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Spinal fracture reveals an accident episode in *Eremotherium laurillardi* shedding light on the formation of a fossil assemblage

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The Toca das Onças cave is one of the most important Quaternary mammal deposits of Brazil. Two different hypotheses have been proposed to explain the preservation mode of its skeletal remains: either the animals climbed down into the cave, or it could have functioned as a natural trap. Evaluation of pathological modifications on three articulated vertebrae of a single adult giant ground sloth *Eremotherium laurillardi* reveals a particular type of bone fracture caused by compressive force on the vertebral column, which split the vertebral bodies in the sagittal plane. This diagnosis suggests that the animal accidentally fell into the cave, in accordance with the second hypothesis proposed to the incorporation mode of skeletal remains into the cave.

The natural world is a tough place, where wild animals need to constantly adapt to different biotic and abiotic conditions to survive. In past animals, evidences of this "fight for survival" can be revealed through different types of analyses of bones preserved in the fossil record (e.g., ichnologic[1]; and isotopic[2]). An interesting category of evidence about the daily life of ancient animals are bone trauma – any break in the bone continuity caused by a force or mechanism extrinsic to the body[3]. This type of bone injury is able to reveal several paleoecological information such as intra and interspecific conflicts (e.g.,[4,5]), occupational activities (e.g.,[6,7]) and accidents[8].

Despite its paleobiological significance, bone fractures in past animals remain underexplored when compared with other types of paleopathological conditions (e.g., arthritis[9], and infections[10]), especially concerning the Pleistocene megafauna from South America. Recently, few cases of fractures have been described to this fauna, including a case in the ground sloth *Nothrotherium maquinense*[11] and two independent cases in the giant ground sloth *Eremotherium laurillardi*[12,13]. Regarding the giant ground sloths, the record of complete and articulated *Eremotherium* skeletons in the Toca das Onças site has enabled inferences about the death and mode of incorporation of these remains into this cave deposit[14,15].

This paper provides a new case of bone trauma in *Eremotherium laurillardi*, the only Pan-American megatheriine giant ground sloth and one of the taxa most often found in the Brazilian Quaternary fossil deposits[16,17]. In addition to detailing the fractures' origin mechanism, we discuss how this particular case of bone injury can be used to shed light on the possible cause of death of the individual studied, on the incorporation of its bone remains into the taphocoenosis of the cave, and on the depositional aspects of caves.

Results

The three vertebrae investigated (DGEO UFPE 5769, DGEO UFPE 7167 and DGEO UFPE 9048) belong to the same individual and show lesions with similar appearance, location, and size. All lesions are in the caudal endplate of each vertebra near the left edges of the vertebral bodies running in the dorsoventral direction with a gently oblique position (Fig. 1). Each lesion appears as a deep and narrow bone discontinuity which has its

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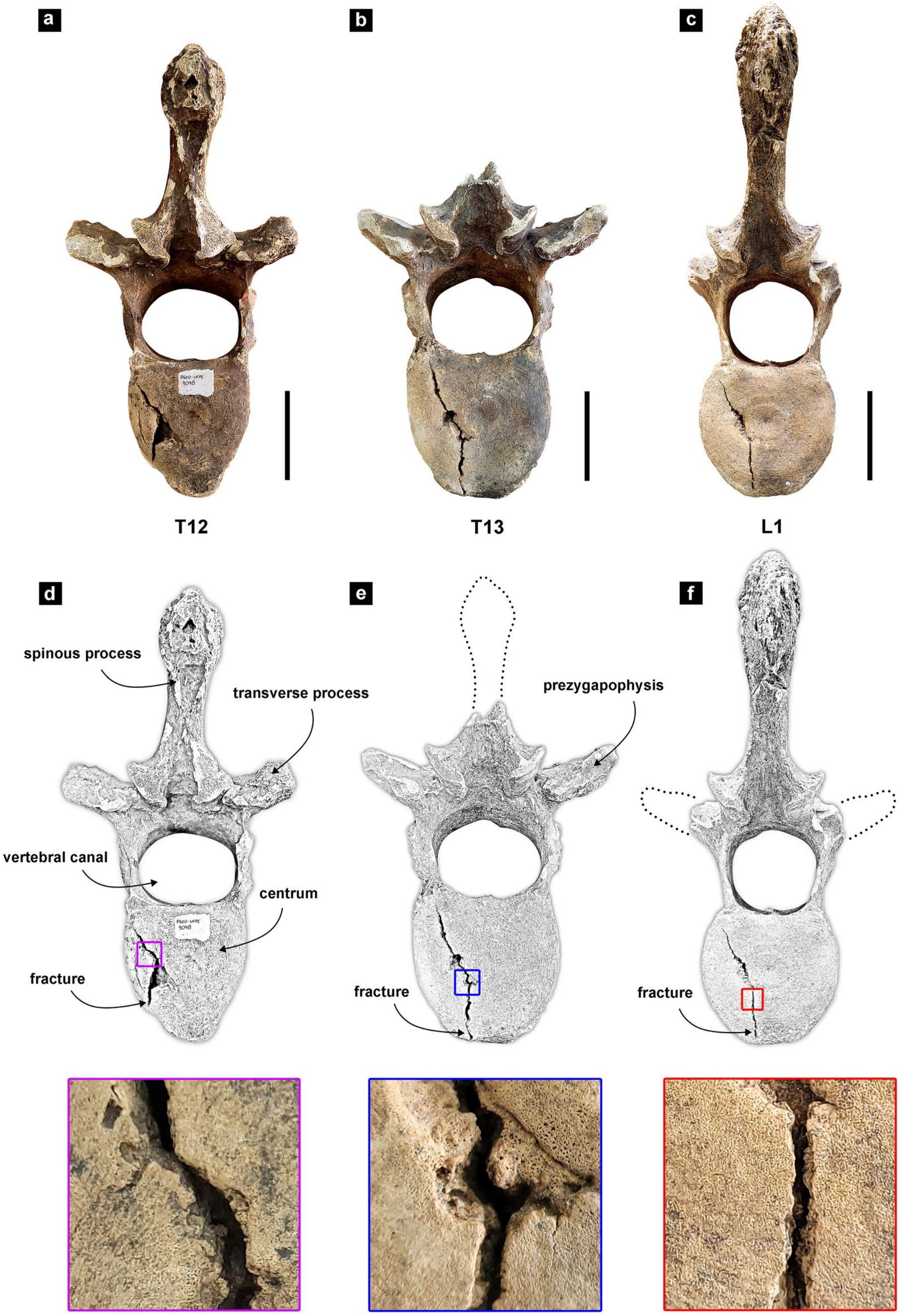

Figure 1. Thoracic T12 and T13, and lumbar L1 vertebrae of *Eremotherium laurillardi*. (**a**–**c**) Photography of T12, T13 and L1 in caudal view, (**d**–**f**) schematic drawing of vertebrae in caudal view and close-up view of the traumatic lesions. Scale bars: 10 cm.

gap widening at the midpoint before narrowing again, something that is most noticeable in the vertebra DGEO UFPE 9048 (Fig. 1a). Each lesion has approximately the following measurements of length: (1) 13.3 cm (12th thoracic vertebra, DGEO UFPE 9048); (2) 13.8 cm (13th thoracic vertebra, DGEO UFPE 7167); and (3) 8.4 cm (1st lumbar vertebra, DGEO UFPE 5769). In addition, it is possible to observe that all lesions have smooth and rounded edges (see images in detail in Fig. 1). There is no macroscopic evidence of new bone formation on the surface of the vertebrae.

Discussion

Since the bone discontinuities noted in the three vertebrae analyzed show no clear sign of bone overgrowth, it is pivotal to rule out the possibility that we are dealing with preservation damages before proposing an accurate diagnosis for the lesions. The close-up view examination of the abnormalities shows that their edges have clear signs of smoothing and rounding (Fig. 1), which represent important evidence of osteoblastic activity[18,19]. Additionally, the similar color of the cortical damage and normal bone can be used as secondary evidence to rule out post-mortem processes as a possible origin of the alterations, since recent destructive processes are lighter than the rest of the bone[19]. Therefore, as taphonomic processes can be ruled out, the pointed evidence strongly suggests that the discontinuities observed are of pathological origin. More specifically, these breaks found in all three vertebrae are indicative of bone fracture.

Based on fracture analysis criteria applied here[20], which consider the location and morphological pattern of the fractures, we classified the fractures noted in all vertebrae as traumas belonging to Type A (vertebral body compression), Group A2 (split fractures), and subgroup A2.1 (sagittal split fracture). This diagnosis implies that the traumatic episode was likely caused by a compressive force on the vertebral column, which split the vertebral bodies in the sagittal plane. This type of injury is considered stable—i.e., the fracture does not have a tendency to displace after reduction—and neurological deficit is uncommon[20,22,23]. Although stable traumas cause only moderate pain, without generating significant movement limitations[20], the *Eremotherium* individual here analyzed died with unhealed bones, as there is no evidence of callus formation.

The absence of other skeletal signs that point to the presence of another type of disease concomitantly to the fractures allows us to reject the possibility that they have been generated as a result of a pre-existing disease (e.g., infection, neoplasm). We also consider that the vertebral injuries were not caused by repetitive force (stress fractures) because this type of injury is commonly characterized as a nondisplaced line or crack in the bone, called hairline fracture[3]. Those refer to situations where the broken bone fragments are not visibly out of alignment and exhibit very little relative displacement[21]. Although the *Eremotherium* vertebrae fractures' can be described as nondisplaced, they also have a noticeable gap between their edges that is mostly narrow with wider parts in the middle, something found in split fractures[20] but that is not characteristic of hairline fractures. Lastly, the subgroup C1.2.1 (rotational sagittal split fracture) might be a source of confusion due to similar morphological pattern with subgroup A2.1 (sagittal split fracture). However, in subgroup C1.2.1 there are compressive and rotational forces acting simultaneously, producing total separation into two parts[20], which clearly did not occur in the vertebrae analyzed here.

In humans, compression fractures are most commonly caused by osteoporosis, although infection, neoplasm and trauma can also be etiological factors[23–25]. However, as aforementioned, the absence of other pathological skeletal marks is an important characteristic to take note as it serves to disregard the possibility of the fractures' genesis to be secondary to another pathology. As such, in this case, osteoporosis, infection and neoplasm are unlikely etiologies. On the other hand, a compression fracture in a healthy individual is commonly generated after a severe traumatic event such as a fall from great height[23,26]. This scenario seems to better explain the origin of the vertebral fractures in the case of the *Eremotherium* ground sloth herein studied.

The three fractured vertebrae were recovered in the Toca das Onças site (Fig. 2), a small cave considered as one of the richest paleontological sites of the Brazilian Quaternary[15]. Two complete skeletons of *Eremotherium laurillardi* and fragments belonging to at least thirteen other individuals, together with several other bones assigned to different smaller species are known to this cave[14]. It comprises of a single dry chamber that can only be entered through vertical entrances approximately 4.5 m high (Figs. 2b–d and 3). Two different hypotheses concerning the depositional process of Toca da Onças were previously proposed: (1) the animals climbed down into the cave in search of water[14]; or (2) due to the vertical character of the cave entrance, it could have functioned as a natural trap where animals accidentally fell into the cave[15].

The first hypothesis would indicate that the animal fell into the cave during an attempt to climb down. However, there is no report in the literature indicating that *Eremotherium laurillardi* could have been a climbing animal. In addition, the vertical morphology of the cave entrance would be a limiting factor for climbing behavior (see Fig. 3).

Therefore, based on the type of fracture (compression sagittal split fracture) observed in the three vertebrae of *Eremotherium* as well as the inferred origin mechanism (fall from a great height), the presence of the individual here analyzed in the fossil accumulation of Toca das Onças is more likely explained by the second hypothesis. This idea is not particularly new as 'entrapment due to fall' has been described as a fossil accumulation mode to several other caves worldwide (e.g.,[27,28]). However, the use of bones fractures as an indicator of fossil accumulation mode is an interesting novelty. Of course, a detailed taphonomic investigation in the Toca das Onças still needs to be conducted in order to accurately interpret the formation of this important Quaternary fossil accumulation from Brazil.

In sum, we suggest that the animal accidentally fell into the cave, fractured at least three sequential vertebrae (12th, 13th thoracic vertebrae and 1st lumbar vertebra) after the impact on the ground, survived for a while, but succumbed trapped inside the cave without food and water (Fig. 4). Other animals found in the cave, but without signs of bone fracture, may have fallen and not fractured their bones or not survived after the fall, especially the smaller ones. Finally, the proposal of falls to explain the unusual record of giant ground sloth fossils preserving much of its skeleton in caves, as reported for Toca das Onças site, contrasts with the better-documented pattern of skeletal accumulation via hydraulic action.

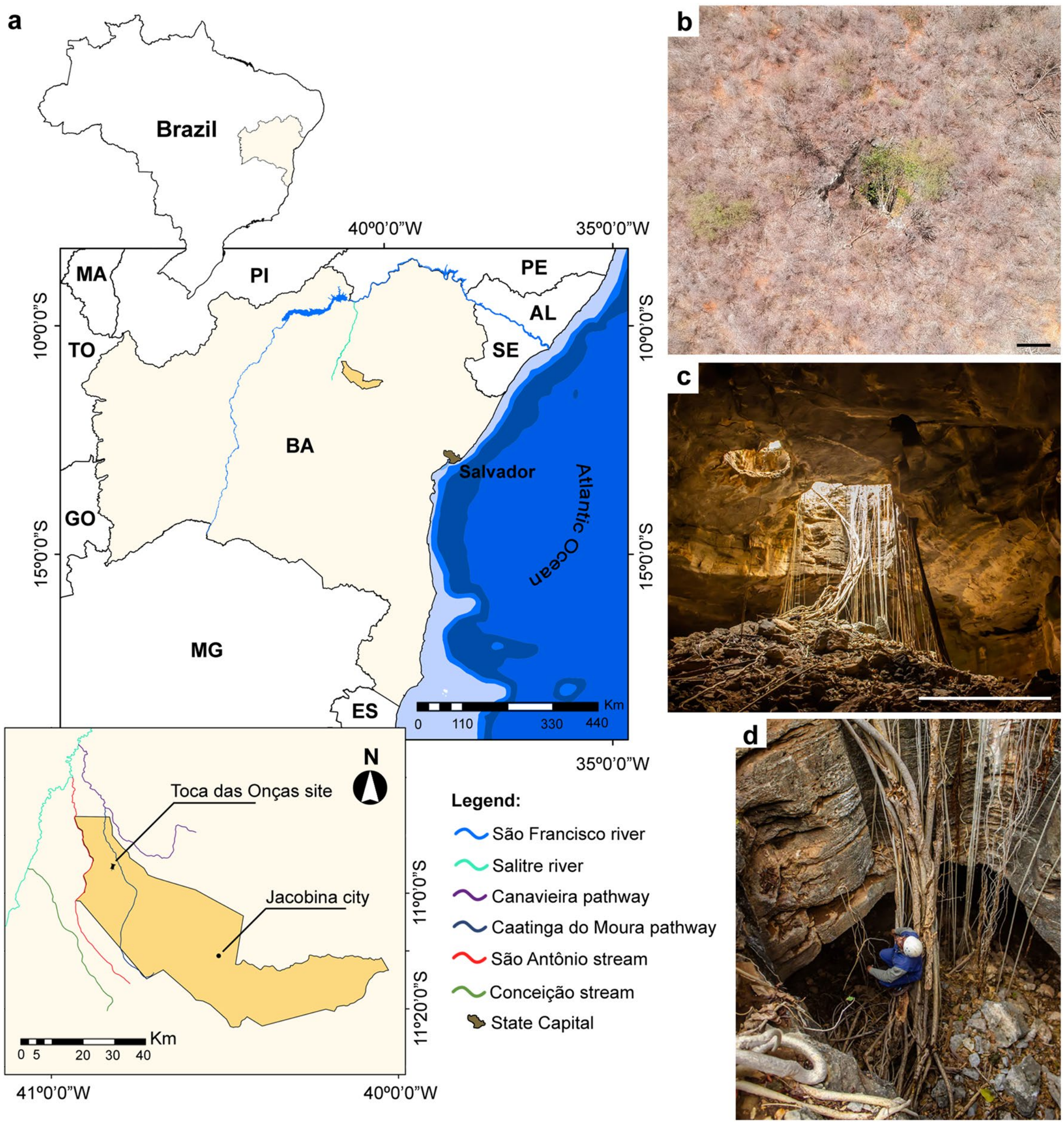

Figure 2. Location map of the Toca das Onças site and images of the cave. (**a**) Detail of the location, (**b**) cave entrance area view, (**c**) view from inside the cave, (**d**) Cave entrance detail. Scale bars 10 m in (**b**) and 5 m in (**c**). This figure was generated by Adobe Photoshop CS6 software (https://www.adobe.com/br/products/photoshop.html).

Materials and methods

The material herein analyzed consists of three articulated vertebrae of an adult—indicated by the presence of vertebral plates completely fused—individual of *Eremotherium laurillardi*, as follows: (1) the twelfth thoracic vertebra (DGEO UFPE 9048); (2) the thirteenth thoracic vertebra (DGEO UFPE 7167); and (3) the first lumbar vertebra (DGEO UFPE 5769). The specimens were recovered from the Toca das Onças site (WGS84-UTM 300,604 m E; 8,791,416 m N), a small cave deposit located at the village of Caatinga do Moura, municipality of Jacobina, State of Bahia, Brazil (Fig. 2) and are housed in the Paleontological Collection of Geology Department of the Universidade Federal de Pernambuco (DGEO UFPE), Recife city, State of Pernambuco, Brazil.

The Toca das Onças site was developed in the Neoproterozoic dolomitic rocks of the Salitre Formation, Una Group. The cave has a single vertical entrance with a drop of approximately 4.5 m and a total area of 16 m^2[29]. It consists of a single chamber with a linear development of 23 m and a volume of 63 m^3[29].

Each vertebra was macroscopically examined to characterize the pathological changes. We adopt here the fracture classification system proposed by Magerl et al.[20] to describe the lesions studied. This classification system

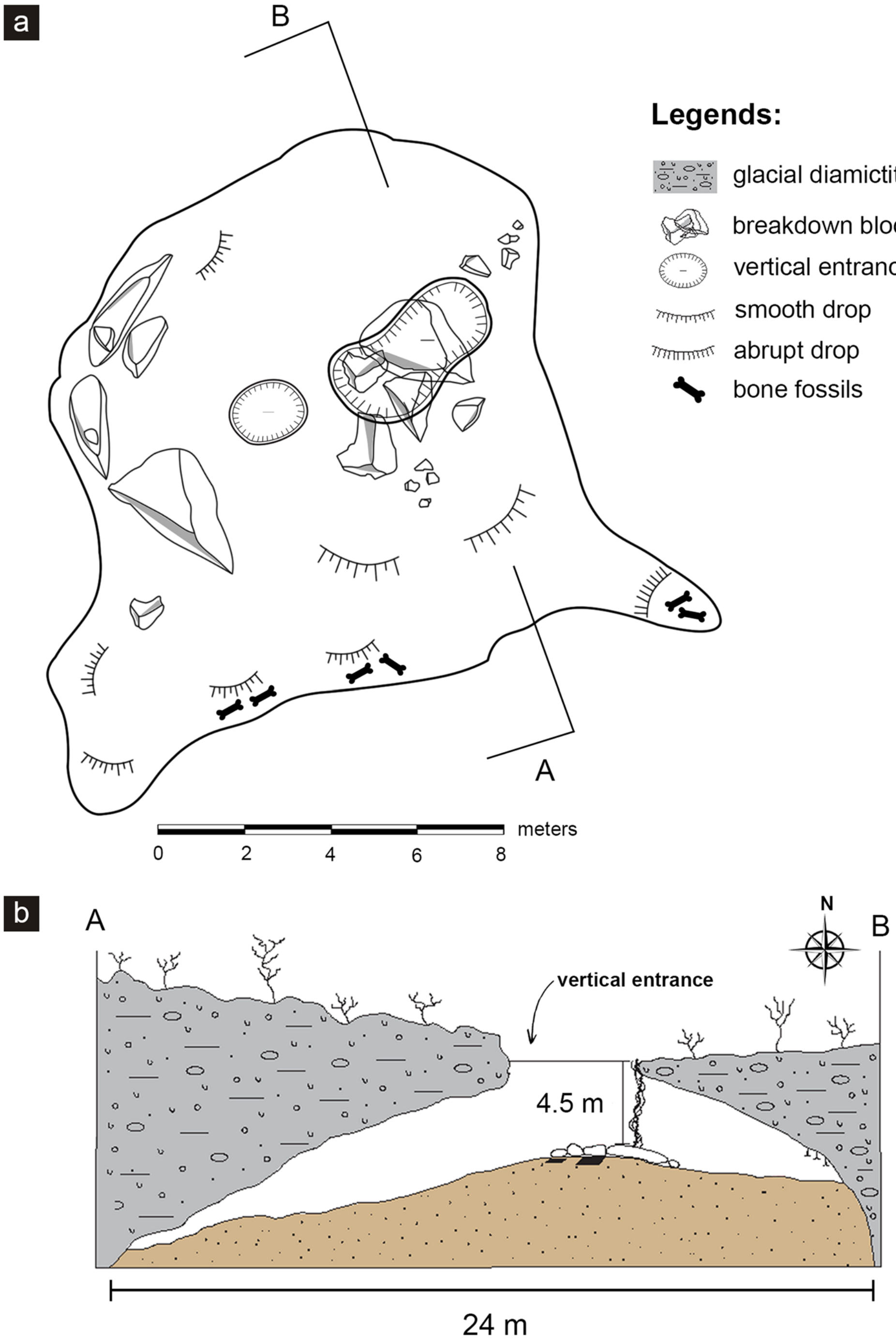

Figure 3. Schematic representation of the Toca das Onças site. (**a**) Ground plan of the cave illustrating its morphology and dimension, (**b**) Cross-section illustrating the abyss-shaped entrance.

was created specifically for thoracic and lumbar vertebral fractures and is based on morphological patterns that can be divided in a set of three main categories of lesions (Type A, Type B and Type C). Each category reflects the effect of a force and the mechanism that was involved in the origin of the type of lesion and its subtypes. The system presents a hierarchy of types, groups and subgroups that are ranked according to its progressive severity and are accompanied by detailed morphological features (see[20] for more details). The length of each fracture was measured using the open-source platform Fiji[30].

Figure 4. Artistic reconstruction of the suggested fall of the individual *Eremotherium laurillardi* into the cave. Artwork by Júlia d'Oliveira.

Data availability
All data analyzed during this study are included in this work.

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Author contributions

F.H.S.B conceived the study, analyzed the data, prepared the figures and wrote the manuscript. I.C., H.I.A-J., A.V.A. and E.V.O. analyzed the data and wrote the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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