellets and viable in germination tests in a humid chamber. The ingestion of Bryophyta for the skuas contribute to the dispersion of different moss species, including to areas recently exposed by the ice retreat. This is the first demonstration that skua pellets effectively act in the dispersion of Antarctic mosses.

Key words: Antarctica, birds, propagation, vegetation.

INTRODUCTION

The warming of the Antarctic Peninsula over the last 50 years has been greater than any other terrestrial ecosystem in the Southern Hemisphere, with consequences being observed in the cryosphere and biology of species. The most affected regions are the Antarctic Peninsula, Maritime Antarctic, and the majority of western Antarctic (Bromwich et al. 2013, Siegert et al. 2019). This warming has resulted in the loss of ice and glaciers, with exposure of soil and rocks (Cook et al. 2014, Convey & Lewis Smith 2006, Thomazini et al. 2014). This ice cover retreat provides new habitats for the colonization of plants, animals, and microorganisms (Parnikoza et al. 2009, Siegert et al. 2019), but the widely reported warming trend has paused since the late 1990s (Turner et al. 2016).

Antarctic terrestrial vegetation is restricted to ice-free areas, occurring directly on rocks or soil at different developmental stages. The main plant formations are composed of bryophytes (116 species), lichens (ca. 400 species), macroscopic terrestrial algae (four species), and two species of native vascular plants, *Deschampsia antarctica* Desv. (Poaceae) and *Colobanthus quitensis* (Kunth.) Bartl. (Caryophyllaceae) and the invasive *Poa annua* L. (Øvstedal & Lewis Smith 2001, Putzke & Pereira 2001, Ochyra et al. 2008, Pereira & Putzke 2013, Câmara & Carvalho-Silva 2020).

Information regarding the colonization of mosses in newly exposed areas is attributed to the dispersion of fragments of bryophytes or their spores by the wind (Seppelt et al. 2004). An increase in the frequency of sporophyte formation and, consequently, spores may be occurring and would likely be expected, according to more recent studies, which is probably associated with climatic changes (Convey & Lewis Smith 1993, Lewis Smith & Convey 2002, Casanova-Katny et al. 2016, Erin et al. 2017).

Animal-mediated dispersion of Bryophyta has been discussed in numerous works around the world, including studies with mammalians (Heinken et al. 2001, Pauliuk et al. 2011, Parsons et al. 2007, Barbé et al. 2016), ants (Rudolphi 2009), slugs (Kimmerer & Young 1995) and birds (Chmielewski & Eppley 2019, Wilkinson et al. 2017, Osorio-Zuñiga et al. 2014, Breil & Moyle 1976), but only recently were studied in Antarctica.

In some regions of Maritime Antarctic, birds have been described as important vectors for the dispersion of plants and the transportation of seeds and plant fragments during nesting activity (Marshall & Convey 1997, Vera 2011, Parnikoza et al. 2012). Birds of the *Stercorarius* genus (Antarctic skuas) are an example, as they use different types of substrates to build their nests, including mosses, lichens, and angiosperms (Albuquerque et al. 2012, Costa & Alves 2008, Parnikoza et al. 2009). However, the participation of these transporting plant propagules in the Antarctic requires better evaluation (Parnikoza et al. 2012).

Evaluating hummingbird nests, it was found that incorporated bryophyte leaves and stems established and grew, suggesting that nesting behavior can disperse bryophytes (Osório-Zuñiga et al. 2014). Some experiments have demonstrated that waterfowl may be able to vector bryophyte material (spores and plant fragments) internally (Proctor 1961, Wilkinson et al. 2017). The presence of mosses associated with bird pellets has been also reported in the literature. The moss *Aplodon wormskioldii* (Hornem.) R.Br. (Splachnaceae), for example, grows in owl pellets, and uses this substrate for its growth and development in Alaska (Koponen 1990).

Skuas from the Signy Islands were observed breaking up mosses, which were then blown by the wind. This type of action is common throughout the Antarctic, with the removal of mosses to make nests or for other reasons, which can contaminate feathers, legs, and beaks and with fragments ingested probably accidentally (Davis 1981). Skuas can feed on animals or their remains, including placentas and carrion from different marine mammals, fish, and krill, which are normally also consumed on ground sometimes covered by mosses (Carneiro et al. 2014, Reinhardt et al. 2000).

Unlike other regions, in cold environments, animals ingest many mosses, which might be due to the presence of arachidonic acid that confers greater resistance to the cold environment (Prins 1982). However, some authors still believe that the ingestion of mosses by birds is incidental and do not play an important role in dietary requirements (Russo et al. 2020).

Using bryophytes as food or material to build their nests, birds can contribute to their dispersion. Spores and fragments use wind dispersal to reach other environments; however, attaching to the body of an animal may be another transport mechanism (Chmielewski & Eppley 2019, Russo et al. 2020).

Pellets are the food remains of carnivorous birds, which are composed of nondigestible parts, mainly feathers and bones that will later be “vomited” in the form of pellets (Votier et al. 2003). *Stercorarius* spp. (former *Catharacta*) pellets as vectors of plant dispersion in the Antarctic have not yet been analyzed because most studies have focused on the type of diet and foraging of the species (Votier et al. 2003, Borghello et al. 2019, Steele & Cooper 2012, Mund & Miller 1995, Malzof & Quintana 2008, Baker & Barbraud 2001).

The presence of mosses and other unidentified plant fragments in skua pellets found in the Antarctic has been mentioned, but only because they were ingested probably to clean the digestive tract of parasites (Santos et al. 2012). The marked change in the composition of *S. maccormicki* pellets from a predominance of penguin feathers at Potter Cove (King George Island) to mosses at Cierva Point (Antarctic Peninsula) suggests an alternative function of feather ingestion (Santos et al. 2012). The elimination of undigested material in pellets impedes the growth of gastric parasite populations in birds that feed on fishes (Piersma & Van Eerden 1989).

Studying areas of recent ice retreat at Stinker Point (Elephant Island) and Byers Peninsula (Livingston Island), we found a large number of pellets partially covered by associated moss formations, indicating some relationship type. The influence of this form of dispersion and colonization by mosses in environments recently exposed to de-icing is analyzed and discussed here. The present study aimed to analyze skua (*Stercorarius* spp.) pellets as a source of moss inoculum for colonization of newly exposed areas in the Antarctic region.

MATERIALS AND METHODS

Study area

The Stinker Point (Elephant Island) and Byers Peninsula (Livingston Island), 340 km apart, where chosen among the South Shetland Archipelago to do this study due to the ease of access provided by the Brazilian Antarctic Program.

The Stinker Point region (61° 13’ S, 55° 21’W) is located on the southwest coast of Elephant Island, Antarctic (Figure 1), north of the South Shetland Archipelago, approximately 153 km from King George Island. Stinker Point has a coastline that is 4,300 m in length, with 13 beaches composed of sand, pebbles, and boulders. In addition to having plateau areas with steep cliffs and large fields of moss on top (Petry et al. 2018), it is rich in floristic diversity and is composed of two vascular plant species, *D. antarctica* Desv. (Poaceae) and *C. quitensis* (Kunth.) Bart. (Caryophyllaceae), 38 moss species, seven species of liverworts, 68 species of lichens, and four species of macroscopic fungi (Pereira & Putzke 1994, Schmitz et al. 2020).

The Byers Peninsula (62°34’35’S, 61°13’07’ W) is located at the western end of Livingston Island, and is the second largest island in the South Shetland Archipelago, Antarctic (Figure 2), comprising an area of 60,35 km^2. This area has extensive beaches, and is 12 km long and 900 m wide (Praia Sul), and is the most extensive in the South Shetland Archipelago (Ivanov 2015). The peninsula has a wide variety of periglacial relief forms, such as felsenmeers, terrains with patterns, rocky glaciers, and raised marine platforms (Quesada et al. 2009). During the summer, the peninsula contains many streams and more than 60 lakes and ponds (Toro et al. 2007). The vegetation cover consists of lichens that colonize inactive or weakly active periglacial landforms and rocky outcrops and moss carpets, which are abundant in poorly drained areas. There are two vascular plants, *D. antarctica* and *C. quitensis*, found in the highest marine terraces (Vera 2011). The peninsula was originally designated as a specially protected area because of its high Antarctic biodiversity levels (Toro et al. 2007).

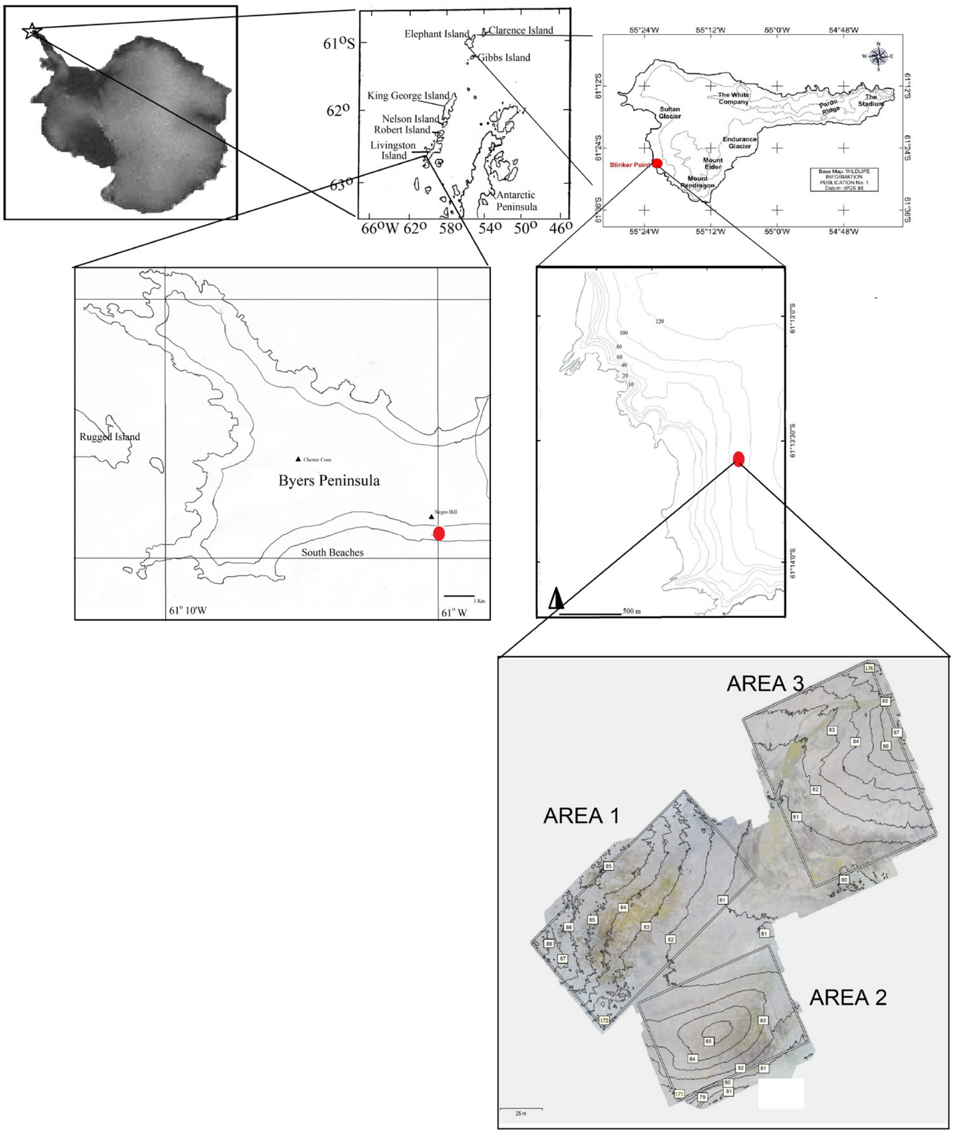

Figure 1. Location of collection areas on Elephant Island and Livingston Island (red dots) detailing the sampled areas on Stinker Point.

Sample collections

During the southern summers of 2018 and 2020, *Stercorarius* spp. pellets were collected and analyzed in ice-free areas in the regions of Stinker Point, Elephant Island, and the Byers Peninsula, Livingston Island, approximately 340 km from each other.

The samples were collected and packed in paper bags and taken to the camp, where they were dehydrated and then transported to the Universidade Federal do Pampa laboratory in southern Brazil. They were analyzed under a magnifying glass (Olympus model SZ51), after each was disassembled in a Petri dish using tweezers and separating all the material found. The materials that adhered to the outside, including vegetal fragments, were discarded to avoid further contamination. The remains of prey, such as bones and feathers, were separated from the plant material found inside the pellet. The identification of plant species in the sampled material was based on the specific literature of Antarctic vegetation (Øvstedal & Lewis Smith 2001, Ochyra et al. 2008, Putzke & Pereira 2001). All plant materials found inside each sample were assessed for their capacity

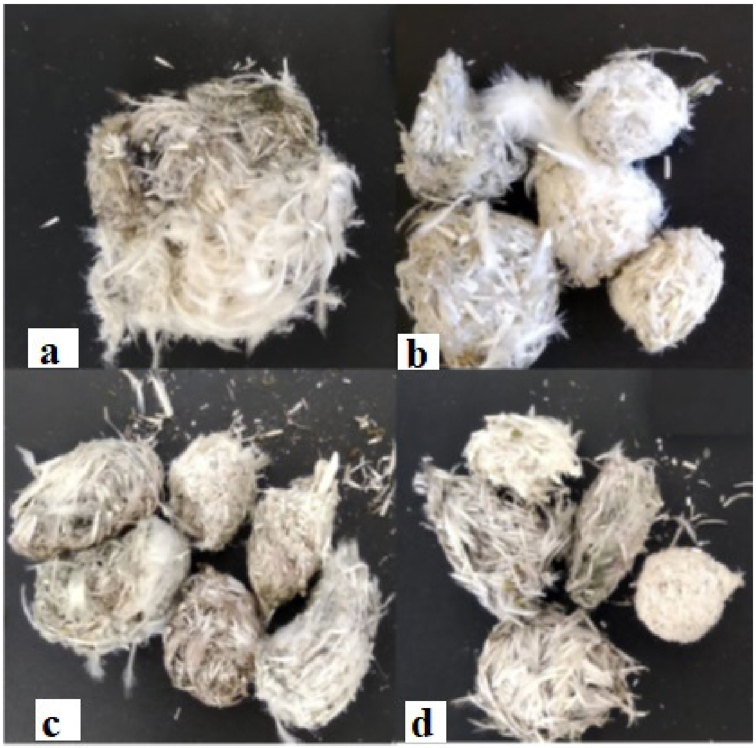

Figure 2. **Samples (a–d) of pellets collected at Stinker Point, Elephant Island, Antarctica in 2018.**

to regenerate by the fragments being placed in a humid chamber. To this experiment the fragments isolated from each pellet were placed in Petri dishes upon several thicknesses of filter paper which had been saturated with distillated water and maintained at 25 (±2) °C and 12 h of continuous light. The experiment was weekly checked for regeneration of the fragments and maintained for three months.

A recent ice retreat area at Stinker Point (located at 61°13'36.06' S and 55°21'15.68' W) in an early stage of plant colonization was assessed for the presence of old pellets (that were at least partially buried in the sediment) and evaluated for the presence of associated plants. The area was entirely covered by a glacier when two of the authors (JP and ABP) visited it in 1990 and 1994, yet it was free of ice in 2012 and 2018. Pellets colonized by vegetation were counted, and the vegetation cover was estimated. Using the images captured by a Phantom 4 drone from the site (100 m high), a map was created, and three rectangles were identified to study the vegetation (Figure 1):

- Area 1: 8685.6 m^2, formed by a gentle slope facing southeast;
- Area 2: 5766.5 m^2, south of Area 1, created by a low elevation (with a top 4 m high in relation to the base);
- Area 3: 8361 m^2, east of Area 1, formed by an elevation with a southwest slope.

RESULTS

During field work there were collected 17 pellets in Stinker Point, Elephant Island (Figure 2) and 60 samples in Byers Peninsula, Livingston Island. The number of samples is different because the Livingston area was more protected from the direct wind interference, retaining more pellets. In all samples the plant material was restricted to small fragments (less than 1 cm long), being impossible to evaluate their proportion (or weight) in relation to the other components of the pellet. In Stinker Point 88% and Byers

91.6% of pellets presented plant fragments. One species of green algae (*Prasiola crispa*) and five moss species, *Sanionia uncinata, S. georgico-uncinata, Warnstorfia sarmentosa*, *W. fontinaliopsis* and *Hennediella heimii* were found (Figure 3). In Byers, only the green algae species was absent (Table I) being the mosses found the same.

In the wet chamber test, all moss samples regenerate (100%), forming new branches and demonstrating their ability to survive the digestive tract of the bird and the conditions of the interior of the regurgitate. After assessing the area where the ice retreat was most recent (last 20 years) at Stinker Point, Area 1 had more developed vegetation, forming a continuous carpet, especially of *Sanionia uncinata*, whereas the other areas did not have any apparent cover. In the count of the oldest pellets, 58 samples were found in the plant formation surroundings because in its interior the carpet of mosses prevented the visualization of older regurgitates (Figure 4).

In Area 2, no old pellets colonized by vegetation were found, perhaps because this area is at the top of an elevation, preventing the stabilization of pellets. In Area 3, 38 skua pellets were found, all presenting associated growing mosses and in places that held practically no vegetation (Figure 5). In the three areas, many scattered bones were observed, indicating that the pellets had been disintegrated by the time of exposure or that they had arrived at the site by the wind regardless of being integrated into the pellets.

DISCUSSION

During the summer period in the Maritime Antarctic region (November to March), after the melting of the ice deposited in the winter, birds migrate to the region in search of a place to rest, feed, and reproduce (Harris et al. 2011). Among these, the skua (*Catharacta*/*Stercorarius*) has a regurgitating feeding habit because they are carnivorous birds and eliminate feathers and bones (in pellets) that are not digested (Santos et al. 2012). The kelp gull (*Larus dominicanus*) also regurgitates in Antarctica and could be investigated for plant dispersal too, despite

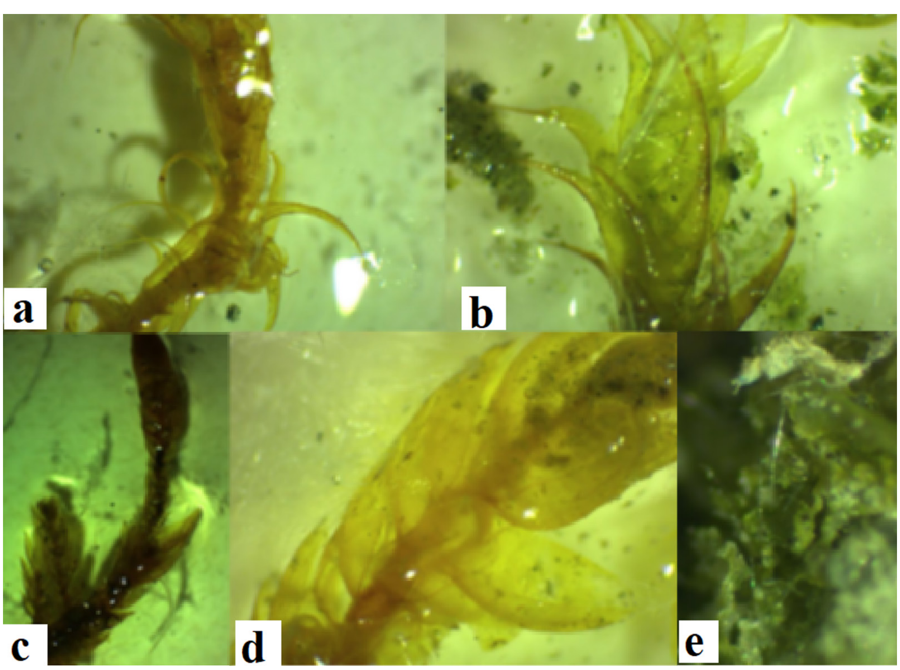

Figure 3. Species of Bryophyta/green algae found inside the pellets: **a)** ***Sanionia uncinata*****, b)** ***S. georgico-uncinata*****, c)** ***Warnstorfia sarmentosa*****, d)** ***W. fontinaliopsis*****; e)** ***Prasiola crispa*** **(green algae).**

Table I. Plant species found inside pellets of *Stercorarius* spp. (Skua) in the Stinker Point region, Elephant Island and Byers Peninsula, Livingston Island, Antarctica.

Species	Group	Stinker Point	Byers Peninsula
Sanionia uncinata (Hedwig) Loeske	Bryophyta	X	X
Sanionia georgico-uncinata (Muell. Hall.) Ochyra & Hedenäs	Bryophyta	X	X
Warnstorfia sarmentosa (Wahlenb.) Hedenäs	Bryophyta	X	X
Warnstorfia fontinaliopsis (Müll. Hal.) Ochyra	Bryophyta	X	X
Hennediella heimii (Hedw.) R.H. Zander	Bryophyta	X	X
Prasiola crispa (Lightfoot) Kützing	Green algae	X	-

Legend: (X) – present; (-) – absent.

eating more marine invertebrates (Coulson & Coulson 1993, Lindsay & Meathrel 2008).

In the present study, we found the presence of fragments of different moss species in the pellets, which was previously noticed, but was associated with digestive tract cleaning (Santos et al. 2012). Another possibility is that during the reproductive period, these birds use plant species, such as mosses, lichens, and angiosperms to build their nests (Albuquerque et al. 2012), which is also undertaken by other birds, such as seagulls (*Larus dominicanus*) (Convey 2012) and probably they accidentally ingest fragments of these plants. In the nest, plants serve as a protective barrier for climatic variations and are a more comfortable environment than rocks (Walsberg 1985).

The Antarctic birds are efficient in the dispersion of mosses, via the transport of vegetal fragments and spores adhered to their body (Lewis et al. 2014, Schlichting et al. 1978), disregarding the possibility of mosses being associated with regurgitated pellets. The results suggest that this association might imply another form of moss dispersion for areas exposed to melting in Antarctica. The implications of this association are unprecedented in studies of moss dispersion in this region, being the percentage of pellets with mosses considerable, with our findings (88 to 91,6%) similar to those found in literature (Santos et al. 2012). Migrant birds might just potentially also bring in pellets containing material of currently non-Antarctic plant species, for instance if they eliminate those pellets with any material foraged in Southern South America or subantarctic islands, when they first arrive at the beginning of the season. But this needs to be better investigated.

Despite being formed by a pile of remains of bones, hair, and feathers that are not used in digestion, the pellets constitute an excellent source of nutrients in areas recently devoid of ice, where rocks and sandy sediments predominate. Infiltrating a pellet can allow rapid plant development, once they are partially decomposed, after being expelled, providing essential nutrients to the mosses whose fragments are inside the pellet.

Cough pellets left by raptors, such as the common kestrel (*Falco tinnunculus*), are another likely mode of secondary dispersal of many organisms, including fungi (Watling 1963). Keratinophilic fungi are commonly isolated from regurgitated pellets, indicating a close relationship with the bird and this digestion mode (Bohacz et al. 2020). Therefore, the agents

Figure 4. Pellets with vegetation associated found in Area 1.

responsible for decomposition are also present in these pellets, accelerating the availability of nutrients.

Bryophytes are part of the diet of some high Andean birds and may disperse bryophytes internally, via endozoochory, in the sub-Antarctic zone, being present in 84.6% and 90.9% (white-bellied seedsnipe, *Attagis malouinus*, and *Chloephaga* spp. geese, respectively) of the fecal samples studied (Russo et al. 2020). This is also the case for Antarctic skuas, where mosses are used as gut-cleaning materials (Santos et al. 2012). In this way, the ingestion of mosses, which allow the elimination of parasites, might include fragments of mosses in the pellets.

Animals that consume mosses in cold environments are related to high concentrations of arachidonic acid in Bryophyta, which gives them higher cold resistance (Prins 1982). The ingestion of arachidonic acid can benefit animals in several ways, including it being a precursor of some prostaglandin hormones; its low melting point (-49.5 °C) means that it might contribute to lowering the melting point of fats in the animal extremities; and it protects cell membranes against the effects of cold (Feng & Bai 2011).

The presence of arachidonic acid is common in mosses, unlike other plants (Anderson et al. 1974), and it has been found in three species of Antarctic mosses (*Bryum pseudotriquetrum, Ceratodon purpureus*, and *Grimmia antarctici*) (Wasley et al. 2006). Thus, it is possible that the Antarctic skuas are making use of mosses as food, eliminating part of them in the regurgitates, and enabling the dispersion of this vegetation to new areas.

The weight of each pellet is small because they are dehydrated and formed mostly by feathers, allowing it to be carried easily by the wind. Therefore, it is highly unlikely that pellets at such concentrations were deposited directly in the area by birds, as they would be easily displaced by wind action. The pellets found partially buried in sediments must have been carried by winds to the glaciers and incorporated into the cracks, remaining stored for a long time until total melting in the area, when they grew back normally after being exposed. The Antarctic moss *Chorisodontium acyphyllum* remained alive after being frozen for more than 1500 years (Roads et al. 2014). Mosses buried for more than 600 years by a glacier were re-exposed by the retreat of the ice, and parts of the moss could activate again and grow normally "in vitro" (Cannone et al. 2017). Therefore, the resistance of these species is very high and they can remain viable for a long time, waiting for the

Figure 5. Seven old pellets found in Area 3, covered by mosses around them.

right moment to colonize the pellet, which is its only source of nutrients.

The potential could also apply to native flowering plants, especially seeds of the grass *Deschampsia antarctica*, a species that skuas are also known to move around and incorporate in their nesting material, but this needs to be investigated (Parnikoza et al. 2009, 2012). It is also important not to let skuas scavenge around stations, since seeds of food plants can easily be ingested and eliminated in pellets later in the natural environment.

The occurrence of mosses in pellets, from the ingestion of these by the skuas, represents another way of dispersion of Bryophyta in the Antarctic region, associated to wind and uses for nest building, reinforcing similar findings already made for the Arctic.

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