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Research Article

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The bones of Livingston Island – history of plant succession in Antarctica

Ossos da Ilha Livingston – história da sucessão em plantas na Antártica

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Abstract
The bones found in the beaches of Byers Peninsula, Livingston Island - Antarctica are testimonies of almost two hundred years ago when the area was full of seals and whales hunters. The remaining´s of that period are composed of complete skeletons and dispersed bones, most of them around the area called Southern Beach, which was surveyed in 2020 and 2023. The plant coverage of 33 whale bones was evaluated using a square of 20 x 20 cm, and species found were collected for identification. The soil surrounding five complete seal skeletons was studied, and its plant community evaluated. The whale bones were found colonized by 16 plant species, being *Pertusaria* sp. (lichen) the most frequent and *Deschampsia antarctica* (the Antarctic grass), *Brachythecium austrosalebrosum* and *Ditrichum* sp. (both mosses) are reported for the first time on this substrate. There were found 5 mosses, 12 lichens, and one flowering plant associated directly to seal bones and other associated with the soil in the surroundings of the skeletons. Plant succession on bones in Antarctica is also occurring and any movement of them caused by anthropic or other interferences can change the community entirely.

Keywords: Plant succession; Ecology; Pinnipedia; Skeletons.

1. Introduction

With the discovery of the South Shetland Islands in the Maritime Antarctic around 1819, trips to hunt marine mammals began. About 1000 people were involved in hunting in the South Shetland archipelago beaches and as many also embarked. Precarious camps were set up on land, the main point being in the Byers Peninsula on Livingston Island, but along other islands and even on the Antarctic Peninsula other groups of hunters were also established[1].

The hunting period ranged from ca. 1820 to 1960, and abandoned carcasses and bones that have not been carried into the sea by erosion or winds currently remain at the seashore[2]. Vegetal communities develop in bones and in their surroundings, exploring what they can offer in terms of nutrients for the environment[3]. Calcium, phosphorus, carbon, nitrogen, and sulfur are nutrients found in bones and they are essential for land plant communities[4].

Plant composition on old mammalian bones were scarcely studied in Antarctica. Olech[5] reported 23 lichens and two mosses on whale bones. Albuquerque et al.[6] cited 14 lichens and two mosses. Øvstedal and Smith[7] make reference to only two species on whale bones and three on seal bones on the revision of all lichens reported to Antarctica. Ochyra et al.[8] cited only 3 species of mosses on bones in their revision of Antarctic bryophyta. Duckett[9] refers about 7 moss species associated to bones from South Georgia and South Shetland Islands. Putzke et al.[10] described modifications around a whale skeleton assembled in King George Island by Jacques Cousteau team in 1972, indicating a *Synchitria* species associated with the nutrients offered by the skeleton. Putzke et al.[3] studied the whale bones vegetal association in Keller Peninsula – King George Island, reporting 4 mosses and 19 lichens associated.

The bones can be essential substrates for vegetation and/or be mere springboards for plants to conquer other areas, and the purpose of this work is to try to give some highlights to this question studying the plant communities associated with them in Byers Peninsula, Livingston Island - Antarctica.

2. Materials and Methods

2.1. Study area:

The whale and fur seal bones were studied in the South Beaches of Byers Peninsula on Livingston Island, one of the main islands of the South Shetland Archipelago – Antarctica during the 2019/2020 and 2021/2022 austral summers (Figure 1).

There were located in this work 33 whale bones that presented some vegetal covering and then chosen to do this study (Figure 2). In the flattened part of each whale vertebra having plant communities, a wooden square of 20 x 20 cm was laid on to calculate coverage and frequency of each species using the Braun-Blanquet11 (1932) method. In the laboratory, the data observed in the field and the photographs taken were used to hand-color the figures to study its phytosociology.

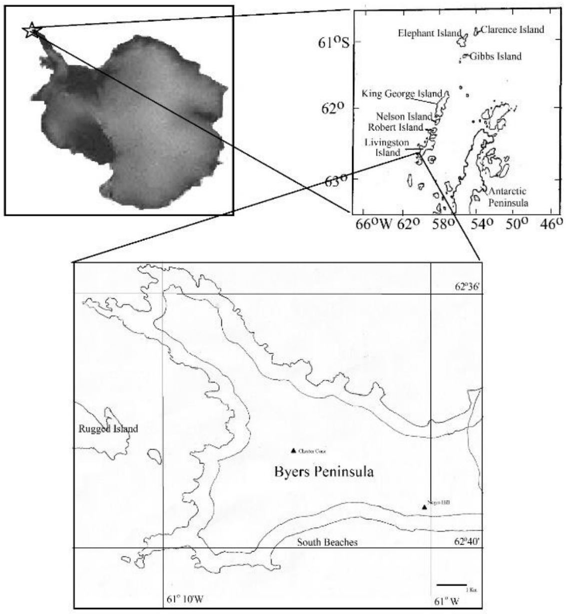

Figure 1. Schematic map of Livingston Island location and the Byers Peninsula studied, indicating the South Beaches.

Figure 2. A whale bone chosen and under analysis in the field work in Byers Peninsula.

2.2. Study of Pinnipedia bones:

The vegetation surrounding five seal skeletons selected (two with skin remains, and three only bones alone) was also analyzed (Figure 3). A map of the surrounding vegetation was assembled, and the species identified.

The mosses and lichenized fungi were identified in situ, or small samples were collected to do laboratory studies. The species identification was done basically following Putzke and Pereira[12] and Ochyra et al.[8] for mosses, and Redon[13] and Øvstedal and Smith[7] for lichens.

Figure 3. The seal skeleton area 1 studied and with soil samples analyzed

A complete fur seal skeleton, probably one of the oldest found in the South Beach (since the leather was almost completely decomposed) was also studied for soil chemical composition, collecting samples and studying the vegetation associated (Figure 3).

An undisturbed soil sample was collected below the fur seal skeleton between 0 and 20 cm depth. The field-oriented and preserved block collected in field was oven dried at 40°C for one week and vacuum impregnated (-5 kPa) with polyester resin diluted in 30% (volume) styrene monomer. The micromorphological study was done in a Transmission Electron Microscope. The description of the thin sections followed the propositions of Stoops[14].

A micro x-ray fluorescence spectrometer Shimadzu determined the contents of Ca, Fe, K, P, and Si in the thin section. The chemical elements were quantified by the Fundamental Parameter method (Quantitative - FP). Calibration consisted of adjusting the sensitivity coefficients of each element analyzed. The sensitivity coefficients of the Quantitative were achieved by FP method, based on four reference samples: Montana Soil II - NIST 2711a, BHVO - 2 - Basalt - USGS, COQ - 1 - Carbonatite - USGS, and SDC - 1 - Mica Schist – USGS.

One soil profile was dug, taken, and described in the site to represent the soils without the influence of bones. Diagnostic horizons, attributes, and properties were identified according to descriptions of color, texture, consistence, and thickness. The soil profile was classified according to the World Reference Base for soil resources (IUSS Working Group WRB, 2015)[15]. Soil samples were collected in each horizon, from the surface down to the lithic contact, at each pedon.

Samples were air-dried and sieved through a 2 mm sieve before texture and chemical analyzes[16]. Coarse sand (CS), fine sand (FS), silt, and clay were determined by the pipette method after dispersion with 0.1 M NaOH. Soil pH was measured with a glass electrode in a 1:2.5 suspension v/v soil and deionized water. The potential acidity (H+Al) was extracted by 1 M ammonium acetate solution at pH 7. The content of exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} was determined in a 1 M KCl extract. Exchangeable K^{+} and Na^{+} were determined after Melhich-1 extraction. From these results, the sum of bases (SB), base saturation (V), equivalent cation exchange capacity (ECEC), and total cation exchange capacity (CEC) was calculated.

The available phosphorus content (PM) was determined by a Mehlich-1 extraction solution. The total organic carbon (C) was determined by wet combustion[17]. The P adsorption capacity of the soil was determined after stirring it for 1 hour with 2.5 g of soil in 0.01 M CaCl2 containing 60 mg of P L-1. The suspension was filtered, and the remaining P in the solution (PREM) was determined by photocolorimetry[18]. Therefore, the lower the value of PREM, the higher the affinity of soils for the P in the solution.

RESULTS AND DISCUSSION

Soil background

The soil profile was dug in the upper marine terrace at 22 m.a.s.l. The soil is derived from marine sediments. Pedon was classified as Pantohypereutric Protic Akrofluvic Arenosol (Ochric, Pantonechic, Endoraptic). Lithic contact is at 200 cm depth. Epipedon is classified as ochric. The single grain is the structure of all horizons. The horizons are abruptly differentiated by texture and color (Table 1).

Table 1. Micromorphological description of the surface horizon of soil influenced by bones

Microstructure		Single grain
Porosity		Simple packing voids Vesicular voids
Groundmass	c/f Related distribution 2μm	Chitonic
	Coarse fraction (size, sphericity, roundness, mineralogy)	Fine sand smooth subangular quartz grains Silt smooth subangular biotite grains
	Fine fraction (size, limpidity, birefringence, color)	Clay dirty undifferentiated b-fabric 7.5YR 5/8 Clay dirty crystallitic b-fabric 7.5YR 8/3
	Organic residues	Absent
Pedofeatures		Typic Ca-rich coating associated with the coarse fraction Link capping clay coating associated with the coarse fraction

The texture is dominantly sand, and fine sand (FS) dominates fine particles. The horizons are neutral and have base saturation (V) above 80% in all horizons. $Ca^{2+}>Mg^{2+}>Na^{+}>K^{+}$ is the base dominance in the exchange complex. The contents of bases, soil organic carbon (SOC), total nitrogen (N), and extractable P by Mehlich-1 (PM) increase irregularly with depth. This pattern suggests that parent material is the main source of these elements. High values of remaining P (PREM) indicate a low affinity between minerals and P.

Soil influenced by bones

The single grain is the microstructure of thin section (Figure 4). Quartz, biotite, and plagioclase are present as silt and fine sand. Simple packing voids are between the coarse grains. Vesicular voids indicate the exclusion of gases during freezing of active layer. Coarse grains are generally coated by: a) neoformed brown clay minerals of undifferentiated birefringence; b) pink clay of crystallitic birefringence.

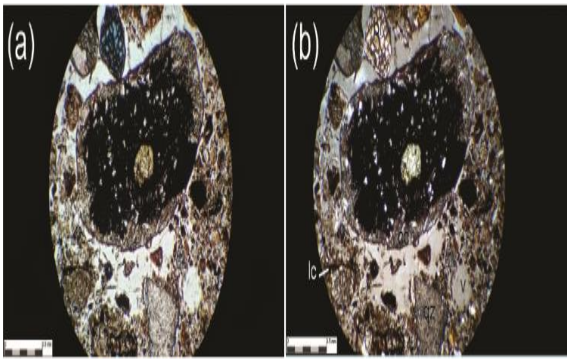

Figure 4. Thin section of soil under bones in plane-polarized light (a) and cross-polarized light (b); bi = biotite grain; cc = $CaCO_3$ coating; lc = link capping clay coating; qz = quartz grain; v = vesicular voids.

The XRF analysis indicates that the pink clay crystallitic birefringent coating is Ca-richer than the surrounding (Figure 5). The low spatial affinity between the Ca, P, and Si suggests that $CaCO_3$ composes the coating. Weathering of bones is an additional source of Ca and PO_4 ions, but they have different chemical behaviors. Water percolation promotes a limited translocation of dissolved Ca^{2+} ions because clay minerals strongly adsorb bivalent cations. The roots and microbiological respiration yield CO_2 in the atmosphere of soil. During freezing of the activity layer in winter, slowly percolating water is trapped by clasts. The residual solution becomes supersaturated and $CaCO_3$ precipitates as laminar caps in the bottom of coarse grains[19, 20]. Cryoturbation moves the grains, and, eventually, there is an alteration of $CaCO_3$ coating[21]. On the other hand, the high PREM values indicate a low affinity between P and clay minerals. Consequently, P percolates from the surface to deeper horizons. The lower P input in soils influenced by bones compared to ornithogenic soils did not guarantee apatite formation[22].

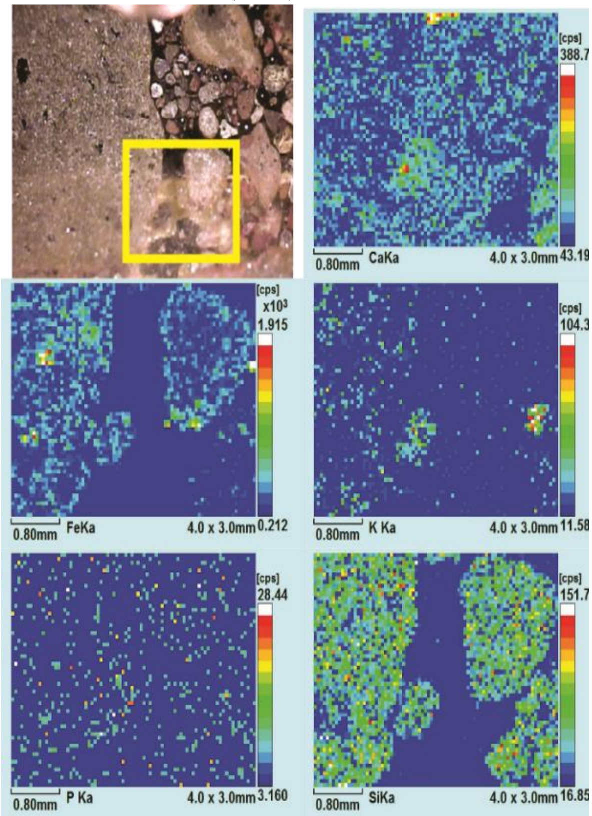

Figure 5. Spatial distribution of elements determined by XRF in thin sections

Vegetation composition

In the 33 whale bones studied (Figure 6) there were found 10 lichenized fungi, 5 moss species and the Angiosperm, *Deschampsia antarctica* Desv. (Table 2 and 3). The Antarctic grass was found for the first time in this substrate but with some sand sediments already deposited on them (Figure 8). This was also the case of *Brachythecium austrosalebrosum* and *Ditrichum* sp., both moss species found for the first time on bones. Among the mosses, *Pohlia nutans* (Hedw.) Kinb., *Brachythecium subpilosum* (Hook.f. and Wilson) A. Jaeger and *Syntrichia magellanica* (Mont.) R. I-I. Zander are cited to whale bones[8]. *Ceratodon* sp., *Bryum* sp., *Pohlia nutans*, various *Syntrichia* spp., *Brachythecium subpilosum*, *Drepanocladus* sp. and *Sanionia georgico-uncinata* were found on bones of the British Antarctic Survey and Natural History Museum collections, sampled on South Georgia and South Shetland Islands[9].

Pertusaria sp. was the species most frequently found (8 squares – 24.2%), what is not according other works published (Table 4) [23, 24]. This species had also the higher Ecological Value index (121.2).

Table 2 - Species list of plants found in the 33 whale bones studied

Group/Family	Species
Lichen/Caliciaceae	*Buellia* 1
Lichen /Caliciaceae	*Buellia*2
Lichen /Teloschistaceae	*Caloplaca sublobulata* (Nyl.) Zahlbr
Lichen	*Muscicolous lichen*
Lichen / Pertusariaceae	*Pertusaria* sp.
Lichen	*Gray sterile lichen*
Lichen	*Placoid sterile lichen*
Lichen / Lecanoraceae	*Rhizoplaca aspidophora* Vain.
Lichen	*White sterile lichen*
Lichen /Verrucariaceae	*Verrucaria* sp.
Moss/ Ditrichaceae	*Ditrichum* sp.
Moss/Pottiaceae	*Syntrichia filaris* (Müll. Hal.) R.H. Zander
Moss/ Pottiaceae	*Hennediella heimii* (Hedw.) Zand
Moss/Brachytheciaceae	*Brachythecium austrosalebrosum* (Müll. Hal.) Paris
Moss/ Amblystegiaceae	*Sanionia uncinata* (Hedw.) Loeske
Angiosperm/Poaceae	*Deschampsia antarctica* Desv.

Verrucaria sp. had the highest coverage, what can be justified by the disposition of bones too close to the sea shore, since *Caloplaca sublobulata* was also found in the community (three on the same square) and both are associated to high salt availability[13].

In one square (bone 32) a giant thallus of *Lecidea* sp. was found, with 9.5 cm diam., in a very old and fragmentary bone. This is an indication that if bones are stabilized, lichens can grow at considerable diameters and that bones are a suitable substrate for very old growing lichens and need to be protected.

Sanionia uncinata was found on three bones only (9.1%), sometimes greatly covered by muscicolous lichens, differently from what was found in other islands[23]. *Sanionia* species had the highest coverage of all species in cryptogamic communities of Antarctica[25, 26], but this is not the case of Whale bones in Byers Peninsula.

Table 3. Species coverage (%) on each sampled area of the whale bones in Byers Peninsula.

	B1	B2	CS	ML	PR	GL	PL	RA	WL	VR	DS	SF	HH	BA	DA	SU
01			2.2							0.9						
02			0.1		2.9	24.5										
03										25.7						
04			0.5							19.3						
05										11.6						
06				12.8							18.9					
07	3.3				8.1	1.1										
08	2.2				4.3	2.5										
09					6.6											
10					9											
11					10.5											
12					13.3											
13			3.7		0.9											
14												6.7				
15			5.7									6.6				
16															16.2	
17												1.6				
18													0.6			
19														31.9		
20		0.5				7.2										
21							3.7	3.1					0.4			
22													0.5			
23								8.2								
24		3.3														
25		4.2														
26		0.5				26.6			12.7	8.3						
27								9.1								
28								9.6								
29				48,9									7.6			
30				39.3									4.4			4
31				9.8							1.4					3.8
32								0.4	16.6				0.1			
33				37.5									1.1			5
Total	5.5	8.5		148.3	55.6	39.9	3.7	30.4	20.3	65.8	20.3	14.9	14.7	31.9	16.2	12.8

B1 - *Buellia* sp. 1 (greenish); B2- *Buellia* sp. 2 (yellowish); CS - *Caloplaca sublobulata*; ML - Muscicolous lichen; PR - *Pertusaria* sp.; GL - Gray lichen; PL - Placoid lichen; RA - *Rhizoplaca aspidophora*; WL - White lichen; VR - *Verrucaria* sp.; DS – *Ditrichujm* sp.; SF - *Synchitria filaris*; HH - *Hennediella heimii*; BA - *Brachythecium austrosalebrosum*; DA - *Deschampsia antarctica*; SU – *Sanionia uncinata*.

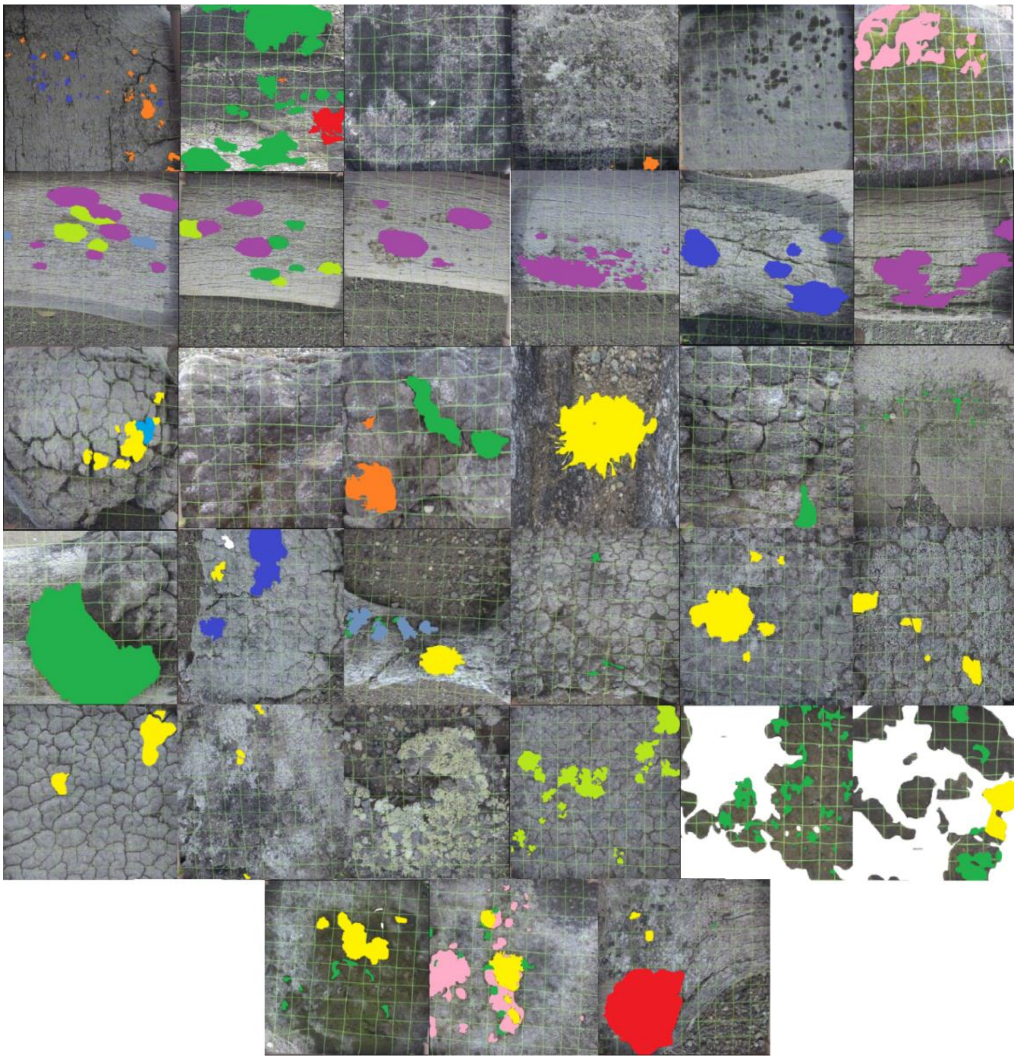

Figure 6. Images of the 33 whale bones quadrats studied and hand colored plant coverage for phytosociological evaluation

Table 4. Species with higher frequencies found on whale bones in Southern Beach, Byers Peninsula, Livingston Island – Antarctica.

Species	Nº of squares	F (%)	IES
Muscicolous lichens	5	15.15%	90.9
Caloplaca sublobulata (Nyl.) Zahlbr	5	15.15%	45.45
Gray sterile lichen	5	15.15%	60.6
Rhizoplaca aspidophora Vain.	5	15.15%	60.6
Verrucaria sp.	5	15.15%	75.75
Pertusaria sp	8	24.24%	121.2
Hennediella heimii (Hedw.) Zand	7	21.21%	63.63
Deschampsia antarctica Desv.	1	3.03%	9.09

Nº = number of squares in which the species was observed; F = (%) frequency of the species in 33 squares studied; IES = Ecological value Index.

This is probably because the bones are very old and muscicolous lichens are already colonizing the moss formations on this substrate (15 % of frequency and coverage of 148.3, the highest among all species found). This is an observation that allows us to conclude that plant succession on bones in Antarctica is also occurring and that any movement of the bones caused by Anthropic interference can change completely the community as already demonstrated[25].
From the five seal skeletons studied (Figure 5), three of them were represented only by pure bones and two also presented skin remains. In one skeleton without skin only *Deschampsia antarctica* was present forming tufts up to 10 cm and in the another two only *Polytrichum piliferum* was present. When skin is still among the remains, the vegetation is dense, with Sanionia uncinata forming small carpets and *Polytrichum piliferum* and/or *Ditrichum* sp. forming tufts. In one of those skeletons the alga *Prasiola crispa* was also present. The muscicolous *Ochrolechia frigida* was constant in one skeleton with skin remains, indicating the old condition of this piece. Probably the skin remains contribute highly to plant establishment while pure skeletons usually have only poor vegetation directly associated.

The skeletons without skin are probably remains of the hunting period when this part of the seals was collected to be sold in the around the world markets. So, based on our results, probably the huge amount of skeletons without skins in South Beach of Byers Peninsula contributed scarcely to plant establishment.

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Conflicts of interest

The authors declare no conflicts of interest.

Authors Contribution

All authors contributed equally to the conception, design, data collection, analysis, and writing of the manuscript. Fernando Augusto Bertazzo-Silva, Jair Putzke, Lilian Pedroso Maggio, Angela Silva Miasaki, José João Lelis Leal de Souza, Marisa Terezinha Lopes Putzke, and Carlos Ernesto Gonçalves Reynaud Schaefer have read and approved the final version of the manuscript.

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