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# 1            **Landscape-scale spatial variations of pre-Columbian anthropogenic** 2            **disturbances at three ring ditch sites in French Guiana**

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7  
8    Key words : Pre-Columbian societies, ring ditch, Amazonia, Guiana shield, French Guiana, forest  
9    landscapes, interfluvial region, anthropogenic disturbances, geoarchaeology, soil properties, charcoal,  
10    radiocarbon dating, Amazonian Dark Earths, anthrosols, Amazonian Brown Earths, *terra mulata*,  
11    ferralsol, gleysol.

## 12 13    **Abstract**

14    In the past two decades, repeated discoveries of numerous geometric earthworks in interfluvial regions  
15    of Amazonia have shed new light onto the territorial extent and the long-term impact of pre-Columbian  
16    populations on contemporary landscapes. In particular, the recent development of LiDAR imagery has  
17    accelerated the discovery of earthworks in densely forested hinterlands throughout the Amazon basin  
18    and the Guiana Shield.

19    This study aimed to evaluate the extent and landscape-scale spatial variations of pre-Columbian  
20    disturbances at three ring ditch sites in the French Guiana hinterland. We carried out extensive soil  
21    surveys along approximately 1 km-long transects spanning from ring ditches through the surrounding  
22    landscapes, and drawn upon multiple indicators, including archaeological artifacts, macro- and micro-  
23    charcoals, soil colorimetry, and physicochemical properties to retrace the pre-Columbian history of these  
24    sites in terms of occupation periods, anthropogenic soil alteration, and ancient land use.

25    Our results revealed a perennial occupation of these sites over long periods ranging from the 5th and  
26    15th centuries CE, with local enrichments in chemical indicators (Corg, N, Mg, K, Ca) both within the  
27    enclosures of ring ditches and in the surrounding landscapes. Physicochemical properties variations  
28    were accompanied by variations in soil colorimetry, with darker soils within the enclosure of ring ditches  
29    in *terra-firme* areas. Interestingly however, soil properties did not meet all the characteristics of the so-  
30    called Amazonian Dark Earths, thus advocating a paradigm shift towards a better integration of  
31    Amazonian Brown Earths into the definition of anthropogenic soils in Amazonia. Soil disturbances were  
32    also associated to local enrichments in macro- and micro-charcoals that support *in situ* fire management  
33    that could be attributed to forest clearance and/or slash-and-burn cultivation.

34    Taken together, our results support the idea that pre-Columbian societies made extensive use of their  
35    landscapes in the interfluvial regions of the French Guiana hinterlands.

## 36 **Introduction**

37 Covering more than 5,500,000 km<sup>2</sup>, the Amazon rainforest is one of the largest tropical forests in the  
38 world. Despite increasing attention to its extraordinary biodiversity, the Amazon rainforest remains  
39 largely unexplored and has long been considered by environmental researchers as an undisturbed,  
40 pristine forest. From another point of view, archaeological research has shed new light on pre-  
41 Columbian occupation in Amazonia, suggesting high population density and long-term impact on soil  
42 and vegetation. This recent paradigm shift is accompanied by hot debates over the territorial extent of  
43 pre-Columbian societies, their long-term impact on contemporary wild landscapes and underlying land-  
44 use strategies (1,2).

45 **The Territorial Extent of Pre-Columbian Societies in Amazonia.** Geometric earthworks represent  
46 one the most meaningful proxy of the territorial extent of pre-CE 1492 societies in Amazonia. However,  
47 they are often hidden below the forest cover, and, until recently, they were mostly discovered by  
48 pedestrian surveys in easily accessible areas. This long fueled the idea that pre-Columbian societies  
49 settled mainly along major rivers and coastal areas (3), which represent a very restricted fraction of the  
50 Amazon region. However, both extensive deforestation and fast development of airborne imagery  
51 technologies (e.g., LiDAR) in remote, densely forested areas has accelerated the discovery of numerous  
52 earthworks all over the region, thus arguing for a reconsideration of the pre-Columbian population  
53 density both in the Amazon floodplains and in interfluvial (*terra-firme*) forests (4–7). On the southern  
54 rim of the Amazon, geometric earthworks are organized into complex and continuous networks (4,8,9).  
55 Pärssinen et al. (10) reviewed the distribution of earthworks in the Brazilian state of Acre (western  
56 Amazonia), totalling about 200 sites over a region more than 250 km across. In 2022, Prümers et al. (5)  
57 mapped monumental settlements in a savanna-forest mosaic in Llanos des Mojos (Bolivia, western  
58 Amazonia), arguing for a region densely and continuously populated. Other authors, on the contrary,  
59 argued that human occupation was heterogeneous in western Amazonia. For example, McMichael et al.  
60 (11) surveyed 55 sites over a surface of 3,000,000 km<sup>2</sup> in central (Brazil) and western Amazonia (from  
61 Peru to Bolivia) and detected only sparse evidence of human impacts in interfluvial forests. The  
62 distribution of earthworks is not restricted to the Amazon basin (that is, the region drained by the  
63 Amazon River). In French Guiana (Guiana shield, northeast Amazonia), ring ditches are found  
64 throughout the hinterland. In the 1990s, about 50 sites of ring ditches were already identified (12). Some  
65 of them have been the subject of dedicated archaeological or paleoenvironmental research (13–16),  
66 while many others have been discovered more recently through preventive archaeology operations (17)  
67 or mapping operations in managed or protected areas.

68 **Geometric Earthworks: Temporality and Functions.** Radiocarbon dates suggest that geometric  
69 earthworks were built over very long periods of time, varying between regions and sites from the first  
70 millennium to the decline of pre-Columbian societies, see supplementary table 1. Earlier periods of ring

71 ditch construction dating back to BCE 1600 were detected in the Acre, Brazil (18), while occupation  
72 prior to ring ditch construction has also been suggested in some regions such as Llanos de Mojos, Bolivia  
73 (19). Geometric earthworks are of various forms and sizes. Although their exact function remains  
74 uncertain, two kinds of architectural-function categories seem to stand out: ceremonial centers on one  
75 side and fortified villages on the other (4,10). Ceremonial centers, such as geoglyphs found in the Acre,  
76 are characterized by almost perfect geometric forms and symmetry combining different shapes (circles,  
77 squares, hexagones), sparse ceramic deposits, the presence of votive artifacts, and no alteration of soils  
78 (18). On the contrary, ring ditch sites are commonly attributed to fortified (i.e., palisaded) villages based  
79 on their asymmetrical – irregularly shaped – enclosures, high-density of ceramics, and soils enriched in  
80 organic matter and burning deposits (i.e., charcoals), suggesting permanent habitation. Ring ditches are  
81 often attributed to Arawak speakers, but determining the exact earth builders is hard due to the linguistic  
82 and cultural diversity in Amazonia (4,6,20). Although geographically distant, the ring ditches of the  
83 Guiana shield share geometric features like those found in the Amazon basin. They are called ‘kalana  
84 tapele’ (i.e., ‘Kalana’s ancient villages’) in Wayãpi oral traditions, a mysterious cultural group that lived  
85 in French Guiana until the 18th century. In 1982, Grenand and Dreyfus recounted the story of a Wayãpi  
86 chief who mentions Kalana villages: *‘Throughout the region, there were many Kalana. They built*  
87 *villages that they protected with ditches two meters wide and one meter deep. The bottom was planted*  
88 *with stakes. Those who did not know fell and died.’* (21). The last traces of the Kalana (also named  
89 ‘Carannes’ by Europeans) are found in French national archives overseas that relate a war between  
90 Europeans and the Kalana in 1703-1704 (22,23) who probably disappeared soon afterwards.

91 **Environmental Impact of Pre-Columbian Societies and Land Use.** The long-term impacts of pre-  
92 Columbian occupation extend beyond the mere presence of geometric earthworks. Both below and  
93 above ground features provide information on the extent of human impact and land use strategies.  
94 Above-ground, modern vegetation helps to understand how pre-Columbian societies lived in their  
95 environment in terms of subsistence and management of natural resources. For example, spatial  
96 variations in present-day vegetation that are correlated with pre-Columbian occupation are interpreted  
97 as evidence of ancient landscape management for plant cultivation (24,25). Such vegetation turnover is  
98 commonly interpreted as ‘domesticated landscapes’ (26) or ‘cultural forests’ (8,27), where secondary  
99 forests replaced primary forests. In 1989, W. Balée (27) has estimated that more than 11% of Brazilian  
100 *terra-firme* forests were anthropogenic. In the same vein, some useful plant taxa and crop species are  
101 significantly more abundant in forest areas containing evidence of pre-Columbian occupation, such as  
102 ring ditch sites, compared to supposedly natural forest areas without evidence of human occupation (28–  
103 30). These observations are also supported by palynological records, which reveal the presence of major  
104 crops (e.g., maize, squash, manioc) during periods of human occupation of ring ditch sites (19). Based  
105 on the abundance of charcoal, paleoenvironmental research has documented repeated fire activity in  
106 Amazonia through the Holocene. Because natural fires are rare in Amazonia, it is commonly admitted

107 that the presence of charcoal in palaeoecological records can be attributed to anthropogenic burning  
108 (31), although fires in evergreen forests probably result from a close interaction between human activity  
109 and natural climate variations (seasonality and El-Ninõ climate oscillation) ; drier periods being more  
110 favorable to burning (32). However, whether burning activity was associated with large-scale  
111 deforestation is unclear and should be considered in light of natural, climate-driven vegetation dynamics.  
112 In the ring ditch region of Llamos de Mojos (Bolivia), pre-Columbian earth builders may have first  
113 settled in preexisting savannas they maintained open through slash-and-burn during late-Holocene forest  
114 expansion (33). The decline of pre-Columbian populations was characterized by a decrease in burning  
115 activity ~600-500 B.P. (i.e., CE 1350-1450) and associated with forest expansion (19). A similar  
116 hypothesis has been proposed in the Acre, where the earthworks were probably built in bamboo forests.  
117 Only localized forest clearances were carried out without involving substantial deforestation (34). Soil  
118 properties may also provide interesting information on the extent of anthropogenic disturbances in  
119 contemporary landscapes. In Brazil, pre-Columbian settlements are commonly associated with the so-  
120 called Amazonian Dark Earths, ADEs (i.e., ‘*terra preta*’), which are acknowledged as highly fertile soils.  
121 Patches of ADEs are frequent along the Amazon River and its tributaries (35) but they are rare, or still  
122 undiscovered in more distant regions and hinterlands (1). Model-based predictions suggest that only  
123 3.2% of Amazonian forests might be propice for *terra preta* formation (36). They further confirm that  
124 the distance to rivers is an important predictor, the occurrence of *terra preta* being more probable within  
125 10 km of a river. ADEs soils are often considered as anthropogenic soils formed by the addition of  
126 inorganic and organic debris (e.g., bones, biomass wastes, excrements) and burning activity (37,38).  
127 Indeed, ADEs are commonly enriched in organic matter and nutrients (38,39). Even if the anthropogenic  
128 origin of ADEs is still debated (38–41), it is commonly admitted that long-term landscape management  
129 alters soil characteristics to varying degrees, ranging from soils with slight to moderate anthropogenic  
130 modifications (i.e., ‘*terra mulata*’, 42–44) to anthropogenic soils or ‘anthrosols’ containing strong  
131 anthropogenic modifications (i.e., ‘*terra preta*’).

132 However, soil properties in interfluvial pre-Columbian sites less propitious to *terra preta* formation have  
133 been less documented. Furthermore, the specific location of French Guiana in northeast Amazonia also  
134 questions the extent of soil alterations at pre-Columbian sites, and empirical data are profoundly lacking.

135 The ring ditches of the Guiana shield have been poorly studied compared to those of the Amazon basin,  
136 thus constituting a considerable knowledge gap. Whether ring ditches located in the Guiana shield are  
137 associated with anthropogenic soil alterations and/or burning activities remains poorly known.  
138 Furthermore, the extent of spatial variations in anthropogenic disturbances within forest landscapes  
139 surrounding ring ditches has rarely been assessed. This knowledge may have important implications in  
140 terms of ecosystem resilience and sustainable land use.

141 In this study, we investigated the landscape-scale extent and spatial variations of pre-Columbian

142 anthropogenic disturbances at three ring ditch sites in French Guiana. We carried out a continuous,  
143 standardized soil sampling along approximately 1 km-long transects that extend across ring ditch  
144 enclosures and surrounding forest landscapes. We built upon an integrated methodology that combine  
145 soil and charcoal analyses to address the following questions:

- 146 • What were the occupation periods of the sites? Do these periods coincide with previously  
147 documented periods of ring ditch construction in Amazonia?
- 148 • Do contemporary forest landscapes surrounding ring ditches contain evidence of long-term pre-  
149 Columbian disturbances? How does the spatial distribution of anthropogenic disturbances vary  
150 in forest landscapes surrounding ring ditches?
- 151 • Do soil properties meet the characteristics of Amazonian Dark Earths?
- 152 • Do soil properties inform ancient land use and landscape management?

153

## 154 **Materials & Methods**

155

### 156 **1. Study Area and Ring Ditch Sites**

157 French Guiana lies to the east of the Guiana shield (northeast Amazonia), a 1.7-billion-year-old  
158 Precambrian craton characterized by a soft relief alternating between low hills and slopes on ferralsol  
159 (i.e., *terra-firme*) and flooded lowlands (i.e., bottomlands) on hydromorphic gleysols. French Guiana  
160 is located in the Guianan moist forest ecoregion (NT0125) and is covered by approximately 97% of  
161 the evergreen Amazon rainforest. This highly diverse rainforest grows in the Af climate according to  
162 the Köppen–Geiger classification (45,46), which is marked by an annual rainfall ranging between  
163 2000 and 4000 mm/year, a wet season that extends from December to July (interspersed with a ‘little  
164 summer’ in March) and an average annual temperature of 26°C. This study focused on three ring  
165 ditches in the French Guiana hinterland: MC87, Nouragues (NOUR), and Mont-Galbao (GALB).  
166 These sites are distributed along rainfall and altitude gradients ranging from ~2700 to ~3700 mm/yr  
167 (Fig.1).

168 **MC87.** MC87 is located in the Kourouaï River watershed (X: 4,057205; Y: -52,67196), Fig.1. The site  
169 occupies the top of one of many palaeoproterozoic bedrock hills of the zone (alt: 85 m AMSL) and is  
170 surrounded by waterways and bottomlands (15). The local rainfall at this site approaches 3800 mm/year.  
171 A previous archaeological and micromorphological survey has been carried out on this site, providing  
172 background information (15). The 2 m deep by 2-3 m wide ditch is located on the top of a hill and  
173 encircles an area of almost 1 ha. Radiocarbon analyses dated the pre-Columbian occupation between  
174 CE 500 and CE 1100. No human occupation has been reported at this site during the colonial period.  
175 Despite a forest exploitation road to the east of the ring ditch, the site has been spared contemporary

176 logging operations and had been impacted by economic activities only at the eastern end of the transect  
177 (i.e., the last pit ‘C20’ in Fig.1).

178 **Nouragues (NOUR).** The Nouragues site lies on the flattened summit of a precambrian granite plateau  
179 in the watershed of the Arataï River (x: -52.086023; y: 4.07993), Fig.1. The climate at this site is slightly  
180 less humid than at MC87, with 3200-3400 mm annual rainfall. The site is located in the CNRS Research  
181 Station within the Nouragues Natural Reserve, a fully protected area since 1995. This station has been  
182 the subject of numerous ecological and archaeological research projects, including the LONGTIME  
183 project (47). This ditch studied here is located in the zone named ‘grand plateau’ and is made up of a  
184 shallow, partially closed ditch 0.5 to 1 m deep and 2 m wide (Fig.1). Today, only an arc of a circle  
185 curved over around one hundred meters is still visible through LiDAR. Radiocarbon datings of the  
186 ditched site indicate occupation between CE 650 and CE 1550 (16). An Amerindian presence in the  
187 region was noted until the end of the 18th century: the ‘Nouragues’ or ‘Norak’ Tupi speakers (21).

188 **Mont Galbao (GALB).** The Mont Galbao site is located on a flat part of the eponymous mountain  
189 range, within the metamorphic chain Inipi-Camopi (x: -53.29267; y: 4.59575), Fig.1. This area lies  
190 upstream of the Makwali River watershed and is part of the protected area of the French National Park  
191 (Parc Amazonien de Guyane, PAG). In 2020, a dozen ring ditches were discovered through a LiDAR  
192 mapping operation ordered by the PAG. The studied ring ditch is an ellipsoidal and extends more than  
193 300 m long and 130 wide. It is up to 3 m deep with a flattened outer edge in its southern section. Due to  
194 the remoteness of this site, which is not served by public transports and is only accessible by helicopter,  
195 no archaeological excavations or radiocarbon dating have been carried out on the site before the present  
196 study.

## 197 **2. Sampling Design and Soil Sampling**

198 → **Fig. 1.** Location of study sites and sampling design. *The LiDAR Digital Terrain Model (DTM) of*  
199 *MC87 was provided by the National Forest Office (Office National des Forêts, ONF). The LiDAR DTM*  
200 *of NOUR was provided by LONGTIME project. The LiDAR DTM of GALB was provided by the PAG*

201 At each study site, we performed a continuous and standardized soil sampling along approximately 1  
202 km-long transects that extended through the ring ditch hill (RH) and the surrounding forest landscape  
203 with little or no evidence of pre-Columbian disturbance (Fig.1). For each transect, the soils were sampled  
204 every 50 meters with an auger (pits named: Cstart, C1, C2, etc.). Additional pits were also sampled  
205 within the ditched enclosure (pits named: RH1, RH2, RH3, RH4) and on an adjacent hill (pits named:  
206 AH1, AH2). For each pit, soil samples were collected every 5 centimeters, from the surface to a depth  
207 of 120 centimeters. However, given the absence of archaeological artifacts in deep samples, we focused  
208 on the first 60 centimeters in the following analyses.

### 209 3. Soil Analyses

#### 210 • Archaeological Artifacts, Soots and Macrocharcoals

211 The bulk soil samples were dried in an oven (50°C), weighed and sieved (<5 mm) to remove roots and  
212 stones and extract archaeological artifacts (i.e., ceramic shards) and macroscopic charcoal (> 5mm).  
213 Macroscopic charcoals (~2-5 mm) and soots were extracted by hand from the sieved fraction. Given the  
214 reduced volume of dry soil obtained every 5 cm, the presence of archaeological artifacts, soots, and  
215 macrocharcoals was evaluated as discrete variables (i.e., presence/absence, encoded '1/0').

#### 216 • Colorimetry

217 The color of the soil samples was measured using a PANTONE CAPSURE colorimeter implemented  
218 with the Munsell color chart. Each sample was subjected to five consecutive measures to determine the  
219 dominant color. The samples were then separated into two different fractions: a 100-200 g fraction was  
220 reserved for physico-chemical analysis. The remaining fraction was kept for evaluation of microcharcoal  
221 abundance.

#### 222 • Physico-chemistry

223 For each pit, physicochemical analyses were carried out on one sample every 10 cm between 5 cm and  
224 60 cm depth in *terra-firme*, totaling 6 samples per pit: 5-10 cm; 15-20 cm; 25-30 cm; 35-40 cm; 45-50  
225 cm; 55-60 cm. In the bottomlands, dry soil samples were always well below 100 g due to important  
226 waterlogging. To remedy this, we pooled surface samples up to 20 cm and then every 10 cm up to 60  
227 cm depth, thus totaling 5 samples per pit: 0-20 cm; 20-30 cm; 30-40 cm; 40-50 cm; 50-60 cm.

228 A total of 410 physicochemical samples were sent for analysis to the SADEF laboratory (Aspach-Le-  
229 Bas, France), which is accredited for the import of non-European soils. A total of 12 soil properties were  
230 evaluated, including granulometry (i.e., particle size distribution) and chemical properties (pH, major  
231 and minor elements). Table 1 synthesizes the methods used and standards, when applicable. The amount  
232 of soil carbonates (Cinorg) was null in all soil samples and was excluded from our analyses.

233 We tested whether soil properties varied between soil types (ferralsols, hydromorphic gleysols) through  
234 Generalized Linear Models (GLM) using R version 3.5.1 (Model 1: Soil property ~ Soil type). We also  
235 tested whether the physicochemical properties of the *terra-firme* soils varied between study sites (MC87,  
236 NOUR, GALB), landscape-scale localization (i.e. ring ditch enclosure and ditch, hilltops and slopes of  
237 the ring ditch, adjacent hills) and depth (Model 2: Soil property ~ Site + Localization + Depth). The  
238 GLMs were encoded using the functions 'glm()' and 'drop1()', with the different soil properties as  
239 response variables. The GLMs were completed by principal component analyses (PCAs) with packages  
240 'ade4' and 'FactoMineR' to visualize variations in soil properties across soil types, study sites and



241 localization in a multidimensional space with  $N_{property}$  dimensions.

242 **Table 1.** Soil Properties, Abbreviations and Methods.

Property	Abbreviation	Method	Standard
Granulometry (i.e., particle-size distribution)	PSD	Pipette method without decarbonation	NFX 31-107
pH	pH	H <sub>2</sub> O extraction (pH <sub>H2O</sub> )	NF EN ISO 10390
Total Carbon	C <sub>tot</sub>	Dry combustion method	NF ISO 10694
Organic carbon	C <sub>org</sub>		
Total carbonates (i.e. carbonates, mainly CaCO <sub>3</sub> )	C <sub>inorg</sub>	Volumetric method	NF EN ISO 10693
Total Nitrogen	N <sub>tot</sub>	Dumas method	NF ISO 13878
Phosphorus (P <sub>2</sub> O <sub>5</sub> )	P	Olsen method	NF ISO 11263
Potassium (K <sub>2</sub> O), Magnesium (MgO) Calcium (CaO) Sodium (exchangeable Na <sub>2</sub> O)	K Mg Ca Na	Inductively coupled plasma-atomic emission spectrometry (ICP-AES)	NFX 31-108
Aluminum (exchangeable)	Al	Molar KCl extraction and ICP-AES	NA

243 **• Microcharcoal Abundance**

244 The abundance of microcharcoals (160 μm - 2 mm) was evaluated every 5 cm from 0 to 60 cm on 8 to  
 245 9 pits in *terra-firme* areas at each study site, for a total of 300 microcharcoal sample counts. To  
 246 deflocculate the clays, 2.5 cm<sup>3</sup> of soil was exposed to Sodium hexametaphosphate at 40 g/L and  
 247 incubated during 12 hours with an orbital shaker. The samples were then sieved (<160 μm) and dried in  
 248 an oven at 50°C for 12 hours (48). Microcharcoals were counted using a Zeiss stereo microscope at 40x  
 249 magnification.

250 We tested whether microcharcoal varied between sites (MC87, NOUR, GALB), landscape-scale

251 localization (i.e., ring ditch enclosure and ditch, ring ditch hilltops and slopes, adjacent hills) and depth  
252 through a Generalized Linear Model (GLM) using R version 3.5.1. GLM was encoded using the  
253 functions ‘glm()’ and ‘drop1()’, with ‘Site’, ‘Localization’ and ‘Depth’ as explanatory variables, and  
254 ‘Microcharcoal count’ as response variable (Microcharcoal count ~ Site + Localization + Depth).

#### 255 • **Composite Index of Anthropogenic Disturbances**

256 To quantify the extent of landscape-scale anthropogenic disturbances, we developed a composite index  
257 based on the acquired data. This index was designed to integrate information provided by the presence  
258 of artifacts (ceramics, macrocharcoals, soots), soil physicochemical properties and soil color in a single,  
259 unidimensional, metric (see supplementary method).

### 260 **4. Radiocarbon Dating**

261 At each study site, 10 macroscopic charcoals (> 10 mg) were selected for radiocarbon dating, totaling  
262 30 macrocharcoals. Macrocharcoals were selected from pits within or close to the ring ditch enclosure,  
263 at depths between 0 and 45 centimeters. Radiocarbon dating was performed by the CIRAM Radiocarbon  
264 Laboratory (Martillac, France). The calibration was performed using the OxCal 4.4 program (49) with  
265 the IntCal20 calibration curve (50).

266

## 267 **Results**

### 268 **1. Radiocarbon Dating**

269 → **Fig. 2.** Radiocarbon date ranges obtained from the three study sites at 95.4% probability. Lower pane:  
270 all dates, upper pane: dates posterior to 430 CE. Radiocarbon data are provided in supplementary table  
271 2.

272 Radiocarbon dates obtained from the three study sites span from the mid-Holocene to the end of the pre-  
273 Columbian period; see Fig. 2 and supplementary table 2. At MC87, five calibrated dates obtained from  
274 the pits RH2 (30-35), C4 (5-10, 10-15) and C5 (10-15, 35-40) were spread over a period ranging from  
275 662 to 945 CE. Four dates, obtained from the pits RH1 (0-5, 10-15) and C2 (15-20, 40-45), were spread  
276 over a period ranging from 1214 to 1398 CE. One intermediate date from RH2 (25-30) was dated  
277 between 993 and 1155 CE. At NOUR and GALB, radiocarbon dates show three and four different (non-  
278 overlapping) chronological periods. At NOUR, one oldest date was obtained from the pit C12 (30-35)  
279 and dated between 4230 and 3982 BCE. The nine other dates were posterior to 430 CE, with two non-  
280 overlapping sub-periods: charcoals from C11 (20-25, 25-30, 35-40), C15 (15-20, 20-25) and C17 (10-  
281 15) spanned over a period from 430 CE to 976 CE, while dates obtained from C13 (10-15, 15-20) and  
282 C15 (5-10) spanned over a period from 1296 to 1446 CE At GALB, radiocarbon dating revealed a more

283 complex chronology. One ancient date calibrated at 7739 - 7588 BCE was obtained from C7 (40-45).  
284 Two other contemporary ancient dates, ranging from 2894 to 2585 BCE, were obtained from RH4 (15-  
285 20) and C11 (20-25). The seven other dates were post-600 CE. As at NOUR, two non-overlapping  
286 subperiods emerged: three dates from pits C3 (5-10) and C12 (20-25, 30-35) ranged between 666 and  
287 891 CE, while the four dates from C10 (10-15, 15-20, 20-25, 25-30) cover the period 1326 - 1490 CE.

## 288 **2. Archaeological Artifacts, Soots and Macrocharcoals**

289 → **Fig. 3.** Spatial distribution of soil colors and archaeological artifacts along the transects in the three  
290 study sites.

291 → **Supplementary figure 1.** Proportion of samples per pit containing ceramic shards (red triangles),  
292 macrocharcoals (gray squares), and soots (black circles).

293 Soil sampling revealed the presence of ceramic shards, macroscopic charcoals, and soots, Fig. 3. At the  
294 three study sites, the presence of artifacts was mostly concentrated in *terra-firme* areas, while none or  
295 few artifacts were found in the bottomlands.

296 At MC87, ceramic shards were found in 8 samples from pits within the enclosure of the ring ditch (pits  
297 C1, RH1, C2) or close to the ditch (pit C3). In these pits, the proportion of samples containing ceramic  
298 shards varied between 8.3% and 36.3%, supplementary fig. 1. At NOUR, no ceramic shards were found  
299 during soil sampling. At GALB, three samples from the ring ditch enclosure (pits C9 and C6) contained  
300 ceramic shards. In addition, an inspection of soil retained within the roots of fallen trees revealed the  
301 presence of ceramics within the ring ditch enclosures at the three sites.

302 In the three sites, macrocharcoals and soots were found in most of the *terra-firme* pits, both in the ring  
303 ditch and in adjacent hills. However, the highest proportions of samples containing charcoals and/or  
304 soots were found in pits from the ring ditches, supplementary fig. 1.

305 At MC87, a total of 48 soil samples from 12 pits contained macrocharcoals and 27 samples from 13 pits  
306 contained soots (out of 291 soil samples from 25 pits). The highest proportions of samples containing  
307 macrocharcoals and soots were found in the pits RH2 (66.67% of the samples in the pit) and C2 (50%  
308 of the samples in the pit), respectively, which were both within the ring ditch enclosure. Secondary  
309 peaks were also detected in pits C5 (58.3% of the samples containing macrocharcoals) and C6 (41.67 %  
310 of the samples containing soots), which were located on the slope of the ring ditch hill. The global  
311 proportion of samples containing macrocharcoals was 28.8% in pits of the ring ditch enclosure and ditch  
312 (out of 59 samples ; pits C1 to C3, RH1 and RH2), 25.0% in pits of the ring ditch hilltop and slope  
313 outside the enclosure (out of 60 samples ; pits Cstart, C4 to C7), and 13.3% in pits of the adjacent hill  
314 (out of 120 samples ; pits C13 to C20, AH1 and AH2). The proportion of samples containing soots was

315 17.0% within the enclosure of the ring ditch, 11.7% on the hilltop and slope of the ring ditch outside the  
316 enclosure, and 8.3% in the pits of the adjacent hill. At the bottom of the slopes of the ring ditch, the C7  
317 pit contained neither macrocharcoals nor soots.

318 At NOUR, a total of 66 soil samples from 21 pits contained macrocharcoals and 40 samples from 16  
319 pits contained soots (out of 296 soil samples from 25 pits). The highest proportions of samples  
320 containing macrocharcoals were found in pits C10 and C12 (75% and 66,7% of samples in each pit,  
321 respectively), while the highest proportion of samples containing soots was found in pit C9 (50% of  
322 samples in the pit). These three pits were located on the ring ditch: C12 was located at the outer edge of  
323 the ditch, and C10 and C9 were located on the plateau and slope of the ring ditch, outside the enclosure.  
324 The global proportion of samples containing macrocharcoals was 40.0% in the pits of the enclosure and  
325 ditch (out of 60 samples ; pits C12 to C15 and RH3), 19.4% in the pits of the plateau and slope outside  
326 the ditch (out of 180 samples ; pits C16 to C20 on the north face of the plateau, and C2 to C11 on the  
327 south face of the plateau and slope), 3.1% in the pits of the bottomland (out of 32 samples ; pits C1,  
328 Cstart and C24), and 25.0% in the pits of the adjacent hill (out of 24 samples ; pits C22 and C23).  
329 Surprisingly, the global proportion of samples containing soots was higher in the pits of the adjacent hill  
330 (29.2% of samples) than in the pits of the bottomland (18.8%), the plateau and slopes of the ring ditch  
331 (12.8%) and the enclosure and ditch (6.7%).

332 At GALB, 20 soil samples from 9 pits contained macrocharcoals and 42 samples from 16 pits contained  
333 soots (out of 248 soil samples from 21 pits). The highest proportions of samples containing  
334 macrocharcoals were found in C10 (33.3%), RH4 (25%), C11 (25%) and C3 (25%). C10 and RH4 were  
335 located within the ring ditch enclosure, while C11 and C3 were located on the slopes and top of the ring  
336 ditch. The highest proportions of samples containing soots were found in pit C4 (41.7%), C10 (33.3%),  
337 RH4 (33.3%) and C12 (33.3%). Pits C4, C10 and RH4 were located within the enclosure, while C12  
338 was located on the ring ditch slope. The global proportion of samples containing macrocharcoals was  
339 8.33% in the pits of the ring ditch enclosure (out of 96 samples ; pits C4 to C10 and RH4), 10.0% in the  
340 pits of the top and slopes of the ring ditch (out of 120 samples ; pits C11 to C14, Cstart, C1 to C3 and  
341 C15 to C16), and 0% in the bottomland and adjacent slope (out of 20 and 12 samples ; pits C17 and C18  
342 in the bottomland and C19 on the adjacent slope). The global proportion of samples containing soots  
343 was 22.9% in the enclosure pits, 16.7% in the pits of the ring ditch plateau and slopes, and 0% in the  
344 bottomland and adjacent hill.

### 345 **3. Soil Colorimetry**

346 Soil colorimetry showed different colorimetric ranges between bottomlands and *terra-firme* areas, while  
347 soils from ring ditches and adjacent hills have similar color ranges. However, slight color variations  
348 were detected in the depth of soil profiles from the ring ditches to the adjacent hills.

349 In bottomlands, gleysol colors varied from dark brown (e.g., 2.5 YR 2.5/2, 5 YR 3/2, 7.5 YR 3/2, 2.5Y  
350 4/2) on the surface to light gray (e.g., 2.5 Y 7/2, 5 Y 7/2) on the depth. At NOUR, one pit (C24) located  
351 in a seasonally waterlogged area was dominated by yellowish brown (10 YR 5/6, 10 YR 5/4, 10 YR  
352 4/4).

353 In *terra-firme* areas, soil colors ranged from strong brown (e.g., 7.5 YR 4/6; 7.5 YR 5/6) to yellowish  
354 brown (e.g., 10 YR 4/4; 10 YR 5/4). At MC87, the dominant colors were brown (7.5 YR 4/4) and dark  
355 yellowish brown (10 YR 4/4). Dark-colored soils were found on the surface of the hilltops as revealed  
356 by the colors reddish brown (2.5 YR 3/4) and dark brown (7.5 YR 3/2), from the Cstart to C3 pits in the  
357 ring ditch (6 pits) and C13 to C19 on the adjacent hill (8 pits). However, these dark soils were thicker  
358 in the ring ditch where two pits showed deep dark soils that extended from the surface to 30 and 35 cm  
359 (pits C2 and RH2), while the thickness of dark soils did not exceed 20 cm in depth (pit C18) in the  
360 adjacent hill. The soil colors in pit 20 showed discontinuous dark soils at depths of 0-5 cm, 20-25 cm  
361 and 35-40 cm in depth, probably due to a soil disturbance caused by recent forest logging. At NOUR,  
362 the dominant color was dark yellowish brown (10 YR 4/4) on the plateau of the ring (pits C20 to C10),  
363 while the soil profiles became gradually dominated by brown (7.5 YR 4/4) at the top of the slope (pits  
364 C8 and C9) and strong brown (7.5 YR 4/6) on the slope (from pit C9 to C2) and on the adjacent hill  
365 (C22 and C23). At GALB, the soil profiles were dominated by strong brown (7.5 YR 4/6, 7.5YR 5/6).  
366 The surface soils of the west face of the ring ditch enclosure were dominated by dark yellowish brown  
367 (10 YR 4/4) up to 30 cm deep (pits C10 to C7 and RH4). This color was also found on the surface  
368 horizon (0-5 cm deep) of the eastern face of the enclosure (pits C4 and C5) and the top of the ring ditch  
369 (C2, C1, Cstart, C15, C16).

#### 370 4. Microcharcoal Counts

371 → **Fig. 4.** Microcharcoal abundance evaluated from soil volumes of 2.5 cm<sup>3</sup>.

372 → **Supplementary figure 2.** Distribution of microcharcoal abundance across sites (GALB, MC87,  
373 NOUR), landscape-scale localizations (ring ditch enclosure and ditch, ring ditch plateau and slope,  
374 adjacent hill) and depth ranges.

375 Microcharcoal counts varied significantly between study sites ( $p$ -value  $< 2.2 \times 10^{-16}$ ), localizations  
376 within the landscape ( $p$ -value  $= 4.6 \times 10^{-9}$ ), and depths ( $p$ -value  $= 2.5 \times 10^{-12}$ ) supplementary figure 2.  
377 As expected, the microcharcoal concentration was lower in deep samples between 35 and 60 cm than in  
378 upper samples between the surface and 30 cm, with a transition at 30-35 cm deep. MC87 had the highest  
379 overall microcharcoal concentration and GALB the lowest microcharcoal concentration. At the  
380 landscape scale, microcharcoal concentration was significantly higher within the ring ditch enclosures  
381 than on the ring ditch plateaus and slopes and on adjacent hills.

382 At MC87, one pit located within the enclosure of the ring ditch (pit C2) showed particularly high  
383 microcharcoal concentrations, whose counts varied between 655 and 1230 in the first 30 cm (Fig. 4).  
384 Microcharcoal counts in this pit were above 250 in the entire soil profile, with a peak at 5-10 cm deep.  
385 In the other pits, the microcharcoal abundance was almost always below 500 and decreased in soil  
386 profiles to less than 100 at depths between 25-30 cm (pit C17) and 45-50 cm (pits RH1, C15, C19).

387 At NOUR, the spatial distribution of microcharcoal counts was consistent with the landscape-scale  
388 position of pits (Fig. 4). Four pits located within the enclosure (pits C15 and C13), on the plateau (C10)  
389 and slope (C7) of the ring ditch showed strong variations within soil profiles. Microcharcoal counts in  
390 these pits varied between 127 (C10) and 323 (C15) from the surface to 30 cm, and between 29 (C15)  
391 and 354 (C10) below 30 cm deep. Pits C13 and C15 had a peak at 15-20 cm (abundance = 303 and 323),  
392 C7 had a peak at 20-25 cm (abundance = 305) and C10 at 30-35 cm (abundance = 354). Other pits (C20,  
393 C17, C4 and C23) show lower microcharcoal abundance (almost always below 200) and flatter curves.  
394 Only the most extreme pit of the adjacent hill (C22) exhibited an intermediate pattern of microcharcoal  
395 concentration, with two peaks at 15-20 cm and 20-25 cm (abundance = 211 and 213, respectively) and  
396 microcharcoal counts below 200 in other samples.

397 At GALB, pits located on the hilltop of the ring ditch (C9, C7, C5, C1) showed microcharcoal counts  
398 between 59 (C7) and 217 (C7) from the surface up to 30 cm deep and between 19 (C7) and 207 (C5)  
399 below 30 cm deep, with higher concentrations between 15-20 cm (C7, count = 217) and 35-40 cm (C5,  
400 count = 207). These pits also showed a plateau of 150 to 200 microcharcoals over 30 to 40 centimeters  
401 from the surface. Except for C13, the pits located on the slope of the ring ditch (C11 and C16) and on  
402 the adjacent slope (C19) had microcharcoal counts below 150 with only slight variations in soil profiles.  
403 Only pit C13 had an irregular profile, with two peaks at 10-15 cm (count = 239) and 25-30 cm (count =  
404 191), while samples below 30 cm deep had low microcharcoal concentrations (counts < 60).

## 405 **5. Physico-chemistry**

406 → **Fig. 5.** Principal Component Analyses (PCAs) illustrating variations in soil properties between soil  
407 types (upper pane) and between landscape-scale localizations in *terra-firme* areas (lower pane).

408 → **Supplementary Fig. 3.** Distribution of averaged values of physicochemical properties according to  
409 study sites, localizations, and depth of soil samples. Averaged values are calculated for each depth from  
410 all pits in the same localization (RD Enclosure & Ditch, RD Hilltop & Slope, Bottomland, AH).

411 Soil properties differed between hydromorphic gleysols and ferralsols (Fig. 5, upper pane).  
412 Granulometry and eight chemical properties varied significantly between soil types at a 1% threshold,  
413 supplementary table 3. Ferralsols contained significantly more clays while hydromorphic soils contained  
414 significantly more coarse silt, total silt, and sand. Only fine silt was not significant between soil types.

415 Hydromorphic soils contained significantly more nutrients (Corg, Ntot, K, Mg, Ca, Na) and had a higher  
416 pH. Only P and Al did not vary significantly between soil types.

417 In *terra-firme*, soil properties varied significantly between study sites, landscape-scale localization, and  
418 depth range. All properties varied significantly across depth ranges at a 1% threshold, except coarse silt,  
419 which showed significant variations at 5% threshold, and P, which did not vary significantly. Significant  
420 differences between study sites were detected for clay, sand, Corg, Mg and Al at a 1% threshold, and  
421 for P at a 5% threshold. Soil properties also varied significantly between the landscape-scale position of  
422 the pits (Fig. 5, lower pane, and supplementary table 3). Pits located on the hills of ring ditches (within  
423 and outside the enclosure) contained significantly more clays, Ntot, Mg and K than adjacent hills at a  
424 1% threshold. The enclosures of the ring ditches also contained significantly more Corg and Ca than the  
425 ring ditch slopes and the adjacent hill at a 1% threshold. Variations in Al and pH were poorly significant.  
426 Al was slightly higher in the slopes of the ring ditches than in the enclosures or adjacent hills, while pH  
427 was slightly higher in adjacent hills at a 5% threshold.

428

## 429 **6. Extent of anthropogenic disturbances**

430 → **Supplementary Fig. 4.** Composite index of anthropogenic disturbances at MC87 in the entire soil  
431 profile (upper pane), between 0 and 30 cm deep (middle pane), between 30 and 60 cm deep (lower pane).

432 → **Supplementary Fig. 5.** Composite index of anthropogenic disturbances at NOUR in the entire soil  
433 profile (upper pane), between 0 and 30 cm deep (middle pane), between 30 and 60 cm deep (lower pane).

434 → **Supplementary Fig. 6.** Composite index of anthropogenic disturbances at GALB in the entire soil  
435 profile (upper pane), between 0 and 30 cm deep (middle pane), between 30 and 60 cm deep (lower pane).

436

437 The composite index quantified the extent of anthropogenic disturbances through a multiple proxy  
438 approach that integrated artifacts (ceramic shards, macrocharcoals, soots), chemical indicators, and soil  
439 color. Variations in anthropogenic disturbances within study sites tend to increase from adjacent hills to  
440 the enclosure of ring ditches (supplementary figures 4 to 6). It is also important to note that this index  
441 was less variable between 30 and 60 cm depth than between 0 and 30 cm depth where variations across  
442 landscape-scale localization and pits were more pronounced. At GALB and MC87, anthropogenic  
443 disturbances were higher within the ring ditch enclosures than outside the enclosures and adjacent hills.  
444 At NOUR, variations in anthropogenic disturbances were less pronounced, and the composite index  
445 tends to gradually decrease from the enclosure of the ring ditch to the adjacent hill.

446

## 447 **Discussion**

448

449 This study provides a comprehensive, multi-proxy overview of anthropogenic disturbances in forest

450 landscapes surrounding ring ditch sites in French Guiana. By exploring multiple indicators, including  
451 archaeological artifacts, soil color, and physicochemical properties, our study provides one of the first  
452 landscape-scale spatialization of long-term anthropogenic disturbances, not only within the enclosure of  
453 ring ditches, but in the extended surrounding landscape.

454

## 455 **1. Occupation Periods**

456 Our different cohorts of radiocarbon dates suggest two main periods of occupation that were coherent  
457 between study sites: one period extending from the 5<sup>th</sup> to the 10<sup>th</sup> century (430 CE - 976 CE) and one  
458 from the 13<sup>th</sup> to the 15<sup>th</sup> century (1214 CE - 1490 CE). These periods are consistent with previous  
459 radiocarbon dating reported at these sites. For example, Brancier et al. (15) reported occupation periods  
460 between 500 and 1100 CE at MC87, while the dates obtained in our study at this site ranged between  
461 662 and 1398 CE. At Nouragues, Bodin et al. (16) reported radiocarbon dates between 688 and 1630  
462 CE from the ring ditch of the ‘grand plateau’ (named ‘site 9’ in Bodin et al. suppl. file), while the main  
463 periods of occupation at this site extended between 430 and 1446 CE in the present study. In two sites  
464 (GALB and NOUR), occupation periods were discontinuous, echoing the bimodal distribution of  
465 radiocarbon dates reported by Bodin et al. (16) at Nouragues and by (51) at another ring ditch site located  
466 along the Oyapock river in eastern French Guiana. This suggests a transitional abandonment of the sites  
467 followed a population re-expansion or reestablishment several centuries later. The radiocarbon dates  
468 obtained in this study are also consistent with previous knowledge on the Amazonian scale. While the  
469 earliest traces of geometric earthwork construction found in West Amazonia date back to the 1<sup>st</sup> to the  
470 2<sup>nd</sup> millennium BCE (6,18), most studies reported that the occupation of earthworks spread from the  
471 first millennium CE (5) to very recent periods (4,8,10,19,33), sometimes after the European Contact  
472 (4,8), see supplementary table 1.

473 Alongside the cohort of Common Era dates, we retrieved four surprisingly old dates between the 8<sup>th</sup> and  
474 the 3<sup>rd</sup> millennium BCE (7739 to 2585 BCE, i.e. approximately 9.7 to 4.5 ka B.P.) at the sites of  
475 Nouragues and Mont Galbao, whose interpretation is uncertain. Indeed, most anthracological and  
476 geochemical studies highlight the rarity of natural fires in Amazon rainforests, thus postulating that  
477 charcoals can be attributed to human activities (52–54). However, Amazonia experienced a drier period  
478 during the early to mid-Holocene. Cordeiro et al. (55) proposed two periods of drought in South-East  
479 Amazonia between 11.8 ka and 4.75 ka B.P. (with a maximum between 7.6 ka and 4.75 ka B.P.), while  
480 Mayle and Power (52) suggested that the dry period extended between 8 ka and 4 ka B.P. in lowland  
481 Amazonia. In French Guiana, Charles-Dominique et al. (56) highlighted instances of paleo-fires over  
482 the periods 10000 - 8000 B.P. and 6000 - 4000 B.P., well before the earliest occupations of French  
483 Guiana that are estimated at 6200 B.P. at site ‘Plateau des Mines’ in western French Guiana (57, p. 135).  
484 Although the anthropogenic origin of these ancient dates cannot be ruled out, a climatic origin remains



485 more probable. In-depth investigations of paleovegetations and paleofires in French Guiana are  
486 necessary to determine the natural or anthropogenic origin of these ancient charcoals.

## 487 **2. Landscape-scale Spatial Anthropogenic Disturbances**

488 Pre-Columbian societies had extended impacts on forest landscapes, not only within ring ditch  
489 enclosures but also on the surrounding territory. The composite index developed is a powerful tool to  
490 capture multi-proxy anthropogenic disturbances in our vast and continuous study areas. As expected,  
491 the composite index had slightly higher values between 0 and 30 cm depth than in deeper soil levels,  
492 where the index values were lower and globally more homogeneous. In general, pre-Columbian  
493 disturbances were stronger in the enclosures of the ring ditches. However, our results at three  
494 independent study sites indicate that anthropogenic disturbances were not limited to the enclosures of  
495 ring ditches. Interestingly, the composite index revealed a common trend between the three sites,  
496 decreasing from ring ditch enclosures to slopes and adjacent hills. This observation is notably supported  
497 by soil color variations and the presence of macrocharcoals. However, dark-colored soils were always  
498 thinner on the adjacent hills than on the ring ditches. At MC87, the colors 7.5 YR 3/2 and 2.5 YR 3/4  
499 extended across the first 35 cm while these soil colors were detected over the first 20 cm on the adjacent  
500 hill. At NOUR, the color 10 YR 4/4 extended across the entire profile on the ring ditch and was detected  
501 only between the surface and 5 to 15 cm. At GALB, the color 10 YR 4/4 was found up to 30 cm in the  
502 ring ditch enclosure and detected on the surface sample (0-5) in the adjacent hill. Similarly, enrichments  
503 in microcharcoals were detected not only within ring ditch enclosures but also on several pits in ring  
504 ditch slopes and adjacent hills. Contrary to *terra-firme* areas, bottomlands contain no or scarce  
505 archaeological artifacts. Nevertheless, this lack of evidence does not preclude that these areas may have  
506 been circulation zones and access to key resources not found in *terra-firme* such as water, hydrophilic  
507 plants (e.g. *Euterpe oleracea*) and gleysols.

508 Our results corroborate previous studies carried out in French Guiana and Amazonia, which also support  
509 the extensive use of forest landscapes by pre-Columbian societies. For example, Bodin et al. (16)  
510 suggested that anthropogenic disturbances affected forest recolonization on the adjacent hill at the ring  
511 ditch site of Saut Pararé, located about 8 km from NOUR site. In the Brazilian state of Acre, Watling et  
512 al. (34) proposed that the joint increase in palm phytoliths and microcharcoals in soil profiles at both  
513 geoglyph sites and surroundings areas (3.5 km apart) is an expression of an overall increase in human  
514 land use. Robinson et al. (58) revealed the existence of anthropogenic brown and black soils near ditched  
515 sites in northern Bolivia. Our results are therefore in line with recent findings that interfluvial regions  
516 were subjected to pre-Columbian socio-environmental dynamics. At a regional scale, LIDAR analyses  
517 revealed that pre-Columbian societies had a complex spatial organization where political, settlement,  
518 and agricultural sites were linked by causeway networks over areas of several hundred km<sup>2</sup> (4,8).  
519 Through a continuous and standardized sampling design, our study introduces a complementary

520 approach to assess fine-scale anthropogenic disturbances in the landscapes surrounding ring ditches.

521

### 522 **3. Moving Beyond the ADE Paradigm**

523 The soil properties within the ring ditch enclosures did not meet anthrosol criteria and cannot be  
524 considered as ADE *sensu stricto* (i.e. *terra-preta*). According to the World Reference Base for Soil  
525 Resources (59), an anthrosol is formed by long and intensive agricultural use. It is defined as a soil with  
526 a pretic horizon thicker than 50 cm, which itself is defined as a dark horizon (Munsell color value  $\leq 4$   
527 and a chroma  $\leq 3$ ) enriched in Corg, P, Ca, and Mg with charcoal and/or archaeological artifacts: shards,  
528 lithic instruments, bones (38,39,44,60–63). The soils of the ring ditch enclosures revealed enrichments  
529 in artifacts, Corg, and nutrients (Ca, Mg, K) over the first 30 to 35 centimeters only, and the darkest  
530 horizons were dark reddish brown (2.5 YR 3/4) to dark yellowish brown (10 YR 4/4) with Munsell  
531 values between 3 and 4 and a chroma of 4.

532 Nevertheless, soil properties revealed a significant anthropogenic influence compared to adjacent soils.  
533 The concentrations of Corg (between 11.5 and 177 g/Kg), Ca (between 0.01 and 0.78 g/Kg), and Mg  
534 (between 0.001 and 0.085 g/Kg) were lower than those commonly found in ADEs (58,60, 62–64) but  
535 higher than those of adjacent soils in our study sites. Indeed, soil modification by human activities is a  
536 multidirectional and gradual process that leads to various trajectories and degrees of soil transformation.  
537 Soil properties in the present study are comparable to the properties of ‘transitional’ soils, also known  
538 as ‘Amazonian Brown Earths’ (ABEs) or formerly ‘*terra mulata*’ (58). For example, ABEs can exhibit  
539 colors ranging from dark brown (7.5 YR 3/2) to yellowish brown (10 YR 5/6), and concentrations of Ca  
540 (0.2 to 0.7 g/Kg) and Mg (0.04 to 0.09 g/Kg) that are comparable to the concentrations found in our  
541 study (39,58,62). This is also consistent with the observations by Brancier et al. (15) who argued, based  
542 on micromorphology and the abundance of anthropogenic artifacts, that the soils in MC87 were closer  
543 to ‘*terra mulata*’ than to ‘*terra preta*’. Although Costa et al. (62) proposed that ‘*terra mulata*’ is the  
544 result of ADE degradation, Robinson et al. (58) argue that these two soil types are the result of distinct  
545 processes driven by different management of resources and space. Moreover, regional differences  
546 between the Amazon basin - where most ADEs are found - and the Guiana Shield, and between fluvial  
547 and interfluvial regions - where ADEs are rare - should be taken with caution as the pedogenesis  
548 processes may differ. The specific location of our study sites in interfluvial areas of the Guiana shield  
549 argues for a better consideration of this region in our understanding of the long-term influence of human  
550 activities on soil properties and pedogenesis in Amazonia.

### 551 **4. Land-use and Landscape Management at Ring Ditch Sites**

552 Both long periods of occupation, artifacts and soil properties argue in favor of perennial settlements.

553 Indeed, soils from ring ditches contained the highest occurrence of macro- and microcharcoals, ceramic

554 shards, and significant enrichments in chemical indicators (Corg, Ntot, Ca, Mg, K). Such patterns are  
555 frequent at pre-Columbian sites and are interpreted as evidence of early domestic occupation  
556 (4,62,65,66) and can unveil ancient land use and management. For example, ceramic shards were almost  
557 exclusively detected within ring ditch enclosures and ditches, suggesting housing areas. The overall  
558 higher concentrations of N, K and Ca within the ring ditches traduce a higher soil fertility. High  
559 concentrations of nutrients at pre-Columbian sites are commonly attributed to an accumulation of  
560 organic wastes of animal and plant origin (62,67), possibly reinforced by plant ash amendments (68).  
561 The present study also revealed the presence of macro- and microcharcoals in the three study areas.  
562 These new results are consistent with the previous study by Brancier et al. (15) that provided evidence  
563 of burned soils within the enclosure of MC87. The frequency of fire indicators in archaeological and  
564 paleoenvironmental records is commonly interpreted as a marker of fire management in Amazonia  
565 (69,70). For Watling et al. (34), charcoal particles larger than 100-125  $\mu\text{m}$  are more likely to result from  
566 a local or supralocal fire signal, and those larger than 250  $\mu\text{m}$  correspond to *in-situ* burning. Therefore,  
567 the abundance of macrocharcoals between 2 and 5 mm found in our study thus suggest *in-situ* fire  
568 management. Differences in microcharcoal concentrations between pits along the transects however  
569 suggest that not all areas were subjected to the same fire regime. Burning was more likely a local process  
570 in small patchy areas than an extensive practice affecting vast areas. Fire management may have served  
571 different domestic (e.g. forest clearance) and/or agricultural purposes that are not necessarily mutually  
572 exclusive. For example, Arroyo-Kalin (71) suggests that microcharcoal concentrations in anthropogenic  
573 soils can be interpreted as evidence of highly localized slash-and-burn cultivation. Bodin et al. (16) point  
574 out, however, that anthracological deposits alone cannot be used to decide whether charcoal is of  
575 agricultural or domestic origin. Indeed, archaeobotanical and isotopic ( $\text{d}^{13}\text{C}$ ) analyses are necessary to  
576 investigate the extent of forest clearance, and to unveil the exact uses of managed landscapes. At NOUR,  
577 Bodin et al. (16) suggested based on anthracological assemblages that human activities favored a  
578 secondary vegetation composed of pioneer and heliophilic taxa, thus suggesting forest openings during  
579 occupation periods. Conversely, Watling et al. (34) suggested that the landscapes remained relatively  
580 closed (i.e. ‘anthropogenic forests’) during the occupation based on phytolith assemblages and  $\text{d}^{13}\text{C}$ .

581 Although it is impossible to conclude about the exact uses of pre-Columbian landscapes at ring ditch  
582 sites, our study corroborates the hypothesis of ‘domestic landscapes’ (25), where human occupation had  
583 extended and long-term impacts on contemporary forest landscapes, either directly (through plant  
584 cultivation by early agriculturists) or indirectly (through landscape management). Nonetheless, the  
585 present study paves the way to in-depth investigations of both contemporary and ancient vegetation to  
586 tackle the exact purposes of landscape management at ring ditch sites of French Guiana.

587

588 **Conclusion**

589 Taken together, our results support the idea that pre-Columbian societies made extensive use of their  
590 landscapes in the French Guiana hinterlands, leaving lasting traces of their activities in the soils of ring  
591 ditch sites and their surrounding territories. Soil surveys revealed anthropogenic alteration corroborated  
592 by local enrichments in chemical indicators, darker soils, and abundant macro- and microcharcoals,  
593 whose overall intensity decreased from ring ditch enclosures to surrounding areas. Furthermore,  
594 detected anthropogenic soils do not meet the characteristics of “Amazonian Dark Earths” *sensu stricto*,  
595 thus arguing for an inclusive consideration of “Amazonian Brown Earths” as Amazonian anthrosols.  
596 Finally, further investigation of ancient vegetation through phytolith analyses is essential to deepen our  
597 understanding of the exact land uses and aims of landscape management at ring ditch sites.

598

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617

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623

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632

### 633 **Conflict of Interest**

634 The authors declare no conflict of interest.

635

### 636 **Protocol and Data Availability**

637 This study complies with the Open Access and FAIR Principles.

- 638 ● The protocol is available under DOI: [dx.doi.org/10.17504/protocols.io.14egn768pv5d/v1](https://dx.doi.org/10.17504/protocols.io.14egn768pv5d/v1)
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641

### 642 **Author Contributions**

643 LB supervised the study. MT, LB and JE designed the study and managed the protocols. JE and MT  
644 installed the transects in the field. MT and KM collected soil samples. MT, LB and JE managed the  
645 samples. JE managed GPS and LiDAR data and created the maps in QGIS. MT and KM performed  
646 laboratory analyses and acquired geoarchaeological data. MT and LB managed the geoarchaeological  
647 data. MT and LB analyzed the data. MT designed the figures. MM provided external advice throughout  
648 the study. MT, LB and JE wrote the article.

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### Supplementary materials

836 **Supplementary Table 1.** Non-exhaustive literature overview of earthwork radiocarbon dates in  
837 Amazonia.

Region	Reference	Radiocarbon dates
North Amazonia (Guiana shield, French Guiana)	Bodin et al. 2020	CE 650- 950 (1300-1000 B.P.) and CE 1350-1550 (600-400 B.P.)
North Amazonia (Guiana shield, French Guiana)	Brancier et al. 2014	CE 500 -1100
South Amazonia (Upper Tapajos, Brazil)	de Souza et al. 2018	CE 1250-1500
South Amazonia (Upper Xingu, Brazil)	Heckenberger et al. 2003	CE 1200-1600
South-west Amazonia (Llanos de Mojos, Bolivia)	Prümers et al. 2022	CE 500-1400
South-west Amazonia (Llanos de Mojos, Bolivia)	Carson et al. 2015	CE 1200-1400 (750-550 B.P.), with decline in population activity 1350-1450 (600-500 B.P.)
South-west Amazonia (Llanos de Mojos, Bolivia)	Carson et al. 2014	CE 1150-1450 (500-800 B.P.)
West Amazonia (Acre, Brazil)	Pärssinen et al. 2009	CE 1244-1378
West Amazonia (Acre, Brazil)	Schaan et al. 2012	BCE 50 – CE 1250 (2000-700 B.P.)
West Amazonia (Acre, Brazil)	Saunaluoma and Schaan 2012	BCE 1600 - CE 1300, with the most intensive period BCE 200 - CE 900

838

839 **Supplementary Table 2.** Radiocarbon dates obtained from the three study sites. The calibration was  
840 performed using the OxCal 4.4 program with the IntCal20 calibration curve.

Study site	pit	depth	cal. age (BCE / CE)
MC87	RH1	0-5	1223 - 1280 CE (95.4%)
MC87	RH1	10-15	1214 - 1278 CE (95.4%)

MC87	RH2	25-30	993 - 1155 CE (95.4%)
MC87	RH2	30-35	707 - 945 CE (95.4%)
MC87	C2	15-20	1282 - 1395 CE (95.4%)
MC87	C2	40-45	1298 - 1398 CE (95.4%)
MC87	C4	5-10	676 - 878 CE (95.4%)
MC87	C4	10-15	686 - 885 CE (95.4%)
MC87	C5	10-15	662 - 774 CE (95.4%)
MC87	C5	35-40	680 - 880 CE (95.4%)
GALB	RH4	15-20	2876 - 2585 BCE (95.4%)
GALB	C3	5-10	666 - 822 CE (95.4%)
GALB	C7	40-45	7739 - 7588 BCE (95.4%)
GALB	C10	10-15	1410 - 1460 CE (95.4%)
GALB	C10	15-20	1326 - 1438 CE (95.4%)
GALB	C10	20-25	1421 - 1490 CE (95.4%)
GALB	C10	25-30	1410 - 1455 CE (95.4%)
GALB	C11	20-25	2894 - 2638 BCE (95.4%)
GALB	C12	20-25	706 - 891 CE (95.4%)
GALB	C12	30-35	690 - 887 CE (95.4%)
NOUR	C11	20-25	442 - 640 CE (95.4%)
NOUR	C11	25-30	430 - 584 CE (95.4%)
NOUR	C11	35-40	660 - 776 CE (95.4%)
NOUR	C12	30-35	4230 - 3982 BCE (95.4%)
NOUR	C13	10-15	1396 - 1446 CE (95.4%)

NOUR	C13	15-20	1296 - 1398 CE (95.4%)
NOUR	C15	5-10	1306 - 1420 CE (95.4%)
NOUR	C15	15-20	648 - 774 CE (95.4%)
NOUR	C15	20-25	664 - 774 CE (95.4%)
NOUR	C17	10-15	772 - 976 CE (95.4%)

841

842 **Supplementary Table 3. Generalized linear model analyses of soil physicochemical properties.**

843 Model 1: Soil property ~ Soil type (with soil type: ferralsols, hydromorphic gleysols). Model 2 : Soil

844 property ~ Site + Localization + Depth (with site: MC87, NOUR, GALB ; location: ring ditch enclosure

845 and ditch, ring ditch hilltops and slopes, adjacent hills). \* p-value < 5%, \*\* p-value < 1%.

Soil Property		Model 1	Model 2 (on terra-firme soils only)		
		Soil type effect (p-value)	Study site effect (p-value)	Landscape localization (p-value)	Depth p-val
PSD	Clay	$2.56 \times 10^{-56}$ **	$8.28 \times 10^{-31}$ **	$4.18 \times 10^{-3}$ **	$1.82 \times 10^{-08}$ **
	Fine silt	0.87	0.08	$4.28 \times 10^{-4}$ **	$1.45 \times 10^{-03}$ **
	Coarse silt	$6.31 \times 10^{-07}$ **	0.07	0.10	0.02 *
	Total silt	$2.66 \times 10^{-3}$ **	0.10	$2.57 \times 10^{-04}$ **	$6.42 \times 10^{-03}$ **
	Fine sand	$3.71 \times 10^{-58}$ **	$9.76 \times 10^{-12}$ **	$1.49 \times 10^{-06}$ **	$1.16 \times 10^{-07}$ **
	Coarse sand	$2.31 \times 10^{-45}$ **	$1.43 \times 10^{-78}$ **	0.77	$5.24 \times 10^{-07}$ **
	Total Sand	$7.90 \times 10^{-64}$ **	$1.19 \times 10^{-68}$ **	0.06	$8.31 \times 10^{-10}$ **
Chemistry	pH	$1.46 \times 10^{-10}$ **	0.71	0.02 *	$7.31 \times 10^{-13}$ **
	Corg	$4.74 \times 10^{-21}$ **	$1.97 \times 10^{-07}$ **	$4.53 \times 10^{-4}$ **	$1.49 \times 10^{-51}$ **
	Ntot	$6.16 \times 10^{-11}$ **	0.23	$1.86 \times 10^{-4}$ **	$1.98 \times 10^{-100}$ **
	P	0.35	$4.51 \times 10^{-2}$ *	0.73	0.93

	K	$5.79 \times 10^{-07}$ **	0.70	0.43	$1.10 \times 10^{-44}$ **
	Mg	$8.09 \times 10^{-23}$ **	$3.84 \times 10^{-24}$ **	$4.71 \times 10^{-09}$ **	$2.94 \times 10^{-13}$ **
	Ca	$1.30 \times 10^{-32}$ **	0.73	$1.75 \times 10^{-3}$ **	$1.16 \times 10^{-09}$ **
	Na	$1.30 \times 10^{-14}$ **	0.10	0.92	$2.77 \times 10^{-13}$ **
	Al	0.29	$3.86 \times 10^{-16}$ **	0.02 *	$2.67 \times 10^{-17}$ **

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847

### 848 **Supplementary Method. Construction of the composite index of anthropogenic disturbance.**

849 A composite index is a metric that combines multiple variables into a single variable. The construction  
850 of such an index relies both on previous knowledge and expectations and empirical variations in a given  
851 dataset. The present index was based on the following soil properties (called  $P$  in the following, where  
852  $P_{\text{pit},d}$  refers to the value of the  $P$  variable in a given pit at a given depth):

853

- 854 ● Presence/absence of ceramic shards (weight =1)
- 855 ● Presence/absence of macrocharcoals (weight =0.5)
- 856 ● Presence/absence of soots (weight =0.5)
- 857 ● Organic carbon content, Corg (weight =1)
- 858 ● Total nitrogen content, Ntot (weight =1)
- 859 ● Magnesium content, Mg (weight =1)
- 860 ● Calcium content, Ca (weight =1)
- 861 ● Aluminum content, Al (weight =1)
- 862 ● Munsell color value (weight =1)
- 863 ● Munsell color chroma (weight =1)

864 Phosphorus (P) and potassium (K) were not included in the present index, as these properties did not  
865 vary significantly between landscape-scale localizations in our study. Microcharcoal counts were not  
866 included in the index as their abundance was estimated in a reduced number of pits only. Because  
867 macrocharcoals and soots provide complementary information, these variables are weighted by a factor  
868 of 0.5 (cf. step 3).

869

#### 870 Step 1. Variable Direction

871 Because some variables are expected to decrease while anthropogenic disturbance increases (e.g., color  
872 variables: the lower the value, the darker the color and the lower the chroma, the stronger the color),  
873 these variables are first transformed to reverse their direction of variation by multiplying each value by

874 ' -1' :  $-P_{pit,d} = P_{pit,d} \times (-1)$

875

876 Step 2. Variable Scaling

877 Data are normalized into a range [0-1] through min-max scaling. This step standardizes variables with  
878 different variation ranges (e.g., variables expressed in different units), while preserving the original  
879 distribution of the variables.

880  $P'_{pit,d} = \frac{P_{pit,d} - \min(P)}{\max(P) - \min(P)}$ , where  $\min(P) = \min\{P_{pit,d}\}_{pit=1;d=1}^{Npit;Nd}$  and  $\max(P) = \max\{P_{pit,d}\}_{pit=1;d=1}^{Npit;Nd}$

881 Step3. Index Computation

882 For each pit and depth,

883  $I_{pit,d} = \sum_{p=1}^{Np} (P'_{pit,d} \times W_p)$ , where  $W_p$  is the weight of each  $P$  variable:

884  $W_p = \{1, 0.5, 0.5, 1, 1, 1, 1, 1, 1\}$

885 Then, for each pit,

886  $I_{pit} = \frac{\sum_{p=1}^{Np} (I_{pit,d})}{Nd}$

887

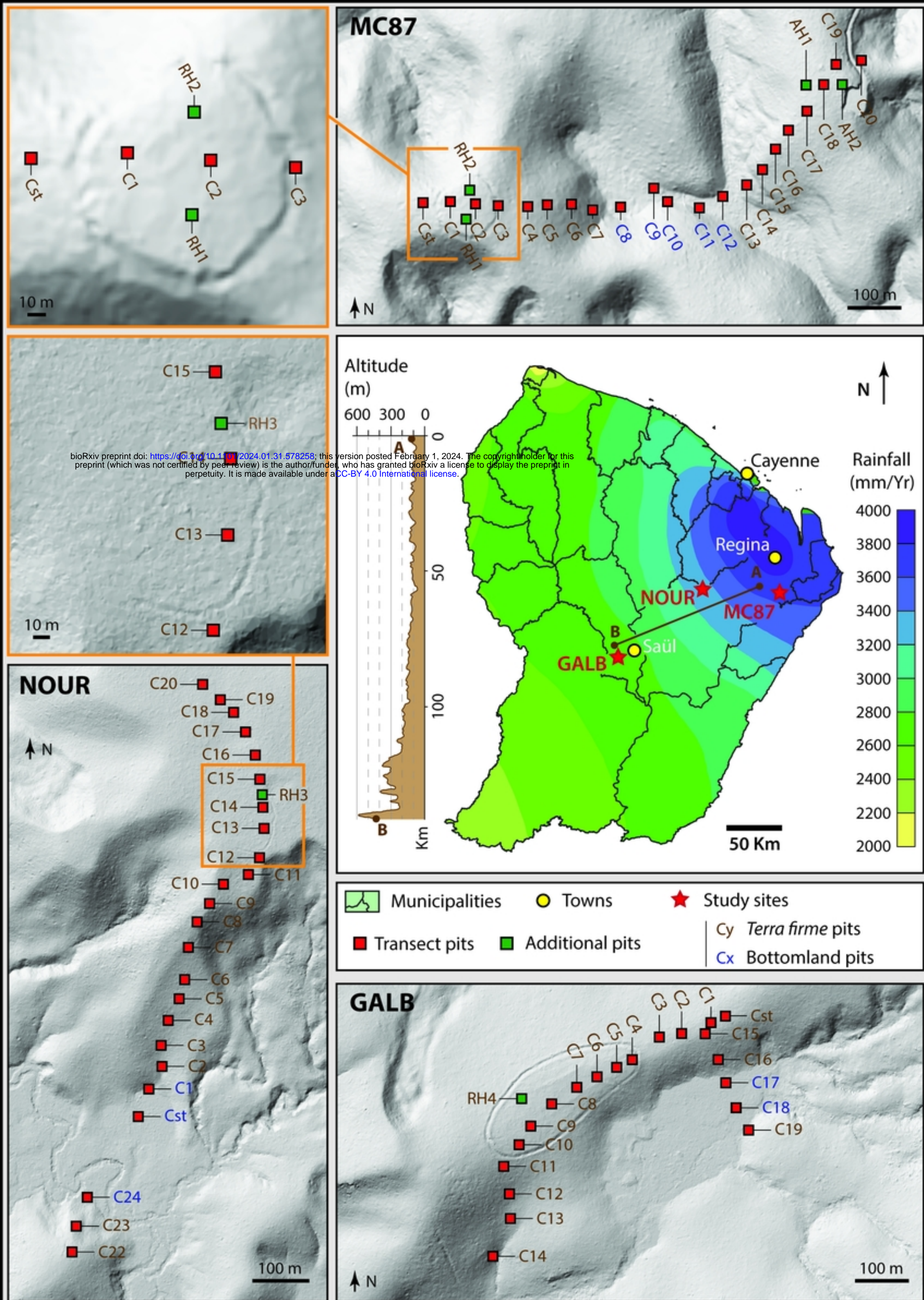


Figure.1



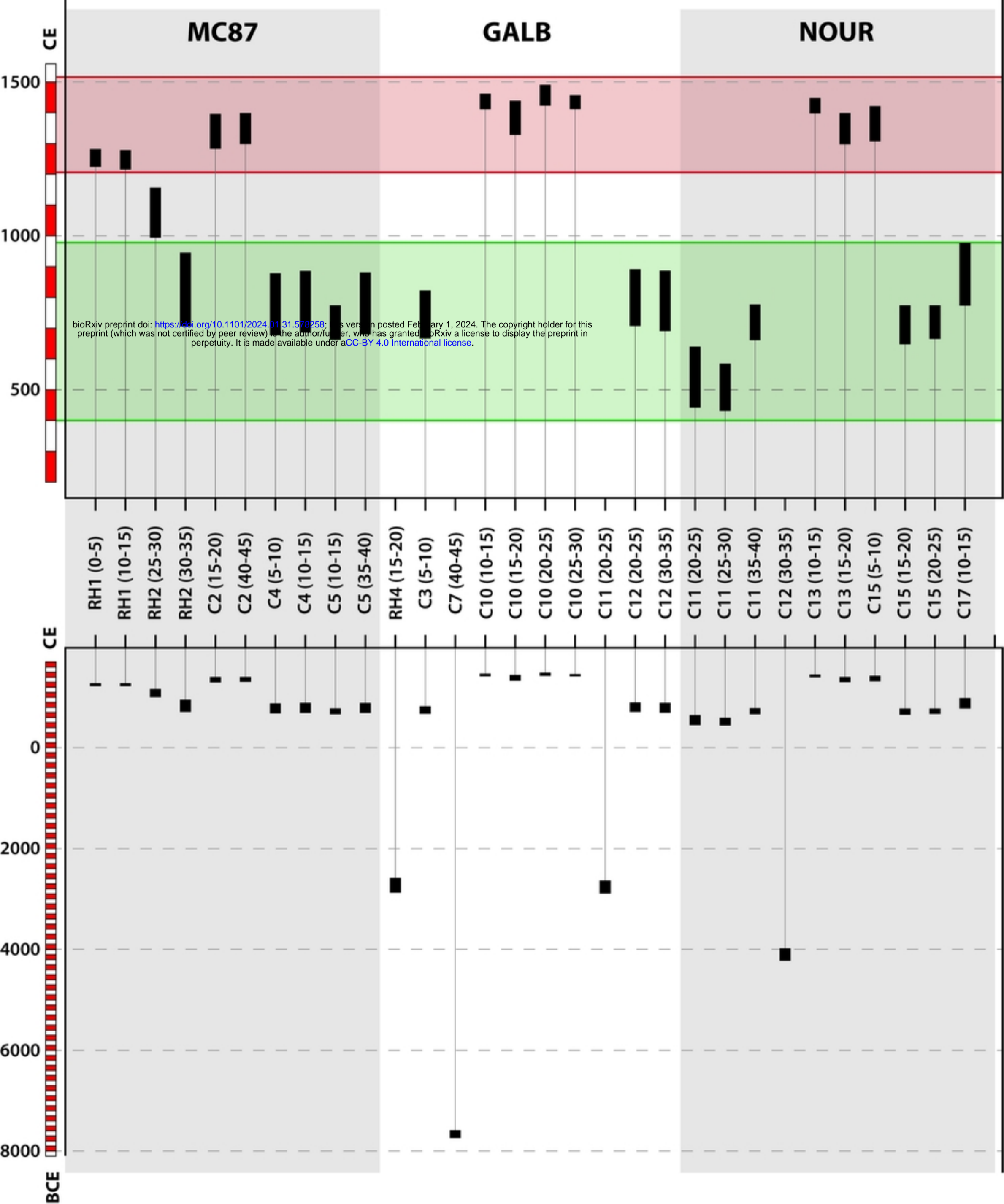


Figure.2

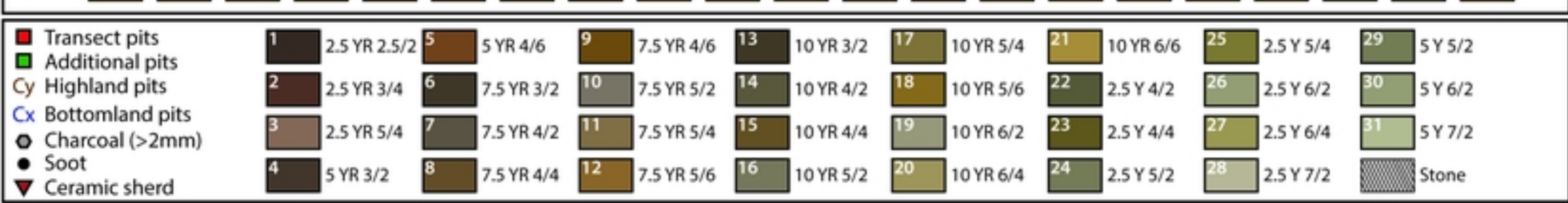
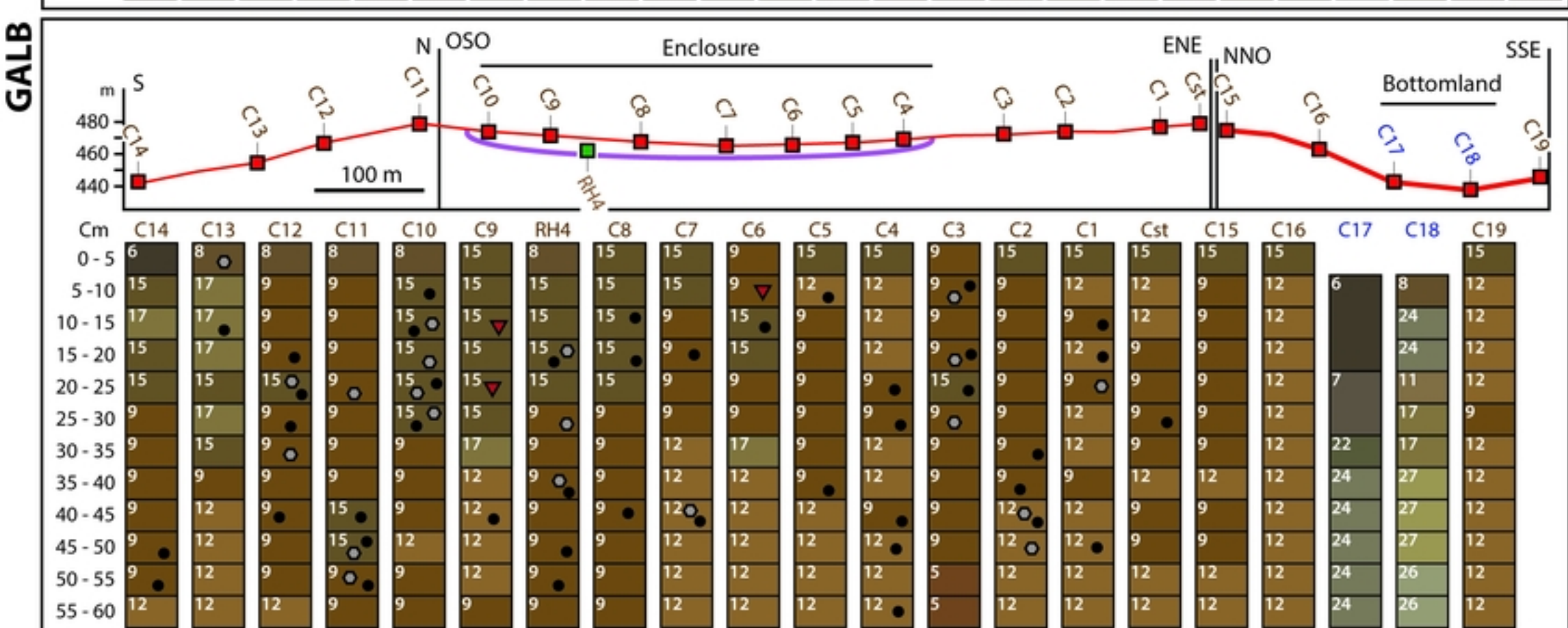
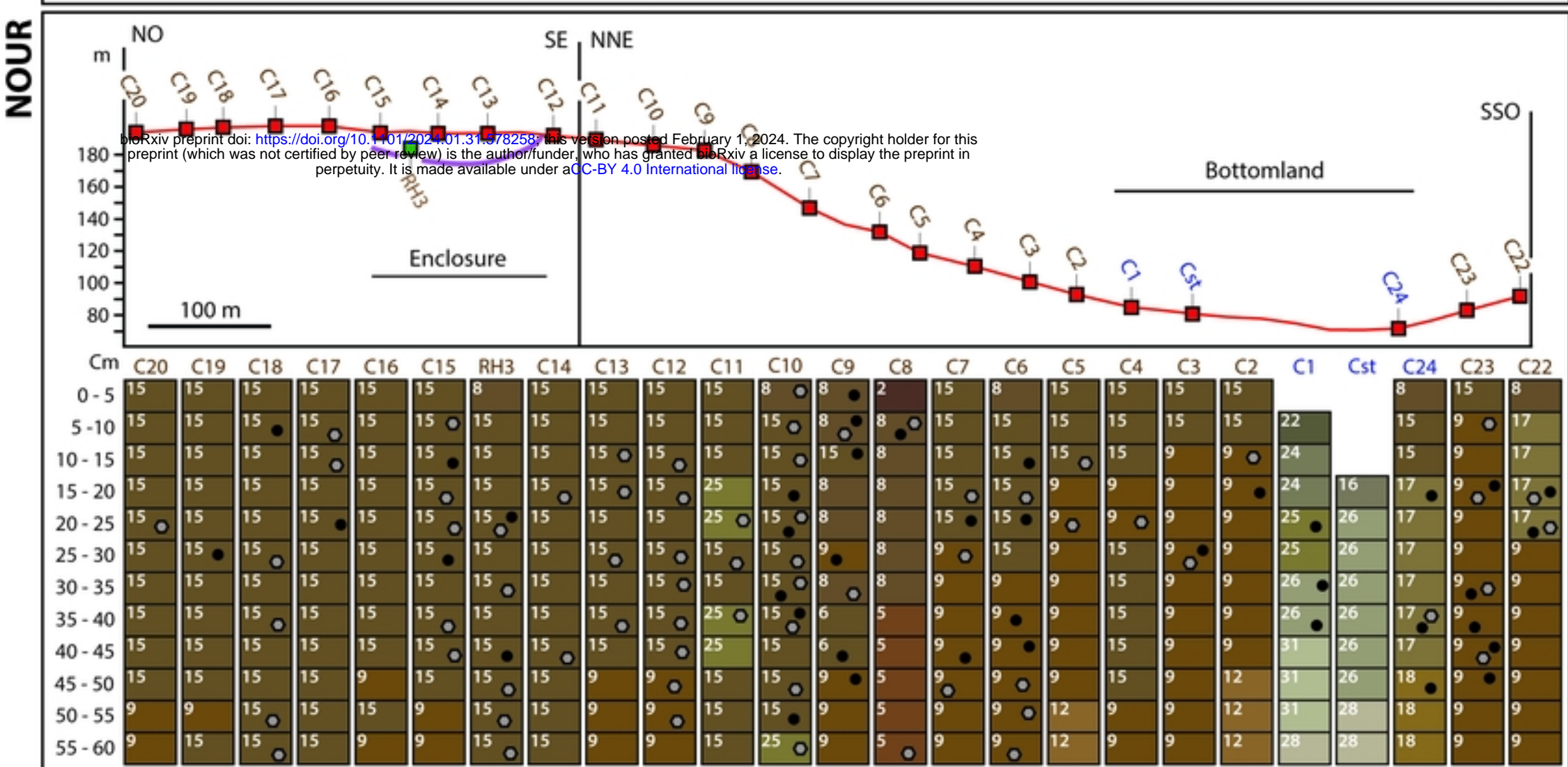
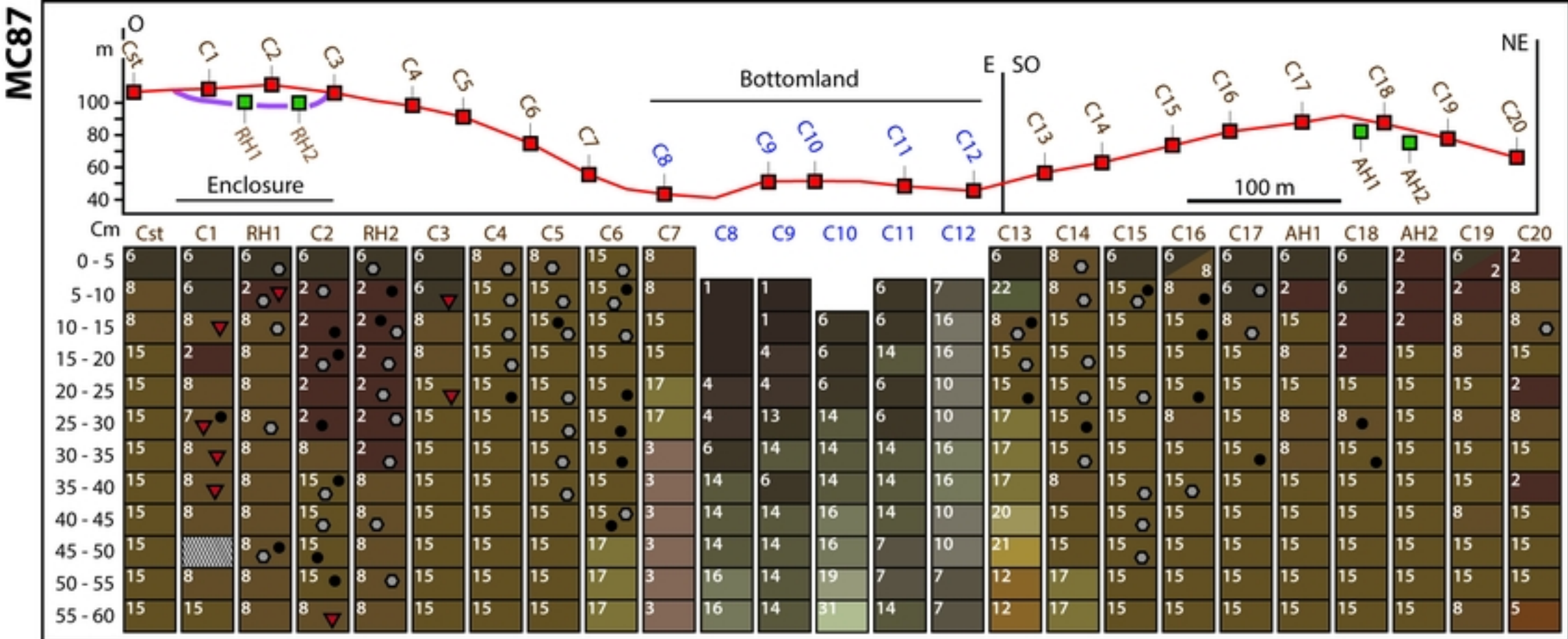


Figure.3

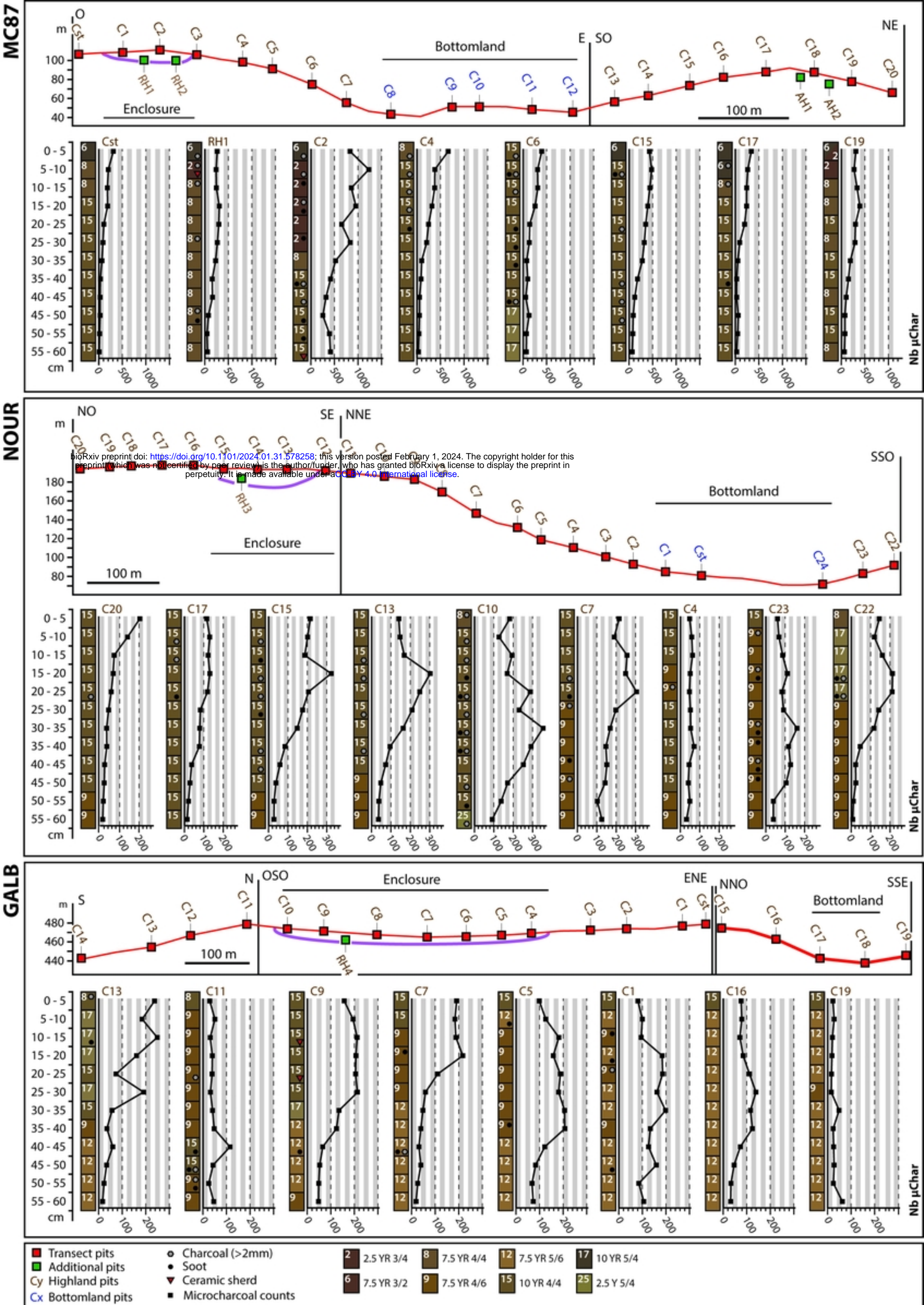


Figure.4

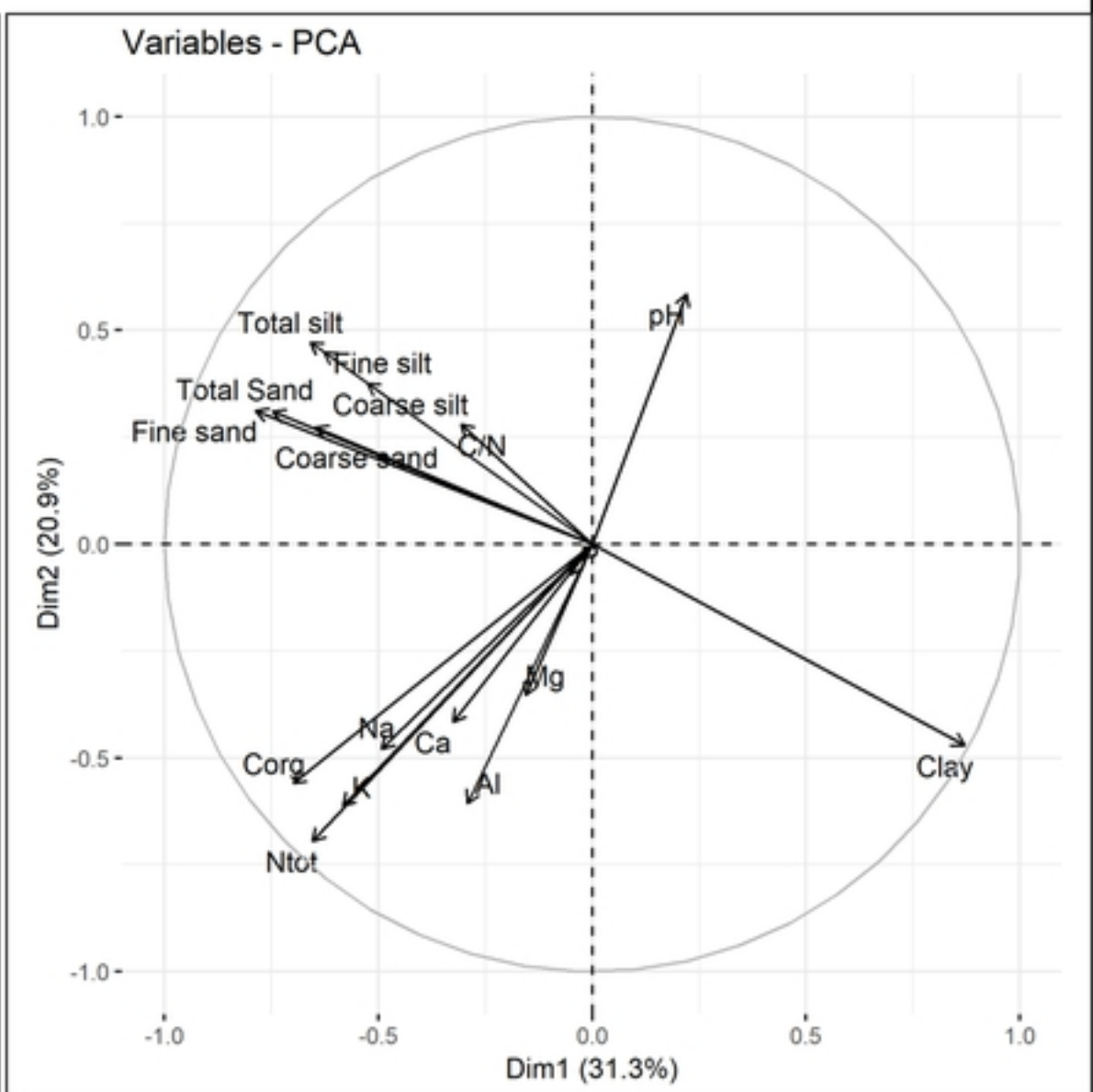
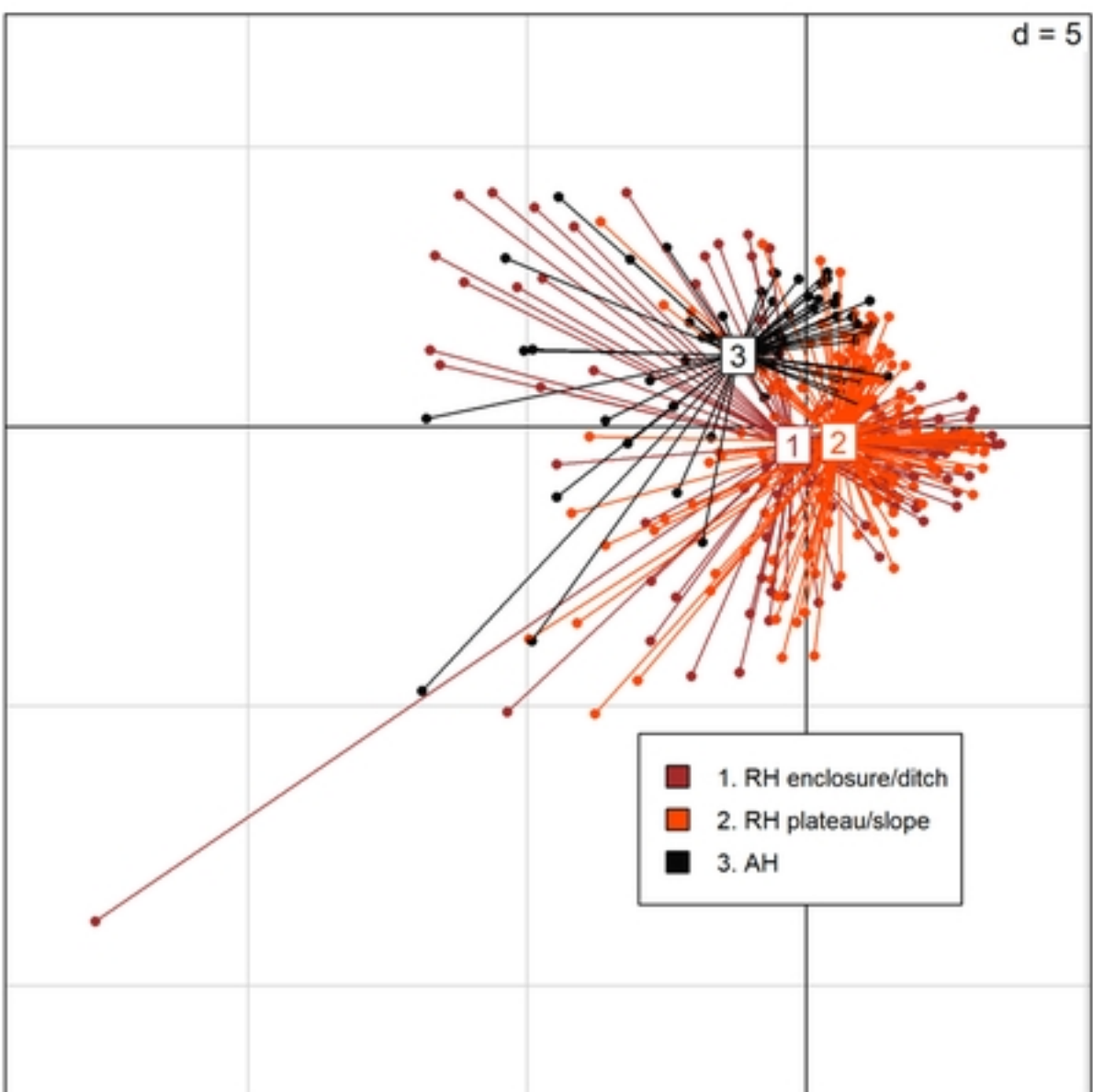
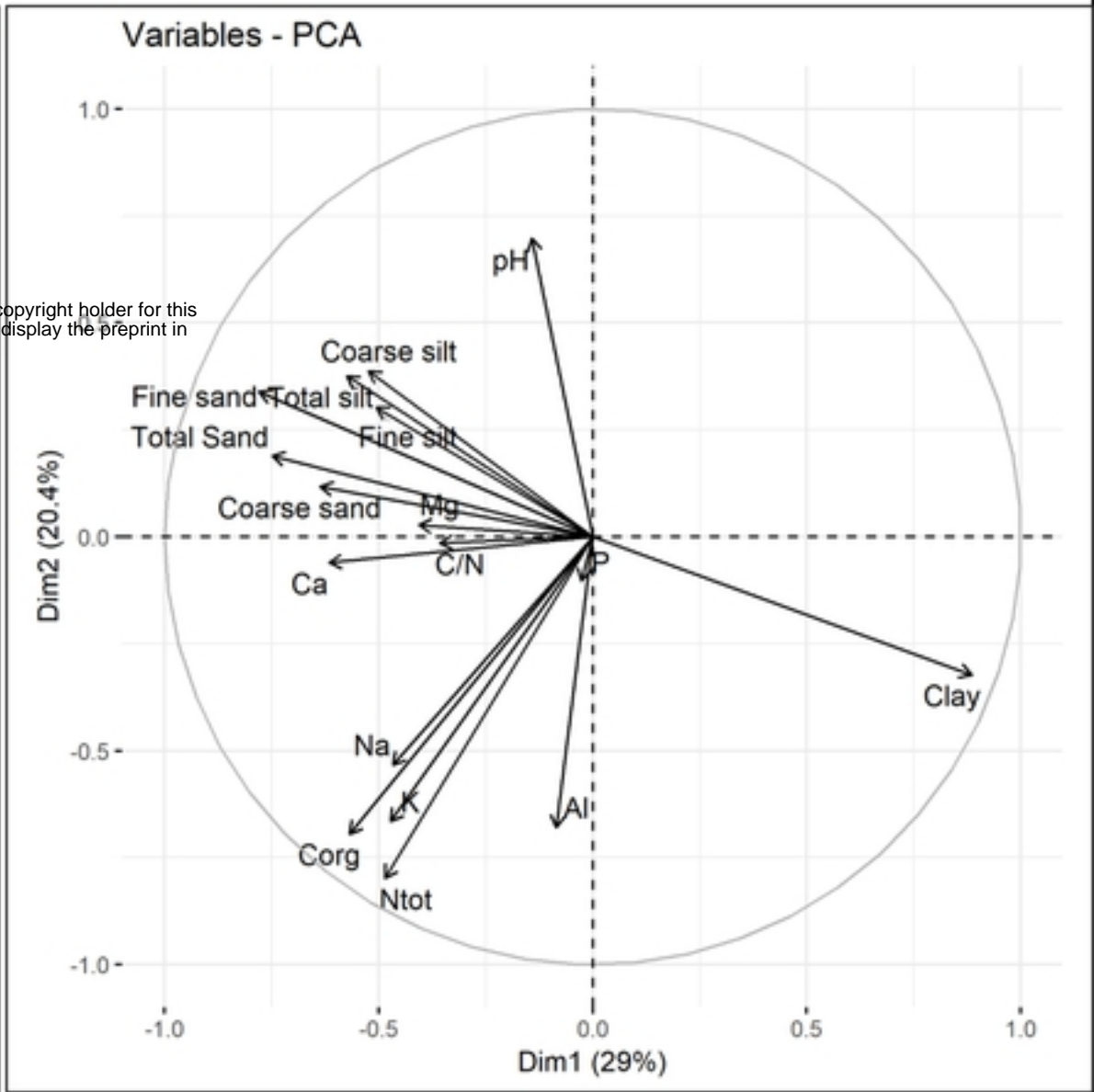
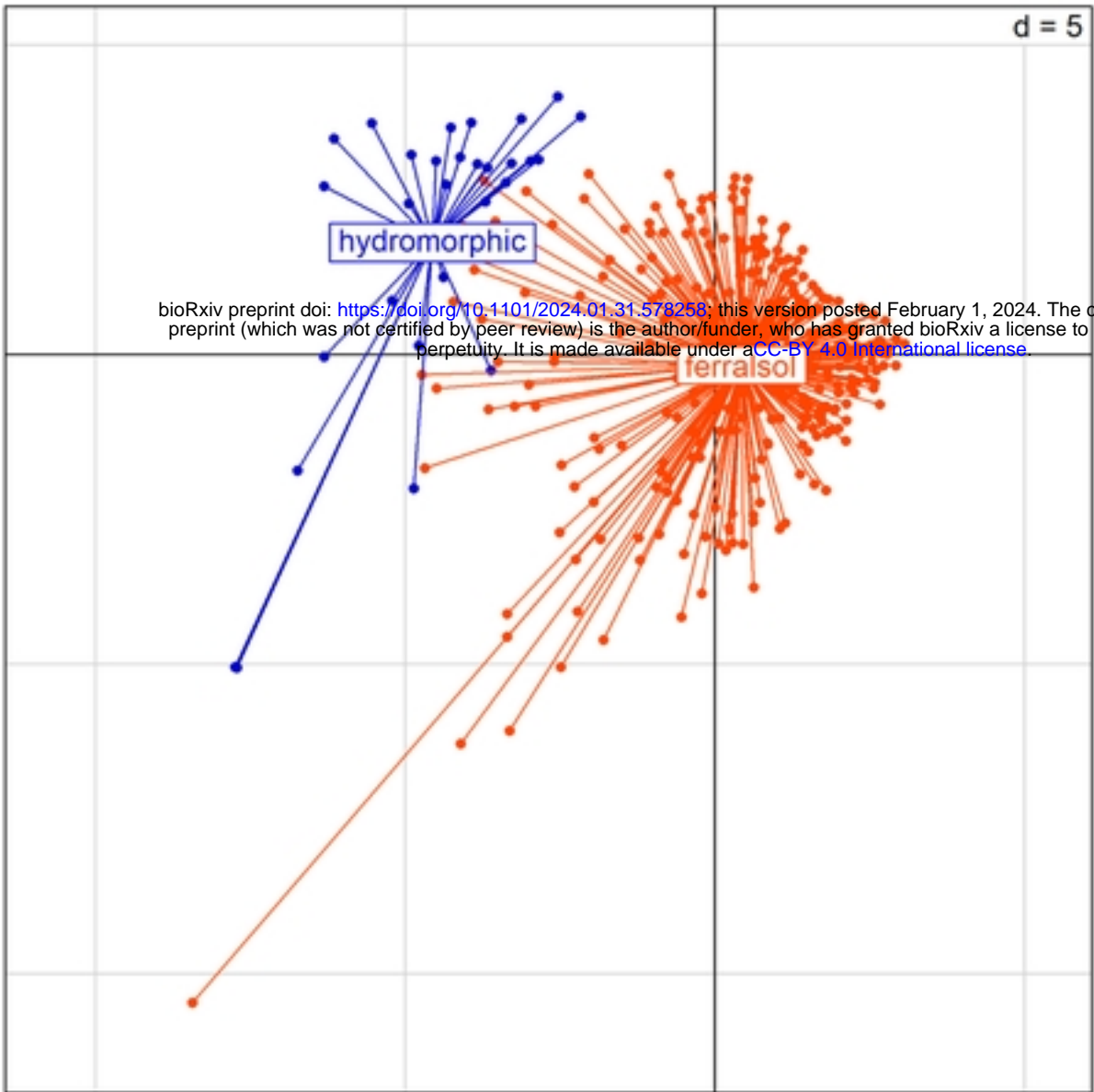


Figure.5