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### ► To cite this version:

Rumsaïs Blatrix, Jose Luis Aramayo, Anne Zangerlé, Bruno Roux, Mikaël Jouanne, et al.. Interpreting landscapes of pre-Columbian raised-field agriculture using high-resolution LiDAR topography. *Journal of Archaeological Science: Reports*, 2022, 42, pp.103408. 10.1016/j.jasrep.2022.103408 . hal-03752156

**HAL Id: hal-03752156**

**<https://hal.science/hal-03752156v1>**

Submitted on 16 Aug 2022

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## Interpreting landscapes of pre-Columbian raised-field agriculture using high-resolution LiDAR topography

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### ARTICLE INFO

#### Keywords:

Floodplain savanna  
Earthwork  
Earth-mound landscapes  
Erosion  
Bolivia  
Llanos de Mojos  
Unmanned aerial vehicle  
Site formation processes  
biogeomorphology

### ABSTRACT

Extensive areas of seasonally flooded savannas in South America are covered with vestiges of pre-Columbian raised fields. The present-day state of these vestiges depends on both initial human agency and the balance between erosion and accumulation by soil organisms. We investigated the taphonomic determinants of mound-shaped raised fields in the Llanos de Mojos, Bolivia, using high-resolution digital terrain models produced by LiDAR mounted on an unmanned aerial vehicle, allowing fine-scale characterization of topographic gradients and of shapes of hundreds of mounds. We found that pre-Columbian farmers built larger and more widely spaced mounds at lower elevation, where seasonal flood level is higher. However, mound size depended also on natural forces that are still in play. As for earthworks everywhere, these forces include the landscape-smoothing process of erosion. But in seasonally flooded savannas, positive feedbacks between topography and activities of soil engineer organisms can drive accumulation of material on mounds. The erosion/accumulation balance hypothesis posits that the balance between erosion and accumulation depends on whether conditions favor local accumulation of soil by engineer organisms. These conditions vary along elevational gradients. At the lowest end of the gradient, deep flooding prevents activity of soil engineers and erosion is unopposed. In intermediate positions, where mounds constitute islands of well-drained soil, soil engineers concentrate their activities on mounds, leading to accumulation that may counter erosion. At the top of the gradient, where all soil is well-drained, conditions for soil engineers are favorable everywhere, and thus no force drives local accumulation in mounds. Erosion is thus again unopposed. Patterns of variation in mound size and shape revealed by analysis of LiDAR imagery were consistent with the erosion/accumulation balance hypothesis. Mounds were largest at intermediate positions along topographic gradients and smaller towards both extremes, until they finally became undetectable. Relative height of mounds (maximal height/ radius at base) decreased as mound size decreased, consistent with the expectation that as mounds erode, they also become flatter. Finally, trees occurred preferentially on mounds, and mounds bearing a tree were less eroded (higher and less flat) than mounds without trees. Data generated by LiDAR thus contributed to archaeological interpretation, supporting inferences about how raised fields were initially constructed and how natural processes have modified their size, shape, and distribution in the centuries since.

### 1. Introduction

Although human-made earthen structures often degrade relatively quickly over time, they have proved to be of prime interest in the

archaeological study of certain civilizations, in particular those that did not make use of stone or metal in construction. This is the case for pre-Columbian civilizations in Amazonia. In keeping with common practice, 'pre-Columbian' is used here to refer to indigenous cultures in the

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<https://doi.org/10.1016/j.jasrep.2022.103408>

Received 22 September 2021; Received in revised form 26 January 2022; Accepted 2 March 2022

Available online 14 March 2022

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Americas before their extensive alteration by contact with Europeans, which in some regions occurred long after 1492. Although Amazonia was long considered to be a pristine environment, it is now widely accepted that at least parts of it were densely occupied before the European conquest, and that the environments we observe today have been managed by human civilizations in the past. The agricultural activities of these civilizations often left few artifacts for archaeological study, but the farmers managed soil in such a way that their impact is often still visible at the landscape scale. Raised-field agriculture is one such ancient practice that had long-lasting effects on the landscape.

Raised fields (hereinafter abbreviated as “RFs”) are “any prepared land involving the transfer and elevation of soil above the natural surface of the earth in order to improve growing conditions” (Denevan and Turner, 1974). They consist of elevated soil structures, probably built by accumulation of the topsoil and vegetation gathered from the surrounding area (McKey et al., 2010). Most archaeological vestiges of RF agriculture in Amazonia have been described from seasonal floodplain savannas (Denevan, 2001; Rostain, 2013), characterized by very slight relief. In these environments, variation in elevation of only a few cm can lead to dramatically different ecological conditions, switching between waterlogged and well-drained soil over short distances, thereby affecting how humans used the landscape. Shape and size of vestiges of RFs in Amazonia vary from small circular mounds about 1.5 m in diameter and 0.5 m in height (or larger) to large platforms several tens to hundreds of meters long and up to 2 m high (Denevan, 2001; Rodrigues et al., 2018). There is no consensus on whether such variation in the design of RFs was driven by environmental factors (farmers adapted field design to local conditions) (Denevan, 2001; Rodrigues et al., 2017; Rodrigues et al., 2018) or by cultural factors (design was independent of environmental conditions) (Erickson, 1995; Walker, 2011).

Variation within the landscape in the form and distribution of the vestiges we observe today results not only from variation in where and how farmers built RFs, but also from variation in the ecological conditions that affected the extent to which these vestiges have been preserved since they were abandoned. Vestiges of RFs thus exemplify one of the major challenges of archaeology: understanding site formation processes to identify patterns created by ancient behaviors and distinguishing them from those created by later cultural and natural processes (Stein, 2001). In Bolivia’s Llanos de Mojos, RF agriculture was abandoned several centuries ago (Denevan, 1966; Walker, 2000). Even the best-preserved vestiges have probably been dramatically altered from their original state. RFs have continuously been subjected to erosion since their abandonment.

While it is recognized that erosion has modified the form of earthworks (e.g., Saunaluoma, 2012), only few studies have attempted to model or to quantify erosion-mediated degradation of earthworks (O’Neal et al., 2005). Furthermore, in some environments where earthworks are frequent, other natural processes may counter erosion (McKey et al., 2010; Renard et al., 2013). Post-abandonment modification is thus not a simple story of erosion and degradation. In seasonal floodplain savannas, positive feedbacks between topography and soil engineer animals are frequent (Choosai et al., 2009; Dangerfield et al., 1998; Sileshi et al., 2010). Engineer organisms such as earthworms, termites and ants create islands of well-drained soil, which these air-breathing organisms require in these seasonally flooded landscapes (Folgarait et al., 2002; Zangerlé et al., 2016). As these organisms continually bring mineral and organic material to places where their activity is concentrated (and as the biostructures they create stabilize soils), these islands grow into mounds (Zangerlé et al., 2016). Such feedbacks can create spectacular earth-mound landscapes of natural origin (Zangerlé et al., 2016). Similar feedbacks act upon the vestiges of abandoned agricultural RFs, because engineer organisms also preferentially concentrate their activities in islands of well-drained soil that already exist, including those made by humans (McKey et al., 2010). In both platform and mound RFs of the Llanos de Mojos, termite mounds are concentrated on the RFs and virtually absent from the surrounding

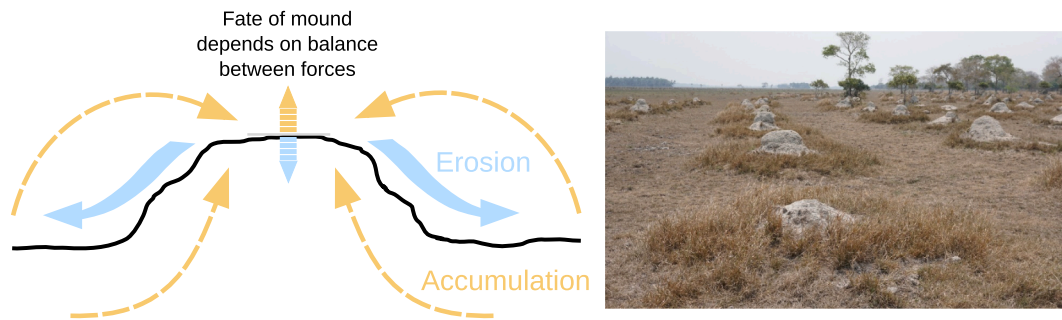
basin (for platform mounds, see Plate 14b in Denevan [1966]; for round mounds, see the photograph in Fig. 1). Under certain ecological conditions, movement of earth by engineer organisms to such islands of well-drained soil is sufficient to maintain the vestiges of abandoned RFs against erosion (McKey et al., 2010).

In seasonal floodplain savannas, natural processes contributing to site formation may thus be particularly complex. According to the erosion/accumulation balance hypothesis (McKey et al., 2010; McKey et al., 2021), vestiges of abandoned RFs will be preserved where the rate of accumulation of material in these mounds (determined by how much material is transported to mounds, and is stabilized by the action of soil engineer animals and plant roots) is equal to or greater than the rate of erosion (see schema in Fig. 1). In contrast, RFs will tend to disappear where erosion is greater than accumulation, disappearing most rapidly where the difference between erosion and accumulation is greatest, and where RFs were built small to begin with.

The ability of soil engineers in these environments to compensate soil erosion and thereby preserve vestiges of RFs depends on various environmental factors. Soil texture and structure, for example, affect the degree to which engineer organisms can stabilize soils. In very sandy soils, aggregate stability is often quite low (Huang and Hartemink, 2020), making it more difficult for soil organisms to counter erosion. In very clay-rich soils, structures of physical origin contribute to erosion resistance, and biogenic structures can be so stable that they resist erosion even long after their production has ceased (see photo in Fig. 1). Other factors influence the rate at which engineer organisms transport mineral and organic matter and—most importantly—the degree to which this transport is directed to, and hence concentrated in, the vestiges of RFs. This concentration is the mechanism that drives positive feedbacks between topography and soil engineers (McKey et al., 2010; Renard et al., 2013). Duration of flooding is expected to be a key factor. When flooding is short-lasting, well-drained soil is not a scarce resource. Soil engineer organisms can establish and conduct their activities everywhere. Thus, no force favors the local concentration of engineer activities and no positive feedback is generated. At the opposite extreme of elevation gradients, deep and permanent flooding excludes many soil organisms, and feedback-generating mechanisms can be weakened when sites are flooded for too long periods. For example, when sites are flooded much of the year, foraging areas (in the intermound basin) of colonies of social insects established on mounds (vestiges of RFs) are restricted for long periods, limiting their ability to accumulate materials and stabilize soil. In contrast, other engineers, such as some earthworms, can forage in waterlogged soil, depositing their casts in well-drained soil where they come to the surface to respire (Zangerlé et al. 2016). Feedback mechanisms driven by earthworms may thus be strongest in frequently flooded soils.

Vestiges of RFs in the Neotropical region, both in Amazonia and in Mesoamerica, are virtually restricted to wetlands. It is thus likely that their size and form have been affected by the complex interplay between erosion and the forces opposing it in these environments, described in the preceding paragraphs. Interpreting the traits of RFs as they were originally constructed depends on understanding the processes acting on vestiges since RFs were abandoned.

These natural processes could also have led to differential preservation of vestiges of RFs across different environments in the landscape. Given the restriction of pre-Columbian RFs to wetlands, it is not surprising that provision of well-drained soil to avoid flooding risk is emphasized as a function of RFs (Boixadera et al., 2019; Lombardo et al., 2011). However, in the Old World, where RFs are constructed and cultivated in many regions today, the distribution of RFs across environments is less simple. Mound RFs are widespread in upland environments in New Guinea today. Writing of this region, Denham (2018) notes that while some researchers have speculated that mound cultivation originated in the wetlands and then spread to dryland slopes, he believes the data support the conclusion that mound cultivation was adopted as a response to environmental degradation and establishment



**Fig. 1.** Illustration of the erosion/accumulation balance hypothesis with a schematic section into a raised field (RF). Once RFs are abandoned by humans, erosional forces contribute to their disappearance. In contrast, activities of soil engineer organisms contribute to their maintenance, because soil engineer organisms transport soil onto mounds—either from above-ground (e.g. foraging by social insects) or below-ground (e.g. nest construction by social insects, foraging by earthworms) activities—and stabilize soil through the biogenic structures they produce, thereby countering erosion. The positive feedbacks between topography and soil engineers only come into play when well-drained soil is a scarce resource (i.e. in wetlands) because, as soil engineer organisms preferentially dwell in islands of well-drained soil (in this case, RFs), they concentrate their activities on mounds. The photo shows vestiges of pre-Columbian raised fields in the Llanos de Mojos, Bolivia, each topped by a rock-hard living termitarium, very resistant to erosion.

of grassland on valley floors, and that “mound technology was not a wetland adaptation, even though early archaeological evidence for it is only preserved in wetlands” (Denham, 2018:199). Moreover, as was made clear in a pioneering review almost 50 years ago (Denevan and Turner, 1974: 29), in the Old World, RFs cultivated today are built not only in floodplain savannas and other wetlands but also in upland savannas, where drainage is not a problem. Denevan and Turner (1974) showed that RFs also have non-hydraulic functions, among them the augmentation of soil fertility by accumulation of topsoil and organic matter. Recent studies of present-day RFs in the Congo Republic showed that in floodplain savannas, RFs perform *both* functions, flood avoidance and fertility management (Comptour et al. 2018; Rodrigues et al., 2020).

Taken together with expectations from the erosion/accumulation balance hypothesis, these facts about present-day RF agriculture in the Old World suggest a new interpretation of the relationship between topography and the distribution of vestiges of RFs in Amazonia: their distribution today may reflect not only where they were built, but also where they have best resisted erosion. Likewise, where they persist, variation in their current state may reflect not only variation in how they were constructed, but also variation in the extent to which they have been altered by erosion. We develop these hypotheses in the following paragraphs.

First, topography probably influenced where and how pre-Columbian farmers built RFs. We hypothesize that RFs were built in a narrow range of elevations: flooded not too deeply or for too long periods, but also not too dry (otherwise drainage would have been useless)<sup>1</sup>.

Secondly, we also hypothesize that height of vestiges of RFs should vary with their position in topographic gradients in the flood-prone basin, for two reasons. (1) In African floodplains, farmers build higher RFs where flood level is higher (Fig. 2). Although the present-day African and pre-Columbian Bolivian contexts are likely different (in particular regarding the kinds of crops cultivated, social organization and population density), we expect that pre-Columbian farmers responded similarly to this physical necessity, building higher RFs at lower elevations in the landscape, where flood level is higher (but avoiding the lowest elevations where flooding is too deep). Over the same span of time, RFs that were built higher should leave higher vestiges than RFs that were initially built lower. (2) Relative position of the

mound in the topography of the basin floor should affect the extent to which soil engineer animals have been able to counter erosion over time. According to the erosion/accumulation balance hypothesis, vestiges of RFs located at intermediate elevations should have experienced lower net rates of erosion<sup>2</sup>. Precise description of topography of the basin and of size and shape of vestiges of RFs is thus required to test the central prediction of the erosion/accumulation balance hypothesis, namely that vestiges of RFs will be best preserved under conditions that favor the activities of engineers and the localized concentration of these activities.

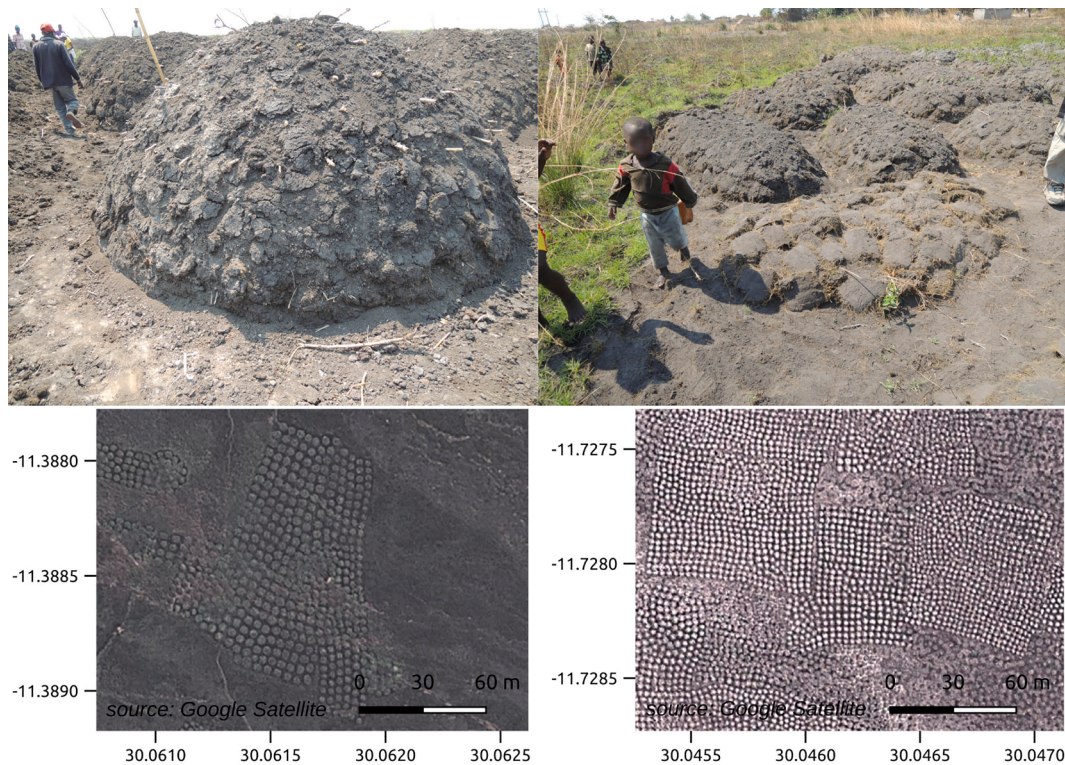
Images of topography obtained by Light Detection and Ranging (LiDAR) technology have permitted spectacular archaeological discoveries in landscapes where forest cover obscures the underlying terrain (e.g. Chase et al., 2011). More importantly for our topic, LiDAR produces both digital terrain models (DTM) and digital surface models (DSM) at a very high resolution. The recent development of airborne LiDAR on unmanned aerial vehicles (UAV LiDAR) allows the production of DTM and DSM at a centimetric resolution, at a much lower cost than aircraft LiDAR. In low-relief landscapes such as seasonal floodplains, such high resolution is essential, for very small differences in elevation are of great ecological importance. This technique was recently shown to be reliable for large-scale detection and measurement of small mounds (termite mounds), even under vegetation cover (D’hont et al., 2021).

In this study, we used UAV LiDAR to produce DTM and DSM of several sites harboring vestiges of pre-Columbian RFs in Bolivia. Digital models allowed precise description of the topographic gradient, of the morphology of hundreds of RF vestiges, and of the vegetation cover, providing robust data for testing predictions of the erosion/accumulation balance hypothesis and investigating the determinants of the present-day state of archaeological vestiges of RFs. Fully testing the predictions of the erosion/accumulation balance hypothesis would require quantifying the level of activity of soil engineer animals. This task is labor-intensive and not compatible with the processing of large numbers of replicates. To take advantage of the large amount of data produced by UAV LiDAR, we only considered the result of combined processes on mound size and shape in relation to mound position in the topographic gradient and did not measure activity of soil engineers.

<sup>1</sup> Based on what is known about RFs in Africa, we could speculate that RF agriculture in Amazonia was also conducted in upland savannas, far from wetlands, but that no vestiges in upland savannas have resisted erosion. We have no data bearing on this hypothesis and develop it only at the end of the Discussion section.

<sup>2</sup> Expectations differ according to the importance of different kinds of engineer organisms in transport and stabilization of soils. Earthworms should be better able to maintain vestiges of RFs in deeply flooded parts of basins than are social insects and plant roots. In our study site, earthworms appeared to be of secondary importance.





**Fig. 2.** In the seasonally flooded savanna of the Bangweulu basin in Zambia, Africa, present-day RFs built by farmers are higher, larger and more widely spaced in the lowest parts (left photo and satellite image) than in the highest parts (right photo and satellite image) of the elevation gradient. The left panels represent the situation near the village of Kasoma, in the Lunga Bank, where the expected water depth in the inundation season is 0.7 m and where RFs are c. 1.7 m high. The right panels represent the situation on the nearby island of Ncheta which is never inundated and where RFs are c. 0.5 m high. Satellite images: Google Satellite. Photos (26–27 September 2013): Doyle McKey.

## 2. Material and methods

### 2.1. Study sites

The study area is located 6–11 km ENE of the town of Santa Rosa del Yacuma, Beni, Bolivia, within a vast floodplain called the Llanos de Mojos (Fig. 3). The Llanos de Mojos are renowned for their high density of pre-Columbian earthworks, such as raised fields, causeways, canals, fish weirs, and occupational mounds, associated with a long history of landscape domestication (Duncan et al., 2021; Erickson, 2006). It is a flat landscape subject to seasonal flooding, fed by both rainfall within the region and runoff from the Andes. The study area lies between the Transitional Zone and the SW Mojos according to the classification by Langstroth (2011). The SW Mojos sub-region is heavily subjected to flooding by runoff from Andean whitewater rivers, is consequently rich in sediments and is on higher ground than the Transitional Zone, which is the richest in vestiges of RFs (Rodrigues et al., 2018). The Transitional Zone is characterized by a high density of vestiges of platform RFs on the east and of mound RFs on the west. It is also particularly rich in anthropic forest islands that were used for crop cultivation in the early Holocene (Lombardo et al., 2020). The mound field area is distinct from the two adjacent sub-regions in having soil characteristics that indicate hydrological conditions hampering organic carbon mineralization (Rodrigues et al., 2018) that may reflect long flooding periods (about 2 months a year according to Ovando et al., 2016; Ovando et al., 2018). The area around Santa Rosa del Yacuma has the highest density of mound RF vestiges within the whole Llanos de Mojos (Rodrigues et al., 2018). The landscape is composed of a mosaic of woodlands on the highest ground and of open savannas, where the RFs occur (Fig. 3b). The area also features a large shell midden near Santa Rosa del Yacuma, similar in some respects to those studied by Lombardo et al. (2013a); Lombardo et al. (2020) (U. Lombardo, pers. comm.; D. McKey and R.

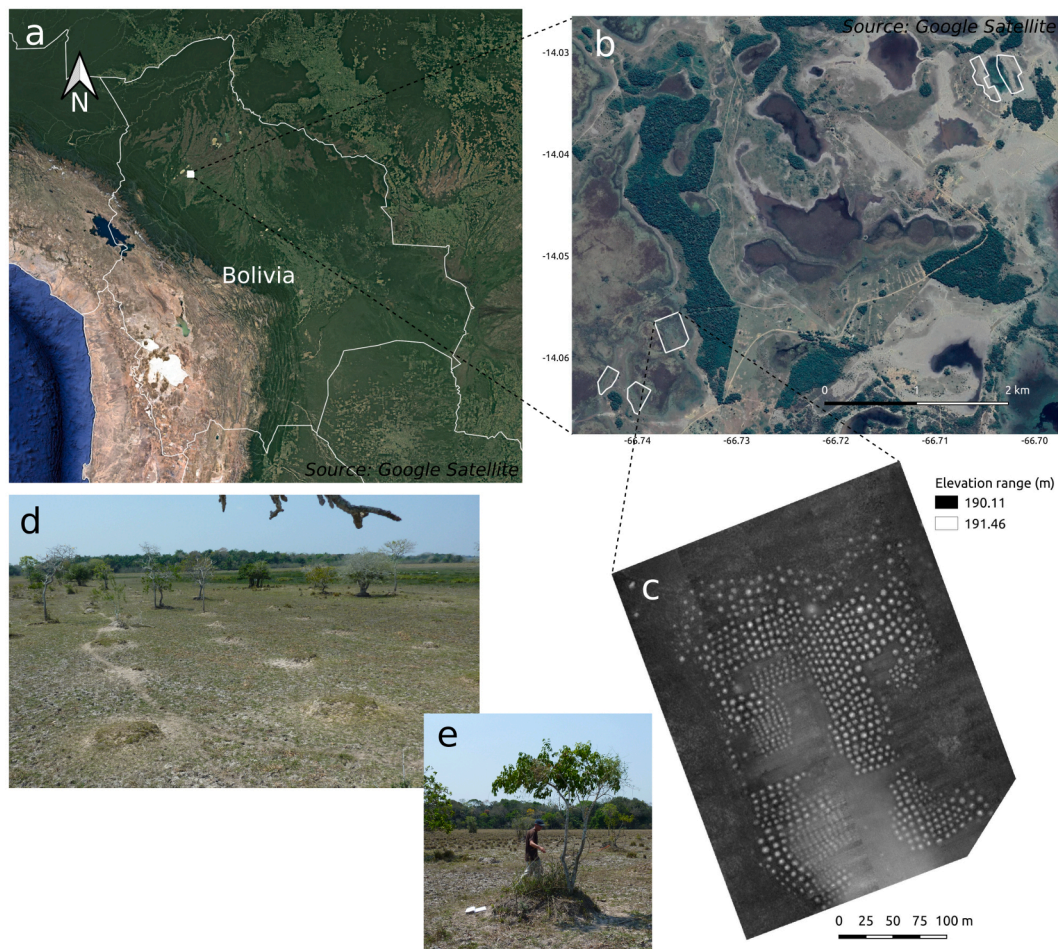
Blatrix, unpublished field notes). Nowadays, the area is used for extensive cattle ranching.

We investigated five field sites corresponding to five patches of open savanna harboring vestiges of pre-Columbian RFs of the circular mound type, i.e. each about 1.5 m in diameter and up to 0.5 m in height (Fig. 3). All of these featured an elevation gradient including a seasonally flooded depression. The sites were selected for their high density of RFs and for their relative ease of access (proximity to a dirt road and to the town of Santa Rosa del Yacuma). Access is a critical issue when transporting the UAV LiDAR equipment. The study sites covered a total of 0.327 km<sup>2</sup>, in which we counted vestiges of more than 2700 RFs by visual inspection of satellite images and DTMs generated from LiDAR data.

In some sites in the Llanos de Mojos with mound RFs, reciprocal positive feedback between topography and soil engineers is clear. For example, in the site shown in the photograph in Fig. 1, each abandoned RF bears a large epigeal termitarium, and termitaria in the site are found only on RFs. In this study, we examine whether predictions of the erosion/accumulation balance hypothesis are validated even in sites where the activities of soil engineers are more discreet. Soil engineer animals, particularly termites, were present in our study sites, and appeared to be concentrated on mounds, but did not always produce conspicuous nest structures. The diffuse nature of their presence and activities precluded quantification of their occurrence in the large number of mounds we surveyed. We did, however, census one group of soil engineers, namely trees, whose extensive root systems can reduce erosion.

### 2.2. Postulates and predictions on RF characteristics

Stemming from the argumentation in the introduction regarding the relative contributions of initial human agency and of erosion/accumulation balance in determining the present-day state of raised fields, we



**Fig. 3.** Study sites in Bolivia. (a) Location of the study area in Bolivia. (b) Extent of study sites. (c) Example of digital terrain model obtained by UAV LiDAR. (d) Alignment of pre-Columbian RFs. (e) Example of a pre-Columbian RF with a tree. Maps were generated by the authors with QGIS 3.16 ([www.qgis.org](http://www.qgis.org)) using Google Satellite images as background satellite data. Photos (17–22 September 2015) (d) and (e): Rumsaïs Blatrix.

think it likely that while post-abandonment processes have produced changes in the size (usually decreases) and shape of mounds, they have not affected the position of mounds. We thus postulated that (i) distance between centroids to the nearest neighbor depends only on initial human agency and was unlikely to be impacted by environmental forces affecting erosion/accumulation; (ii) mound size depends on both initial human agency and environmental forces affecting erosion and accumulation; (iii) Variation in mound shape depends only on environmental forces, as we have no evidence of such variation at a local scale in RFs built today in Africa, which appear to be the most closely analogous to those built by pre-Columbian people in Bolivia (Fig. 2).

As shown by O’Neal et al. (2005), erosion widens and flattens earthworks over time, like any landform composed of fine-grained materials, due to the downslope transport of sediment via soil creep and slope-wash processes. We expect erosion, especially by rainfall, to reduce mound height and to flatten mounds (soil would move from top to bottom). Thus, we postulated that mounds with lower mean height would also have lower relative height (maximal height divided by radius at base), a change in shape resulting from a stronger weight of erosion in the erosion/accumulation balance.

### 2.3. Field work

Fieldwork was conducted in September 2015. In order to validate data produced by UAV LiDAR, mound height ( $N = 52$ ) and vegetation height on mound ( $N = 24$ ) were manually measured and presence-

absence of trees on mounds ( $N = 66$ ) was visually recorded in the field. In one of the study sites, we manually measured the height of 15 mounds on a transect parallel to the elevation gradient in order to describe the relationship between mound height and position in the elevation gradient. In addition, we measured mound height and recorded presence-absence of trees for 20 mounds on a transect perpendicular to the elevation gradient in order to describe the relationship between mound height and tree presence independently of the effect of position in the elevation gradient, based on field measurements.

In order to obtain data on physical features for a large number of mounds and measure the topographic gradient at the scale of the field site, the sites were surveyed by LiDAR using a multirotor octocopter Fox8HD OnyxStar (AliGator, Belgium) drone equipped with a YellowScan Mapper LiDAR (YellowScan, Saint Clément de Rivière, France). The UAV flights were carried out by the mapping operator L’Avion Jaune (Saint Clément de Rivière, France). We relied on the real time kinematic positioning technique to improve absolute precision of the LiDAR point cloud. Flights were performed with  $5 \text{ m}\cdot\text{s}^{-1}$  velocity at a height of 70 m, with a 65 % LiDAR flight line overlap. Ground point density ranged from 50 to 100 points. $\text{m}^{-2}$ .

### 2.4. Processing of data obtained by LiDAR

Point cloud classification into ground points and vegetation points allowed production of a DTM and a DSM for each study site by Delaunay triangulation, using the Terrasolid software (Terrasolid Ltd., Helsinki,



Finland) (Fig. 4a–c). Automatic detection of mound contours involved the successive application of classical methods in signal processing: difference of Gaussian filters, threshold and morphological filters (erosion and dilation operations) (Fig. 4d).

A digital model of mound base ground (hypothetical ground level in the basin floor if mounds had not been present) was obtained by interpolating elevation values of mound pixels with DTM values within a radius of 5 m around each mound (Fig. 4e). Height (of the mound) was computed for each pixel of a mound as the difference between actual values of the DTM and those of the digital model of mound base ground (Fig. 4f).

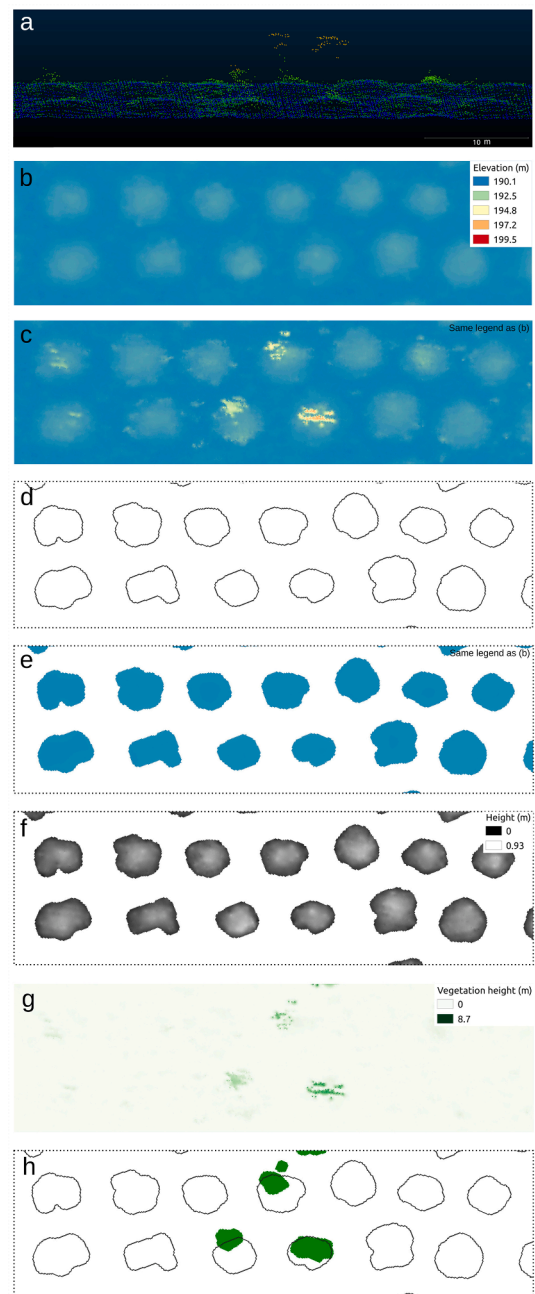
A digital model of vegetation height was computed as the difference between values for each pixel of DSM and DTM (Fig. 4g). Tree crowns were automatically delineated with the following procedure (Fig. 4h). Gaussian smoothing (sigma = 10) was applied to the digital model of vegetation height. Contours of vegetation patches on the digital model of smoothed vegetation height were delineated using a threshold of pixel values of 0.4 m. Vegetation patches were considered to be tree crowns when maximum vegetation height was above 2 m in the initial (not smoothed) digital model of vegetation height. This procedure was required because resolution of the DSM was high enough to distinguish individual branches, and thus, the digital model of vegetation height was not uniform for a single tree. The described procedure avoided erroneously delineating single branches as individual tree crowns. The procedure was validated by comparing trees recorded on mounds by visual inspection in the field in part of one study site and tree crowns that were automatically delineated in the same study area (see section 3.1.).

The following characteristics were computed from digital information for each mound delineated automatically: area, perimeter, volume, maximal height, median height (median of height values for all pixels of a mound), mean height (mean of height values for all pixels of a mound), relative height (maximal height / radius at base), distance between the centroid of the mound and that of the nearest neighboring mound, maximum vegetation height, and tree presence-absence (categorical variable). A tree was considered to be rooted on a mound when its crown intersected a mound. In the area where we validated automatic delineation of tree crowns, all tree crowns intersecting mounds were indeed confirmed to be rooted on mounds by visual inspection in the field. The first eight parameters were indicative of global size and shape of mounds. Of these, we considered that only one (distance between centroids of neighboring mounds) is unlikely to have been affected by erosion (unless some mounds completely disappeared), as erosion does not shift the position of mounds. The seven others reflect both human agency (how mounds were initially constructed) and the effects of post-abandonment natural processes. Relative height should be a good indicator of erosion: as mounds erode, they should not only diminish in height but also become flatter (O'Neal et al., 2005). Terrain elevation at the mound base was computed, for each mound, as the mean of pixel values in the digital model of mound base ground (see above). Although raw elevation was indicative of position in the elevation gradient within sites, it had to be normalized among sites when data from all sites were combined. Thus, elevation values of the DTM (excluding mounds) and of the digital model of mound base ground for all mounds were centered and scaled within each site independently, and then combined across sites, to represent mound position in the elevation gradient.

## 2.5. Statistical analyses

Data processing and analysis were performed with QGIS 3.16.4 (QGIS.org, 2021) and R 4.0.4 (R Core Team, 2021). Data from all study sites were compiled and analyzed together.

Mound distribution along the elevation gradient was described by comparing density functions of elevation values between the DTM after removal of the surfaces on which mounds occurred and the digital model of mound base ground for all mounds. The variances of the two density



**Fig. 4.** The successive steps in processing LiDAR data illustrated with a close-up on thirteen mounds. (a) Point cloud classification into ground points (blue) and vegetation points (green below 3 m in height, orange above). (b) Digital terrain model obtained by Delaunay triangulation of ground points. (c) Digital surface model obtained by Delaunay triangulation of all points (ground and vegetation). (d) Mound contours automatically delineated with difference of Gaussian filters, thresholding and morphological filters. (e) Digital model of mound base ground (hypothetical ground level in the basin floor if mounds were not present) obtained by interpolation of DTM values within a radius of 5 m. (f) Digital model of mound height computed as the difference between actual values of the DTM and those of the digital model of mound base ground (b - e). (g) Digital model of vegetation height as the difference between values for each pixel of the surface model and the terrain model (c - b). (h) Tree crowns (in green) automatically delineated with successive steps of smoothing and thresholding of vegetation height model. The scale, shown on panel (a), is the same for all panels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

functions were compared with a Fisher test. This analysis was also performed on each study site individually, with raw elevation values instead of normalized values.

The postulates defined above (see 2.2.) were used to define explanatory variables in generalized linear models (GLM) aimed at testing the effect of environmental variables (position of the mound in the elevation gradient, vegetation height on mounds, presence-absence of trees on mounds) on mound characteristics (size and shape) and distance to the nearest neighbor. Generalized linear models are based on linear regression and allow specifying (1) an equation that links the response variable to a combination of explanatory variables and regression coefficients and (2) the probability distribution of the response variable (Dobson and Barnett, 2018). When appropriate, linear, logarithmic and second-order polynomial models were compared with the Akaike information criterion (AIC) to choose the best relation between the explanatory variables and the response variable. This criterion is an estimation of the amount of information lost by a model, taking into account the maximum value of the likelihood function and the number of parameters in the model (to penalize overfitting) (Sakamoto et al., 1986). The lower the value of the AIC, the better the model. The effects of explanatory variables on the response variable were tested with analyses of variance. GLMs were similarly applied to each study site individually, in which case raw elevation values were used instead of normalized values.

To test for a statistical spatial association between trees and mounds, we randomized geographic coordinates of tree crowns within the limits of study sites and computed the number of crowns intersecting mounds. Tree crown randomization was simulated 9999 times and the frequency of simulations yielding a number of trees on mounds equal to or greater than the observed number was used as a p-value for testing the association of trees with mounds. This was done within each study site independently because tree density varied among sites.

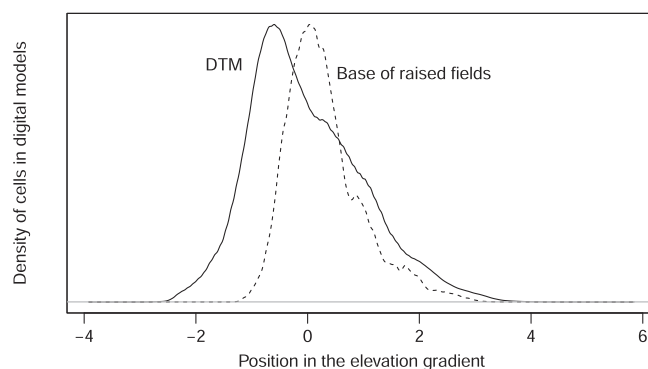
### 3. Results

#### 3.1. Field validation of LiDAR data

Mound height measured in the field and mound maximal height computed from LiDAR data were highly correlated (Pearson correlation,  $N = 52$ ,  $R = 0.73$ ,  $p < 10^{-9}$ ). Field estimates of height of vegetation on mounds were also highly correlated with values computed from LiDAR data ( $N = 24$ ,  $R = 0.97$ ,  $p < 10^{-14}$ ). Nineteen out of 66 mounds investigated in the field proved to harbor trees. The process of delineating tree crowns from LiDAR data resulted in the detection of 17 (90 %) of those trees (17 true positives and two false negatives), and did not produce trees that were not recorded in the field (no false positives).

#### 3.2. Mounds were not distributed uniformly along the elevation gradient

Mounds were restricted to a range of elevation narrower than that represented in each of the study sites. The variance of the density function for elevation values in the digital model of the ground base beneath mounds was significantly lower than that for elevation values in the DTM after removal of the part of the DTM where mounds occurred (F test,  $F = 2.2$ ,  $p < 10^{-15}$ , Fig. 5). This difference in variance between the two density functions was also highly significant within each site individually (Supplementary Fig. S1). Kurtosis of the distribution of the elevation values in the DTM (excluding surfaces where mounds occurred) had a value of 3.1, very close to the value for a normal distribution (3) (Fig. 5). In contrast, kurtosis of the distribution of elevation values in the digital model of mound base ground was higher (4.1). The means of the two distributions also differed, but this is of little interest, as it depended on how much surface area in the two extremes of the elevation gradient is represented in the area covered by the DTM.



**Fig. 5.** Density function of elevation values for the digital terrain model (DTM) after removal of the part of the DTM where mounds occurred (solid line) and for the digital model of mound base ground (dashed line). Elevation values were centered and scaled within each study site (i.e. values within each site have a mean of 0 and a variance of 1, and thus the horizontal axis has no unit) in order to convert raw elevation values into relative position in the elevation gradient of each study site (this allows combining data of all sites for analysis). Note that the vertical axis has no unit as it is a density function.

#### 3.3. Correlations between mound size and shape

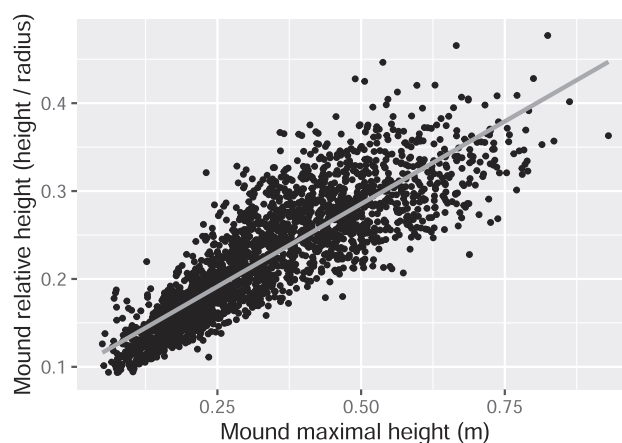
Mound size parameters were highly correlated with one another. Coefficients of correlation between all pairs of the variables computed from LiDAR data (mound area, volume, perimeter, maximal height, median height and mean height) were all above 0.81. Thus, for subsequent analyses we retained only one size parameter, mound mean height, to represent mound size.

Mounds varied greatly in shape. Relative height (maximal height / radius at base) varied between extremes of 0.09 and 0.48, corresponding to mean slopes from summit to base ranging from  $5^\circ$  to  $26^\circ$ . Mound shape varied with mound size: relative height was strongly correlated with maximal height ( $R = 0.86$ ,  $p < 10^{-15}$ ). In other words, as mounds decreased in height, they also became flatter (Fig. 6).

#### 3.4. Distance to the nearest neighbor was correlated with mound size and varied along the elevation gradient

Distance between the centroid of the mound and that of the nearest neighboring mound was significantly, although weakly, correlated with mean height ( $R = 0.31$ ,  $p < 10^{-15}$ ) and area ( $R = 0.30$ ,  $p < 10^{-15}$ ): the larger the mounds, the more distant they were from each other.

The GLM relating distance to the nearest neighbor to position of the



**Fig. 6.** Mound relative height (maximal height / radius at base) as a function of mound maximal height.

mound in the elevation gradient showed a significant effect (anova,  $F = 66$ ,  $p < 10^{-15}$ ). The AIC value was lower with a linear than with a second-order polynomial model. Although the effect was weak, distance to the nearest neighbor was smallest in the highest part of the elevation gradient and increased linearly with decreasing elevation, with no maximum nor minimum in the middle of the gradient (Fig. 7). At the scale of individual sites, the relationship was significant for three sites, but not significant for the two others (Supplementary Fig. S2).

### 3.5. Mound size and shape varied according to position in the elevation gradient and vegetation

#### 3.5.1. Mound size

We assume that position of mounds (and thus the distance between nearest neighbors) reflects only human agency, i.e., post-abandonment processes do not change the position of mounds. As mound height (LiDAR data) was correlated with distance to the nearest neighbor (see section 3.4.), we first built a GLM of the effect of distance to the nearest neighbor on mound height. The residuals of this GLM corresponded to mound height after removal of the effect of distance to the nearest neighbor, and thus could be used to test the effect of parameters other than initial human agency on mound height. These residuals were used in a GLM. A significant effect on the residuals of mound height was found for each explanatory variable tested: position in the elevation gradient ( $F = 87$ ,  $p < 10^{-15}$ ), presence-absence of a tree on the mound ( $F = 143$ ,  $p < 10^{-15}$ ) and vegetation height on the mound ( $F = 512$ ,  $p < 10^{-15}$ ). The AIC values were lowest with a second-order polynomial model for position in the elevation gradient and with a logarithmic model for vegetation height. Mound height was highest for intermediate positions in the elevation gradient and smallest at the extremes of the gradient (Fig. 8a). Mound height increased with vegetation height (Fig. 8b) and mounds with a tree were higher than mounds without a tree (Fig. 8c). At the scale of individual sites, the relationship between mound height and elevation was significant for only one site, the one harboring the largest number of mounds (Supplementary Fig. S3). The significant relationship shown in Fig. 8a is thus driven mostly by this site, for which sample size was greatest, and by the combining of data for a large number of mounds from several sites, but is barely detectable at the level of a single site. In contrast, the relationship between mound height and vegetation height was significant for each site individually (Supplementary Fig. S4). In addition, in four sites, mounds with a tree were significantly higher than mounds without a tree (Supplementary Fig. S5). In the fifth site, the difference was not significant, but the test lacks statistical power as there were very few mounds with trees in this site.

Field investigation of a transect parallel to the elevation gradient,

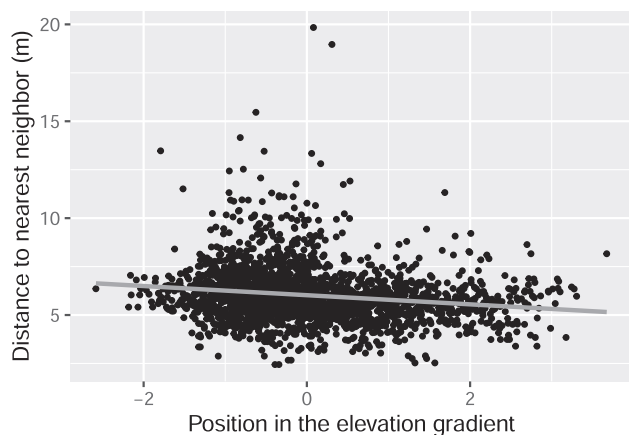


Fig. 7. Distance from the centroid of the mound to that of the nearest neighbor as a function of the mound's position in the elevation gradient.

composed of 15 mounds, revealed that mound height (measured manually) decreased linearly with increasing elevation (Fig. 9), confirming dependence of mound height on position in the elevation gradient. In addition, of the 20 mounds manually measured on a transect perpendicular to the elevation gradient (i.e. all mounds at the same relative position in the elevation gradient), those with trees were significantly higher (Fig. 10a). Thus, field measurements on a small sample of mounds showed trends similar to patterns revealed with LiDAR data from a large sample of mounds.

#### 3.5.2. Mound shape

To test the effect of environmental parameters on mound erosion, we built a GLM on mound relative height (maximal height / radius at base) as it is indicative of mound erosion (see section 2.2.). A significant effect on relative height was found for each explanatory variable tested: position in the elevation gradient ( $F = 16$ ,  $p < 10^{-6}$ ), presence-absence of a tree on the mound ( $F = 163$ ,  $p < 10^{-15}$ ) and vegetation height on the mound ( $F = 533$ ,  $p < 10^{-15}$ ). The AIC values were lowest with a second-order polynomial model for position in the elevation gradient and with a logarithmic model for vegetation height. Mounds at extremes of the elevation gradient were flatter (lower relative height) than those in intermediate position (Fig. 11a). Relative height increased with height of the vegetation cover (Fig. 11b) and relative height of mounds bearing trees was greater than that of mounds without trees (Fig. 11c). At the scale of individual sites, the relationship between mound relative height and elevation was significant for four sites (the site with the non-significant relationship is the one with the lowest number of RFs) (Supplementary Fig. S6). Interestingly, mound relative height was significantly different among sites (Supplementary Fig. S7;  $F = 500$ ,  $p < 10^{-15}$ ), showing that the extent of erosion varies spatially. The relationship between mound relative height and vegetation height was significant for each site individually (Supplementary Fig. S8). In addition, mound relative height was consistently higher for mounds with trees, but there were two sites where the effect was not significant (including one site lacking statistical power given the very low number of mounds with tree) (Supplementary Fig. S9).

On the field transect perpendicular to the elevation gradient, relative height (computed with maximal height measured in the field and radius at base calculated from LiDAR data) was higher for mounds with a tree than for those without a tree (Fig. 10b), confirming with field investigation the result obtained with remote sensing.

### 3.6. Trees occurred more frequently on mounds than off mounds

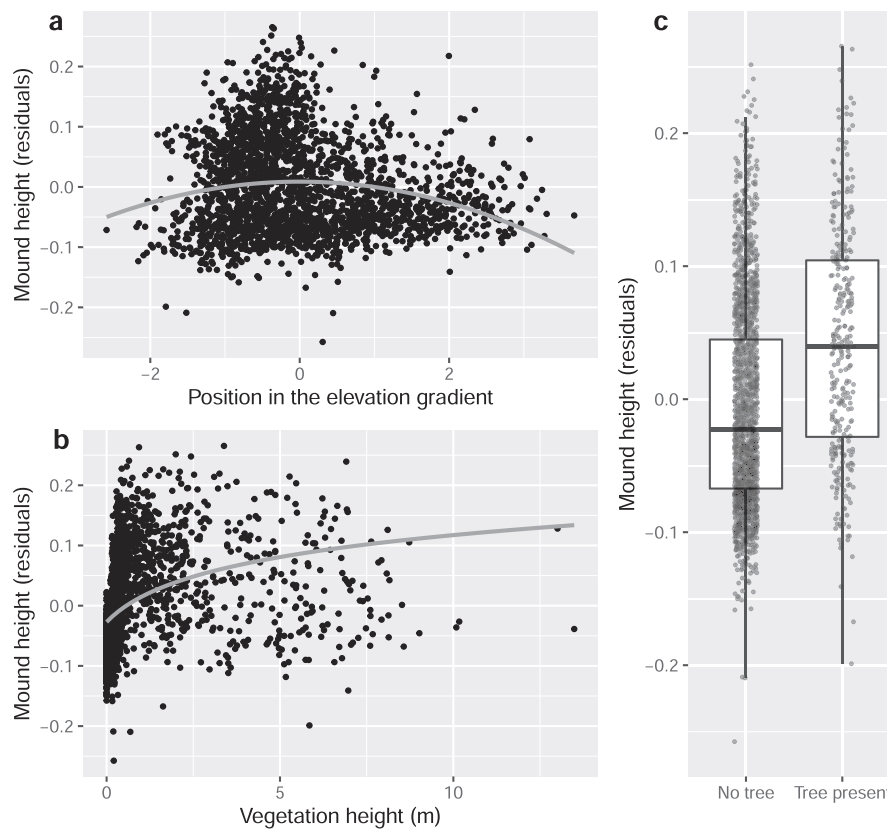
In one study site, only ten trees were detected (from LiDAR data), corresponding to a tree density of 1.76 trees.ha<sup>-1</sup>. This site was excluded from the analysis because of low statistical power. In the other sites, number of trees varied from 46 to 136 and tree density from 11.08 to 16.81 trees.ha<sup>-1</sup>. In all four sites tested, the observed number of trees on mounds was always higher than the number of trees on mounds when a random distribution of the trees was simulated. Thus, the spatial association between trees and mounds was significant (9999 random simulations,  $p < 10^{-4}$ ).

## 4. Discussion

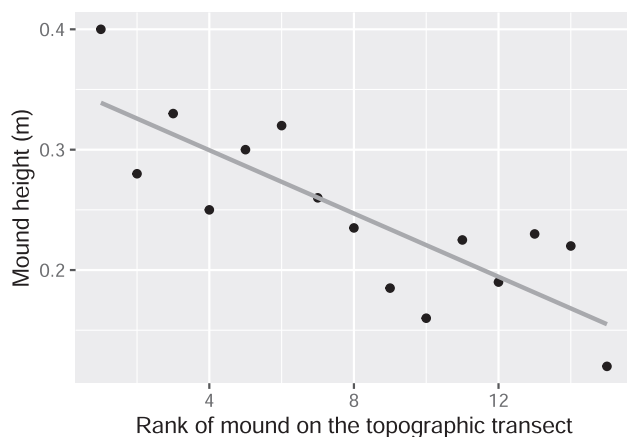
### 4.1. Validation of the methodology using UAV LiDAR data

The data produced by the UAV LiDAR system were highly correlated with field measurements. This was expected for vegetation height but not necessarily for mound height, because type and density of vegetation cover were highly variable among mounds. Such heterogeneity may introduce bias when classifying laser beam points as ground points. Nevertheless, the UAV LiDAR system we used produced reliable data and allowed extraction of both mound shape and vegetation features for hundreds of mounds from data acquired within only a few days of





**Fig. 8.** Mound height (computed from LiDAR data) as a function of position in the elevation gradient (a), vegetation height (b) and presence of a tree (c). Mound height in this figure corresponds to the residuals from a GLM of mound height (raw values) on distance to the nearest neighbor, so that the effects shown here are independent of initial human agency.



**Fig. 9.** Height (measured in the field) of 15 mounds along a transect parallel to the elevation gradient (rank 1 = lowest elevation).

fieldwork. At the scale of our study sites, variation of basin elevation within sites is small but of utmost importance for its consequences on drainage. In such a case, high accuracy and resolution of the basin DTM are required to detect a putative effect on landscape features such as mounds. The UAV LiDAR system allowed building a DTM of the basin with a resolution that would have been nearly impossible to obtain from traditional field measurement with a total station. As a whole, the data from the UAV LiDAR system—proved to be reliable by ground truthing—were produced in a quantity that provided high statistical robustness and thus, sound interpretation of the processes explaining the

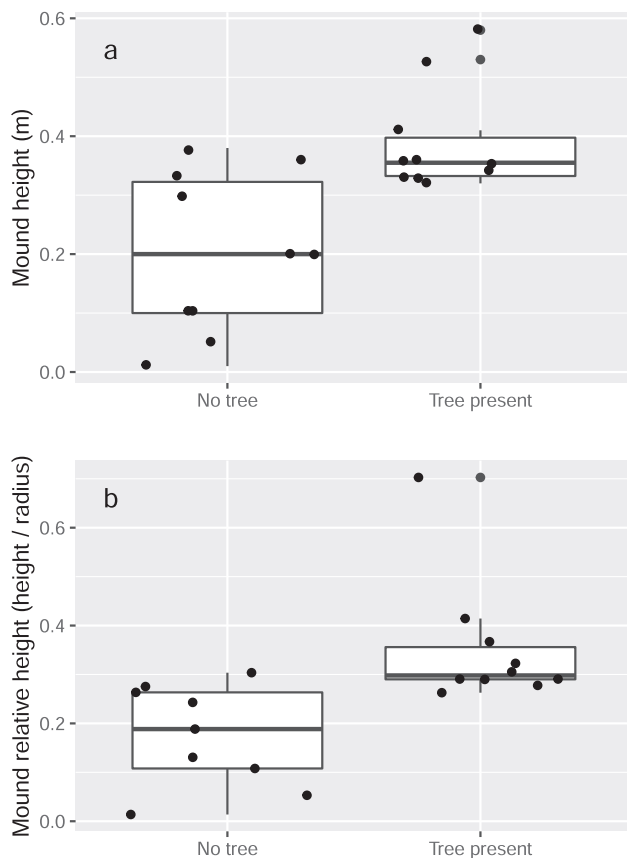
current state of archaeological vestiges of pre-Columbian RFs and relating them to inferences concerning their initial state (i.e., owing solely to human agency).

#### 4.2. A relationship between vestiges of raised fields and current vegetation state

Using simulation of random distribution of trees in the study sites, we showed that trees were found significantly more frequently on mounds than off mounds. Pre-Columbian people were known to manage trees on terra firme in the Llanos de Mojos (Erickson and Balée, 2006). Forested terra firme occurs near our study sites, providing favorable ground for tree management. It is thus unlikely that pre-Columbian farmers built the small circular raised fields to grow trees on them. Trees colonized RFs after their abandonment, probably because conditions on mounds, in particular drainage, were more suitable for them than were conditions in the rest of the basin. Interestingly, we found trees preferentially on mounds that were taller and that had a higher relative height (less eroded), indicating an interaction between mound state, erosion and tree presence. However, the causal relation is difficult to determine: trees may preferentially colonize higher mounds or tree presence may limit erosion, resulting in higher mounds. Furthermore, the two causal relations are not mutually exclusive; there may be reciprocal positive feedbacks between them, like those that exist between topography and soil engineer animals.

#### 4.3. The current state of pre-Columbian raised fields results from combined initial human agency and the erosion / accumulation balance

According to the erosion/accumulation balance hypothesis, the current state of vestiges of pre-Columbian raised fields depends on the



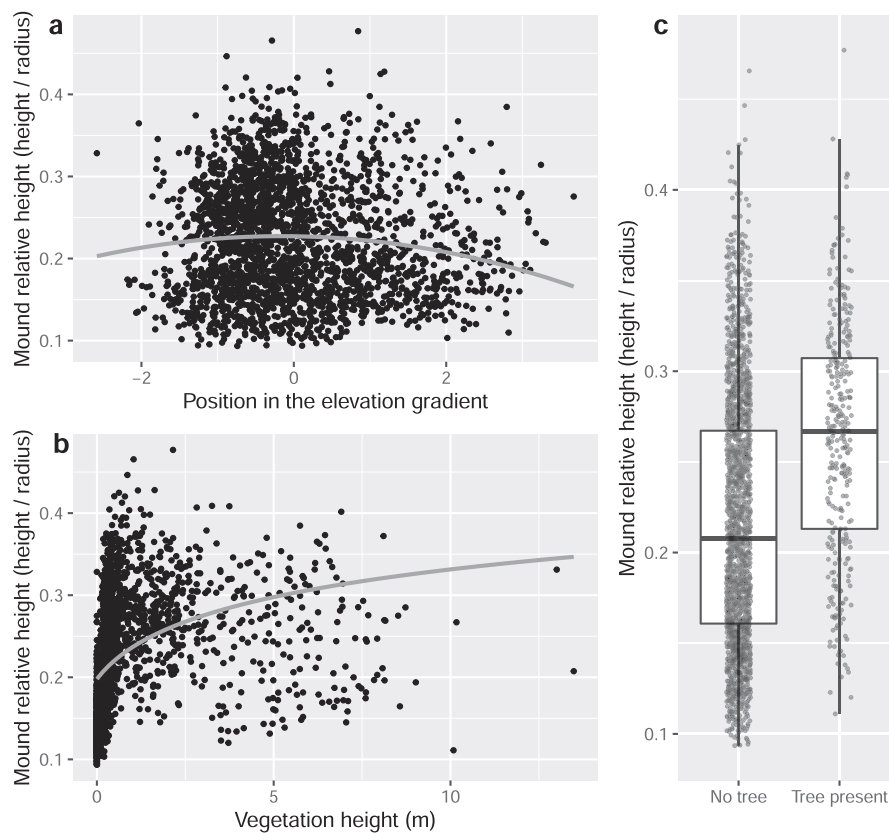
**Fig. 10.** Mound maximal height (a) (measured in the field) and mound relative height (b) (as a proxy for erosion) as a function of tree presence on 20 mounds all located at the same position in the elevation gradient.

balance between the destructuring force of erosion—caused by abiotic factors such as rainfall, whose action is often slowed but sometimes accelerated by the activities of soil animals (Orgiazzi and Panagos, 2018; Whitford and Eldridge, 2013)—and the structuring force of positive feedbacks driven by ecological interactions between topography and soil engineer organisms (McKey et al., 2010; McKey et al., 2021). The initial traits of raised fields, such as mound size and spacing, were defined by human agency, which still contributes to their current state. Natural processes contributing to site formation since the abandonment of RFs, e.g., the environmental factors driving change in mound shape over time, have been little studied. Even less studied are the respective roles of such natural processes and of initial human agency in determining the current state of vestiges of raised fields. Pattern analysis of spatial organization of mounds in French Guiana revealed that the initial organization on a square grid, typical of raised fields being built and cultivated today in Africa (Fig. 2), was still detected in archaeological vestiges of pre-Columbian raised fields (Renard, 2010). Both termite mounds in termite savannas and RFs are regularly spaced, but the former—like other natural earth-mound landscapes (e.g., Zangerlé et al., 2016)—do not have this typical square grid orientation. Spatial organization of mounds has thus been preserved across centuries of abandonment by farmers. We thus considered that in our study sites, the inter-mound distances observed today are solely the result of initial human agency. We found that inter-mound distance decreased when going up along the elevation gradient. Thus, pre-Columbian farmers built mounds more distant from each other in the lower-lying parts of the sites. We found that inter-mound distance was positively correlated with mound size. It is thus reasonable to assume that farmers built larger and more widely spaced mounds in the lower parts. Building higher

mounds in lower parts of the elevation gradient makes sense in flood-prone environments, such as our study sites in Bolivia, because higher mounds are needed to maintain the roots of crops above water level. Higher mounds are necessarily proportionally wider, and thus, require larger inter-mound distances. In Zambia, where agriculture on circular RFs is still practiced today, larger mounds are built in areas more prone to flooding (Fig. 2).

Although mound size and inter-mound distance were correlated in our study sites, the variation in mound size as a function of position in the elevation gradient did not follow that of inter-mound distance. After statistical removal of the effect of inter-mound distance, we found indeed that mound size still depended on the position in the elevation gradient: mounds were larger in the middle of the elevation gradient than in the extremes. Field measurement of mound size along a single transect following the elevation gradient in a single site showed a slightly different pattern: mound size decreased linearly with increasing elevation. Although this observation confirms a relationship between mound size and the elevation gradient, it is not as representative of a general pattern as the analysis of hundreds of mounds based on LiDAR data. However, the relationship we drew between mound height and position in the elevation gradient based on LiDAR data was weak, especially when considering each study site individually. The relationship may have been blurred by local factors independent of position in the elevation gradient. In particular, the type of soil organisms that colonize mounds may affect mound shape. For instance, although large epigeal termitaria, like those typical of termite savannas, are absent, mounds may be higher if they harbor smaller epigeal nests of termites or ants. Exploring this issue would require recording the occurrence of social-insect nests on each RF, a feature that we were not able to investigate from LiDAR data and that requires manual field investigation. In any case, it seems that human agency is not the only driver of variation in current mound size, and that environmental factors are also in play. With the exception of one kind of engineer organism, trees, we did not investigate these environmental factors, which are likely to be numerous and with interacting effects, but only focused on the overall result, i.e., mound size and shape.

We found that as mounds decreased in height, they also became flatter (lower relative height), indicating the impact of erosion. We also found that the extent to which RFs had been altered by erosion was variable: Mean slope from summit to base varied between extremes of 5° (relative height = 0.09) to 26° (relative height = 0.48), and relative height was variable among sites, suggesting that environmental parameters influence erosion level across sites and/or that sites have been exposed to erosion for varying periods of time. Furthermore, we found that mound size and shape (relative height) varied over elevation gradients. Our interpretation of the observed relationship between mound size and shape and position in the elevation gradient is that mounds are well-preserved at a particular level in the elevation gradient, but above and below this level, mounds tend to be smaller and flatter, to a point where they are no longer detectable. This pattern is predicted by the erosion/accumulation balance hypothesis. According to this hypothesis, in the upper parts of the elevation gradient, soil organisms benefit little from using mounds because soil is never waterlogged. They can establish and live everywhere, so that no force drives local concentration of their activities on mounds. Erosion is thus expected to be stronger than accumulation driven by ecological processes, and the mounds should disappear quickly after their abandonment by farmers. For mounds lower in the elevation gradient, benefits to soil organisms from using mounds are expected to increase because most soil is waterlogged for a longer time, driving local concentration of activities of soil organisms on islands of well-drained soil. Their activities thus should increase soil accumulation on mounds and counter erosion. Even further down the elevation gradient, increased flood duration should decrease the activity of most soil organisms, and erosion should thus become stronger than accumulation. In the lowest part of the elevation gradient, high flood duration should prevent accumulation by most soil organisms and RFs, if



**Fig. 11.** Mound relative height (as a proxy for erosion) as a function of position in the elevation gradient (a), vegetation height (b) and presence of a tree (c). Relative height is computed as the maximal height divided by radius at base. The lower the relative height, the flatter the mound.

they were ever present, should be degraded or undetectable. It is unlikely that farmers built raised fields in the lowest parts of the elevation gradient because building raised fields large enough to keep crops out of the water would have required excessive labor. Our observations of the distribution of mound size and shape are thus compatible with the expectations of the erosion/accumulation balance hypothesis. However, they do not constitute a definitive test of the hypothesis. This would require measuring erosion and accumulation, tasks that are beyond the scope of this study.

#### 4.4. Do changes in hydrological conditions since RF construction obscure interpretation of the relation between topography and the size and shape of RFs?

Interpretation of how the size and shape of vestiges of RFs are related to topography could be obscured if hydrological regimes today are different from those that prevailed when RFs were constructed and used: choices made by the builders of RFs may not fit with current flooding patterns. Dating of occupation sites associated with RFs (Walker, 2000) suggest RF agriculture may have been practiced for several millennia. After a dry period between 8 and 4 kyr BP, the region has since experienced a humid phase (Lombardo et al., 2019; Plotzki et al., 2015). Thus, climate-driven, regional changes in hydrological regimes since the period of RF use may not have been very great, unless RFs were already in use before the humid phase, a hypothesis that deserves attention, as crop cultivation at about 10,000 BP has recently been shown not far from our study sites (Lombardo et al., 2020).

While pre-Columbian humans adapted their practices to environmental constraints imposed by natural hydrological regimes (Lombardo et al., 2013b; Rodrigues et al., 2017; Rodrigues et al., 2018), there is evidence that they also modified local hydrological regimes (Whitney et al., 2014), for example, by transforming dry paleochannels into

permanent wetlands as early as 3500 BP (Duncan et al., 2021). When such active management ceased, local hydrological regimes may have changed again. How closely current flooding patterns match those when RFs were in use is thus uncertain. The concomitant dating of RFs and documentation of history of changes in hydrological regime across the Llanos de Mojos would help us understand what present-day hydrological regimes can tell us about the environmental conditions that have favored, or opposed, long-term preservation of vestiges of RFs.

#### 4.5. RF agriculture in South American upland savannas?

Vestiges of RFs are absent from the most deeply flooded parts of the sites because they were probably never built there. However, their absence from the highest parts of the elevation gradient may not have such a simple explanation. The literature on pre-Columbian RF agriculture usually associates them with wetland habitats, because it is only in such areas that vestiges of RFs are found today, despite intensive and meticulous investigation (e.g. Rodrigues et al., 2018), and because this distribution is in line with what has been perceived as their principal function, escaping flooding (Boixadera et al., 2019; Lombardo et al., 2011). However, as mentioned in the Introduction, work on RF agriculture in the Old World, where it is still widely practiced today, has long emphasized that RFs are built in a wide range of environments and that they have many non-hydraulic functions (Denevan and Turner, 1974), including the concentration of nutrients by the piling up of organic matter and topsoil: RFs serve as compost mounds. The nutrient-concentration function has been demonstrated in present-day raised-field cultivation in the dry savannas of the Zambian miombo region (Stromgaard, 1990) and in the highlands of Papua New Guinea (Sillitoe, 1998; Taraken, 2012), for instance. The hydraulic and non-hydraulic functions of raised fields are not mutually exclusive; RFs constructed and farmed today in wetlands of the Congo Basin perform both functions

(Comptour et al., 2018; Rodrigues et al., 2020). In Zambia's Bangweulu Basin, RFs are built in both well-drained and seasonally flooded savannas, being built larger and higher in the latter (Fig. 2). Pre-Columbian farmers may have similarly built RFs in a range of environments, but those built in upland savannas would have eroded quickly after abandonment.

Is the association of RFs with wetlands in pre-Columbian archaeology in part a result of their vestiges being better preserved in such environments than in others where RFs were also built? Addressing this question requires markers of RFs, left in the soil after the epigeal structure has vanished. Unfortunately, such markers still remain to be discovered. In present-day RF agriculture in Africa, the soil stratigraphy and nutrient accumulation that characterize mounds disappear after a few decades of fallow (Rodrigues et al., 2020), and the mounds themselves erode. If our suggestion holds true that upland raised fields may also have existed but have disappeared, the spatial extent of RFs in pre-Columbian times may have been larger than what is currently preserved.

#### 4.6. Conclusion

Although the potential of LiDAR in archaeology is largely acknowledged, it is mostly used to discover new sites and quantify site extent. Our study demonstrates that UAV LiDAR is a powerful tool for investigating fine-scale structural details of archaeological vestiges and contributing substantially to the interpretation of vestiges. In our study sites, UAV LiDAR allowed partial disentanglement of the respective roles of initial human agency and environmental factors in site formation processes determining the present-day state of pre-Columbian raised fields. We show that fine-scale topography is key to understanding the state and the fate of earthen structures, in light of the erosion/accumulation balance hypothesis. UAV LiDAR brings the required resolution and accuracy for characterizing both artifacts and topography in such detail that it opens promising perspectives in the study of vestiges of earthworks. Analysis of LiDAR imagery should now be combined with detailed studies of soil movement by erosion and by the processes of stabilization and accumulation driven by soil engineers. Such studies would further the functional interpretation of earthworks and enable more precise analysis of their initial size and shape, thereby producing better estimates of the volume of earth moved and the labor required in earthwork construction.

#### CRediT authorship contribution statement

**Rumsaïs Blatrix:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft. **Jose Luis Aramayo:** Investigation, Resources. **Anne Zangerlé:** Investigation, Methodology. **Bruno Roux:** Data curation, Formal analysis, Investigation, Methodology, Visualization. **Mikaël Jouanne:** Data curation, Investigation, Methodology. **Brice Anselme:** Investigation. **Marie de Boisvilliers:** Formal analysis, Data curation. **Cédric Krasnopolski:** Formal analysis. **Michel Assenbaum:** Data curation, Methodology, Resources, Validation. **Doyle McKey:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgments

We thank Julieta Ledezma (Museo de Historia Natural Noel Kempff Mercado) for administrative support in Bolivia. We also thank two anonymous reviewers, whose constructive comments greatly improved

the manuscript.

#### Funding

This work was supported by grants to D.M. from the *Institut Universitaire de France*, the *Mission pour l'Interdisciplinarité* of the CNRS, the TOSCA committee (*Terre Solide, Océan, Surfaces Continentales, Atmosphère*) of the CNES (French National Center for Space Research) (grant ref.: FLOODSCAPE), and the LabEx CeMEB (Centre Méditerranéen Environnement et Biodiversité, Montpellier), an ANR "Investissements d'avenir" program (ANR-10-LABX-04-01) (grant ref.: FUNRAFI), and by a grant to R.B. from the *Institut Ecologie et Environnement* (INEE)/CNRS (*Projets Exploratoires Pluridisciplinaires TOHMIS*) (grant ref.: INOCULT).

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2022.103408>.

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