communications sustainability

A Nature Portfolio journal

Article

https://doi.org/10.1038/s44458-026-00128-5

Collective labour and sustainability of pre-Hispanic field systems in La Mojana

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Pre-Hispanic societies of the Colombian Caribbean lowlands built raised field systems spanning over 500,000 hectares. Their re-adoption may offer a potential solution to modern-day water control in the region. Traditionally interpreted as evidence of large-scale projects requiring centralised planning and coordination, the labour organisation behind their construction is nevertheless not fully understood. To leverage archaeological knowledge in assessing potential for their re-adoption, we examine the function and labour input requirements of pre-Hispanic canal-ridge systems within a 500-hectare study area. Conservative estimates indicate the entire system could have been built by local inhabitants in a single dry season. Maintenance requirements were also modest, with full restoration once a generation requiring a few days annual labour. We conclude that the sheer scale of these systems cannot be taken as evidence of top-down control, and highlight the potential of low-cost, cooperative, sustainable approaches to water and land management in the Colombian Caribbean.

Since the onset of satellite imagery in the 1960s, extensive pre-Hispanic raised field systems have been identified across the Americas, from the Central Andes to Mesoamerica[1,2]. Across La Mojana lowland region of the Colombian Caribbean, these artificial land modifications, composed of canals and ridges (*camellones*), span over 500,000 hectares. They are often referred to as the *Zenú* hydraulic systems, after the archaeological denomination of the societies that constructed them in the area near the confluence of the Magdalena, Cauca and San Jorge Rivers, in the Mompós Basin[3] (Fig. 1). They were traditionally interpreted as evidence of a pre-Hispanic engineering feat requiring top-down management, given not only their sheer scale, but also their often-regular patterning with land modifications following main watercourses, marsh bodies and the transition from seasonal to permanent flood zones (Fig. 2).

Q1 –Q5

Understood as multi-functional, the complex network of canals and ridges served the distribution of water and fertile soils away from and to the settled areas, enabled cultivation above water level during the wet season, and moved fish from the permanent marshes closer to the housing platforms. In use from the last centuries BC up until the 10–11th centuries AD, they were key to the successful habitation of the area, with their construction, maintenance, and cultivation coinciding with the development of some of the highest population densities witnessed across pre-Hispanic Colombia[4].

In the absence of concrete evidence for hierarchical social organisation, bottom-up and multi-scalar models have been proposed as alternatives, both within La Mojana[5,6] and elsewhere[7–9]. Despite calls for the revival of these systems as locally managed, sustainable solutions to water and land management[10,11], a proposal echoed in other regions of pre-Hispanic raised field use[12,13], these models have yet to be rigorously evaluated using high-resolution spatial data to assess their practical feasibility in the past. Against this background, our paper has two linked objectives: first, to assess what the spatial organisation, morphology and estimated volumes of raised field systems can reveal about the labour investment and coordination required for their construction, and to shed light on the feasibility or necessity of different forms of social structuring. Second, to use this information in assessing the resources required for their large-scale re-adoption in present-day La Mojana.

The need for alternatives to modern water and land management is pressing: given the turbulent seasonal changes in water level, water control continues to pose a challenge or indeed has been exacerbated in the region over time[14]. While the pre-Hispanic solution involved working with the inundation by redistributing water flow, the Colombian government has historically adopted the opposite strategy. In particular, dikes have been constructed to prevent seasonal flooding, largely driven by present-day land-use needs for cattle farming, thereby resulting in severe deforestation. In practice, however, some of these dikes have often proven incapable of

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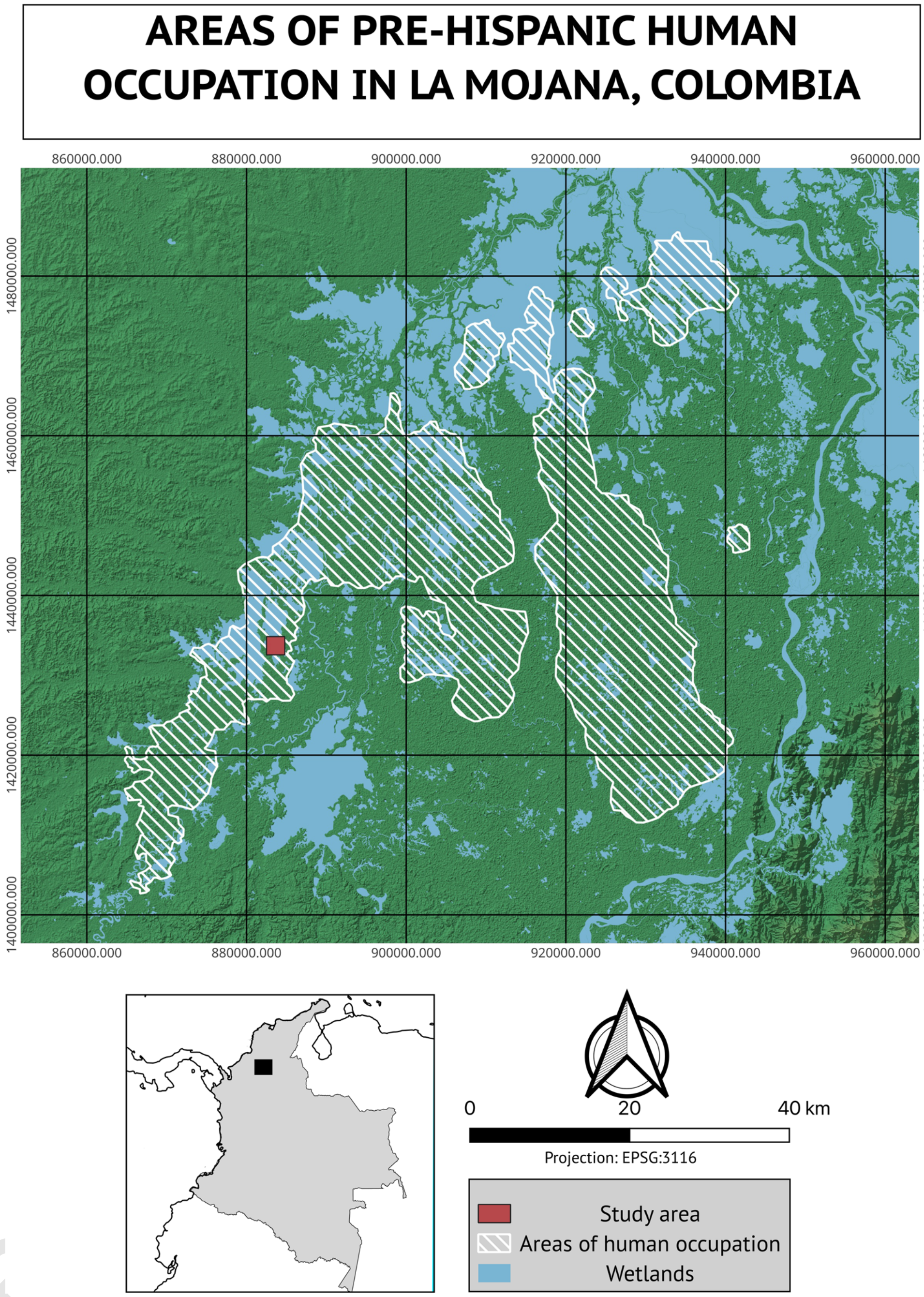

Fig. 1 | Areas of human occupation in La Mojana Region in Colombia. Hillshade based on 1 Arc-Second SRTM data produced by NASA. Wetlands from Ministerio de Ambiente y Desarrollo Sostenible (MADS)[52].

holding back water and have been breached by high-volume currents, resulting in human and environmental catastrophes. Together with climate change, they have also resulted in the drying up of some of the wetlands. Whilst the region thus undergoes periods of heavy rain and uncontrolled flooding, between 2021 and 2023 having affected more than 500,000 people[15–17], at other times it experiences severe droughts. Overall, with these factors accelerating the impacts of climate change and likely contributing to the region's high Multidimensional Poverty Index, the Colombian government has recently launched a new initiative to reassess land-use by restoring the ecosystem's resilience as a water regulator, with the goal of "protecting human lives"[18].

Raised fields in wetlands can store hundreds of thousands of cubic metres of water during heavy rains, gradually releasing it in drier months, buffering against drought and floods[8]. They can simultaneously improve soil quality by deepening the topsoil, enhancing aeration, incorporating organic matter, and draining excess water, leading to higher agricultural productivity compared to slash-and-burn tactics[19]. Present-day communities in La Mojana have already begun reclaiming these benefits in small-scale practice. An initiative led by APROPAPUR, an association for fishers and agriculturalists located in the municipality of Córdoba, has been focused on recovering ancestral Zenú practices and replicating the pre-Hispanic canal-ridge system in a small area of six hectares. This has involved raised field construction every dry season from 2012 onwards, with the help of 30 individuals, and currently directly benefits 80–100 individuals of approximately 30 families. As a result, the members of the community now have access to land during flooding and water during droughts when their neighbours do not[20,21]. Recovering ancestral practices has further been noted to have a positive societal impact through local populations connecting with their heritage through technology[22]. Overall, this initiative has demonstrated the clear potential of crops in raised fields in flood areas.

Fig. 2 | Aerial photograph of hydraulic systems in La Mojana, composed of canals and ridges (also known as camellones). Photo courtesy ICANH archive by Nicolás Jiménez.

However, this test area of six hectares is notably small compared to the scale of pre-Hispanic raised field use. This stands even when accounting for the fact that the complete system represents groups of canals and ridges that together span a chronology of 1000+ years, many of which are unlikely to have been constructed or in use simultaneously[23]. Raised field systems seemingly radiating from the same settlements and sharing typological similarities, hence more likely to have been contemporaneous, can still cover hundreds of hectares. Although their exact temporality cannot be established at present owing to the scarcity of absolute dating evidence, the evidence indicates that pre-Hispanic communities successfully constructed and maintained the systems at these scales. As such, an archaeological understanding of the labour costs and organisation involved in their construction can help assess the scalability of the approach for larger modern-day populations and areas.

As Erickson notes[7], archaeologists often assume that large-scale agricultural systems represent intensive agriculture requiring intensive labour, even when ethnographic and archaeological case studies have frequently shown otherwise. In his own work on pre-Hispanic raised fields at Lake Titicaca, he argued for construction by small groups of farmers[24]. Research from Bolivian Amazonia has also challenged the assumption that raised fields were necessarily used in sustained, intensive, high-productivity agriculture, as is often implicit in top-down interpretations. In some areas, raised fields appear to have primarily functioned as flood mitigation strategies during periods of environmental stress, without promoting increased agricultural productivity[25]. The same area also shows discontinuous use histories, with communities returning to cultivation after extended periods of abandonment or periodically relocating their fields. Overall, the evidence frequently points towards their episodic and environmentally contingent nature[13,26,27]. Near Caño Rabón in La Mojana, possible short-lived phases of use and the reworking of canal and raised-field systems have similarly been identified, perhaps in response to changing flood conditions[28].

Even if employed for stable, intensive agriculture, Erickson further notes the associated assumption that "large-scale intensive agriculture" automatically required centralised socio-political organisation, with local, rural populations seen as incapable of their creation or management. This was long the case with the archaeological interpretation of the Zenú raised field systems, which over decades were seen as representing large-scale, sustained construction projects, requiring top-down planning and labour coordination[3,14]. However, Rojas Mora[5,6] confronted this hypothesis, emphasising that more robust data were needed to evaluate the political organisation behind these landscapes.

It is also important to note that narratives linking control over water management systems to unequal economic wealth and power were originally developed with reference to contexts marked by severe water scarcity[29]. In contrast, tropical floodplains such as those of La Mojana are typically characterised by water excess rather than scarcity. Compared to large-scale irrigation systems that require long-distance coordination, such systems can operate more locally and self-organise under heterarchical principles, without requiring considerable upfront planning[8]. Even in contemporary societies, e.g., in La Mojana, which is known for being organised under local logics of peasants, fishermen, ranchers, and large-scale agricultural producers operating within global capitalist frameworks, documented instances of private control over water management systems are extremely rare[20]. In fact, there are multiple present-day examples of water management systems run sustainably through collective action[30,31].

Lastly, even though rich burials with elaborate goods have been documented in La Mojana, correlations between these and top-down hierarchical power must be proven as such rather than assumed[32–34]. This challenges the notion that local elites necessarily benefited from unequal access to economic resources, which would have enabled them to centrally organise labour for the construction of raised field systems[28]. Overall, therefore, there is no evidence that these societies were hierarchically structured or that coercive power was employed in raised field construction and maintenance.

Recent archaeological research has confirmed that the agricultural system was highly specialised and sustainable, developed by pre-Hispanic populations in fluvial contexts with high seasonal variability. A systematic archaeological research programme has been undertaken by the Colombian Institute of Anthropology and History (ICANH) and the University of Antioquia since 2010, drawing upon a combination of aerial photography, 16th-century documentary sources, archaeological fieldwork, spatial analysis, and the analysis of plant and faunal remains. Aimed at integrating archaeological research with heritage management, it has allowed for the approximation of the dietary and ecosystem management strategies implemented for at least two millennia by societies adapted to periodically flooded environments (see Supplementary Material S1 for more details of previous work).

Initial identifications and cartography of these systems were undertaken by Parsons and Bowden[14] and Plazas and Falchetti[35], with Montejo Gaitán and Rojas Mora having built upon this work more recently with spatial analyses and additional vectorisations[5,6,23,28,36,37]. This work has pointed to a dispersed settlement pattern of the region, in which different canal-ridge systems cluster around groups of housing platforms[6,28,37]. In the same vein, the canal-ridge structures were classified based on their length and arrangement relative to main water courses and bodies, allowing an initial assessment of their differing functions and spatial structures at the broad, regional scales[23]. Nevertheless, this cartography has thus far relied on linear approximations of the canal-ridge systems, limiting insights into their full spatial coverage or exact geometries, and, by extension, fine-grained assessments of their morphology, layout, and spatial relationships.

To further contribute to these discussions, we present the most detailed polygonal cartography of pre-Hispanic raised field systems throughout the Americas to-date, including the vectorisation of 1600 ridges and 63 housing platforms on a case study area of c. 500 hectares in the municipality of San Marcos, Sucre. To assess the degree of upfront planning required for their construction, we produce a classification of canal-ridge typologies and analyse their spatial relationships with the surrounding landscape and with one another. We then assess the labour costs of their construction, using the volumes of earth moved as a proxy, to contribute to a holistic understanding of the social units that could have constructed them, in turn improving overall understanding of Zenú socio-political and economic organisation. The low labour costs suggest that cooperation and organised collective labour could have been effective strategies for human settlement and landscape modification. We further propose that this information can be leveraged in future policy making to gain an informed understanding of the tools and resources needed for their larger-scale re-adoption across La Mojana.

Results

Typology and spatial trends

Unsupervised classification based on the total length and orientation of the ridges resulted in the identification of four main canal-ridge typologies within the case study area (Fig. 3). Clusters 1 and 2 pertain to longer ridges predominantly orientated NW-SE, differentiated from one another by their lengths, with the former being notably longer. In comparison, Clusters 3 and 4 both pertain to notably shorter ridge formations, with the two separated from one another mainly for their orientation, but also the typically slightly shorter ridge length of Cluster 4 (Supplementary Fig. S1).

Many of the longer ridges of Cluster 1 appear to connect the main habitation zones to the permanent water bodies to the northwest, with others connecting to the ancient water body or permanent water bodies to the southeast (see satellite image in Supplementary Fig. S2 for water body locations). The ridges of Cluster 2, whilst having similar overall orientation, are separated into shorter segments, possibly indicating a functional difference. Most Cluster 3 ridges are perpendicular to ancient water courses, although the algorithm also picked up several shorter ridges amongst Cluster 1 and 2 ridges. Cluster 4 ridges are primarily constructions located between the longer ridges of Clusters 1 and 2, with some detected perpendicular to the ancient water channels.

Overall, it is likely that the canal-ridge formations of Clusters 1 and 2 were most functionally significant for the water distribution system, given their length, orientation, and spatial location between the settled areas and

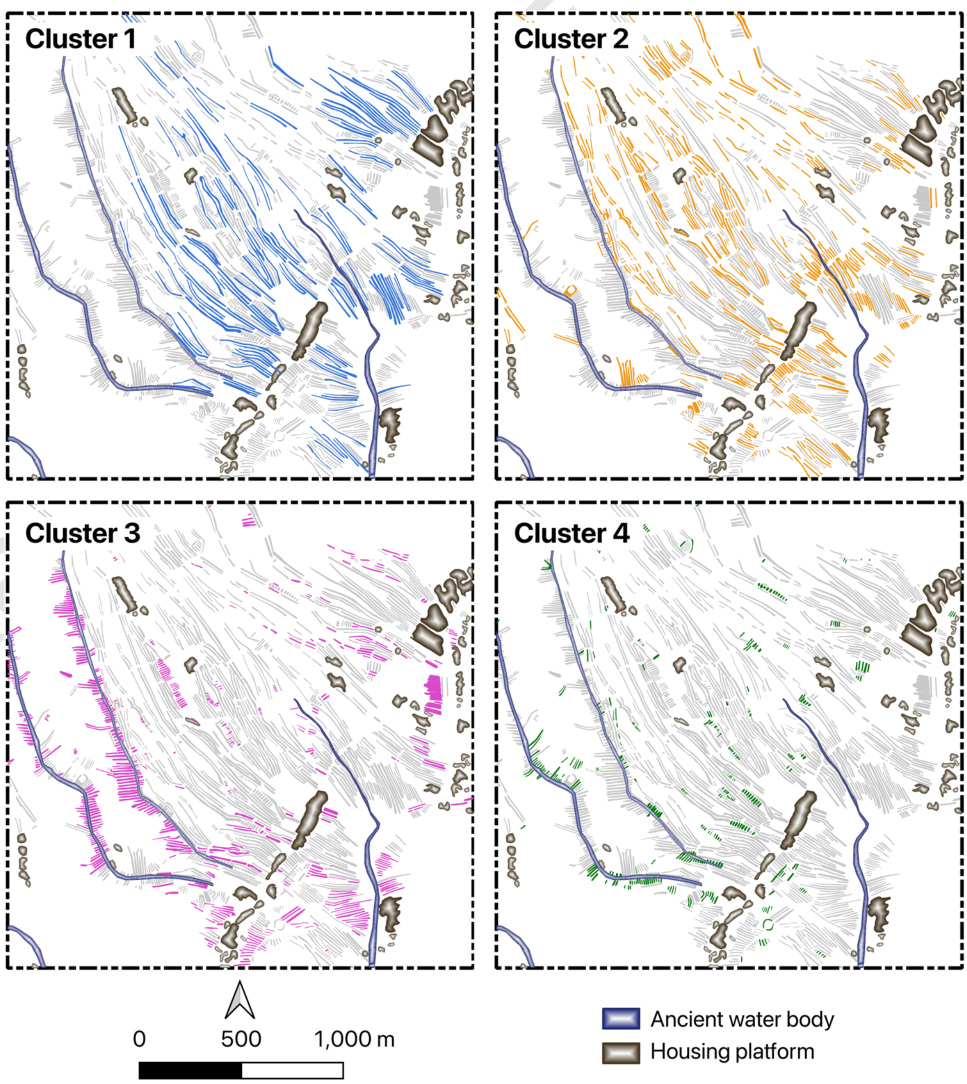

Fig. 3 | Results of K-means clustering on the total length and orientation of the polygonised ridges.

Fig. 4 | Structures hypothesised to have been built as water reservoirs for the capture or maintenance of animal species of interest, probably fish, to facilitate their capture and consumption. Satellite imagery: © Google.

permanent water bodies. In contrast, both Clusters 3 and 4 are more likely to have primarily served to maximise cultivation potential. In addition, Cluster 4 canals may have ensured water distribution between the longer channels, as they are frequently located amongst them. We also visually identified a few constructions that likely acted as water reservoirs, possibly for capturing fish from the larger marshes (Fig. 4).

Network centrality analysis

The results of the centrality analysis indicate that the highest betweenness centrality values are closer to the largest housing platforms located in the southwest of the study area (Fig. 5). The spatial clustering indicates that these platforms may have served as focal points throughout the ridge network, likely areas where social, economic or ritual activities occurred, a hypothesis to be tested and confirmed through field research. The greatest values of betweenness centrality (>90th percentile), which are closer to the platforms, might indicate their role as connector nodes in the hydraulic landscape, acting like strategic hubs. Those nodes, in terms of closeness centrality, would also indicate a strategic accessibility within the network, supporting the idea that the largest platforms in the southwestern part did not exist in isolation but were an integral part of an organised hydraulic landscape (see Supplementary Fig. S3). The overlap of some areas with high-betweenness and high-closeness nodes suggests that certain locations in the southwestern part of the study area were strategically positioned to manage flow within the system, thereby making the whole network accessible. These areas might represent major centres in the ridge landscape.

Population estimates

The population estimates, based on survey and excavation data, yielded a figure of 1600 inhabitants for the 64 elevated platforms within the case study area, which together cover an area of 176,374 m^2. Figure 6 shows the estimates for each individual platform. These results can be taken to suggest a minimum workforce of 800 people, if half of the population contributed to construction work. This is a conservative lower bound, given ethnographic evidence that virtually all households, including many children, are engaged in subsistence farming in Indigenous agrarian communities across different parts of the Americas[38].

Labour costs

The typical labour costs of the longer canal-ridge formations pertaining to Cluster 1 and Cluster 2 exceed household capacity (Table 1). The largest formation alone (2248 m^3) would have required a family of five to work for 90–180 days if working by themselves, while the working community of 800 could have constructed the same canal-ridge formation in half a day or less. In total, all of the 169 canal-ridges belonging to Cluster 1 could have been constructed by the community in two weeks (Table 2). The canal-ridge formations of Cluster 2 have overall lower construction costs per unit (Table 1), but the combined construction costs are on par with Cluster 1 (Table 2). In contrast, the canal-ridge formations of Clusters 3 and 4 both have lower costs, making many of them feasible to construct by an individual family unit alone. In particular, ridges of Cluster 4 typically have construction costs of only a few days per family unit (Table 1).

In any case, even if incorporating these functionally less important canal-ridge formations into the total combined labour calculations (Table 2), the complete system under study could have been constructed by a working community of 800 people in 0.7–1.5 months. On the same assumptions, the whole system under study could have been fully constructed/renewed by the community once a generation (i.e., every 25 years) with only a couple of days of annual work investment.

Discussion

Constructing, managing, and cultivating the raised field systems of pre-Hispanic La Mojana undoubtedly required a degree of technical knowledge among local populations. However, the labour calculations have now revealed that their construction could have been achieved by rural populations in notably short periods across the 500-hectare area chosen for analysis. Even with half the estimated population (Fig. 6) contributing to constructive efforts—a figure well below the agricultural workforce expected in pre-industrial societies[38]—the entire system could have been completed in less than half a 3–4-month dry season (Table 2).

At the same time, Clusters 1 and 2 type ridges, which were likely key to the movement of water and fertile soils away from and to the settled areas (Fig. 3), probably required some degree of upfront planning. Individual formations could take a single domestic unit up to six months of work (Table 1), making them more plausibly the product of labour carried out by groups of domestic units. The need for upfront planning would have been particularly acute if the canals were functionally dependent on one another, requiring a large number to be constructed before they could function successfully. Hydrological simulations in the future could improve our understanding of how water movement was altered by anthropogenic modifications. This, in turn, will help better assess the extent to which engineering-related decision-making was key to the process.

In any case, whilst well within their capacity, the initial construction of the system likely required local populations to come together to coordinate and organise constructive efforts. Interestingly, as revealed by the network centrality analysis, the canal–ridge system radiates from the largest platforms in the southwestern part of the case-study area (Fig. 5). We proposed

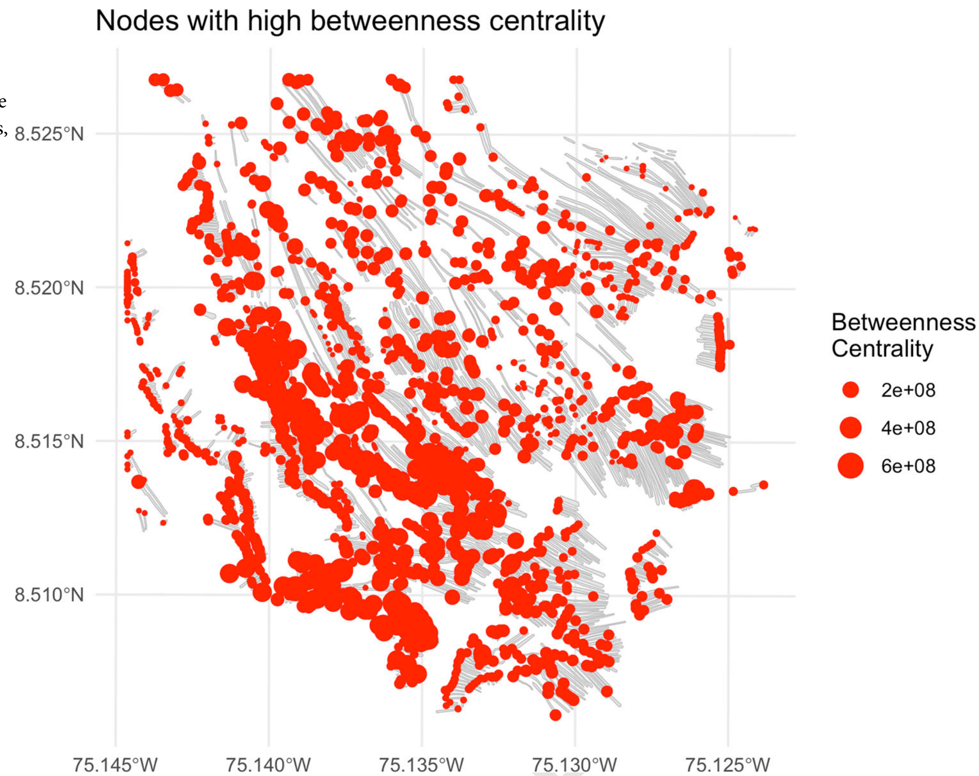

Fig. 5 | Nodes with high betweenness centrality detected in the ridges network, suggesting the southwestern ones as focal points in the general hydraulic system. Red points indicate nodes above the 90th percentile of betweenness centrality values, with point size proportional to centrality score.

that the prominence of the nodes towards this area could indicate strategic accessibility to other parts of the network. It may thus now be hypothesised that the large platforms were not isolated structures but integral parts of a well-organised hydraulic landscape, in which they served as focal points for raised-field construction and cultivation. This would be consistent with the proposition that spatial distribution and connectivity of ridges promoted agricultural productivity and social cohesion, with the larger platforms acting as hubs of social, economic and ritual activity[10].

The labour calculations also highlighted that, once the overall system was in place, any maintenance requirements directly related to construction were fundamentally low when tackled collectively. The whole system, including the main canal-ridge formations, could be fully renewed within a single generation, with the community spending only a couple of days on yearly maintenance. Moreover, many of the shorter Clusters 3 and 4 formations fall well within the capacity of individual households (Table 1). This is consistent with their likely function as opportunistic constructions intended to maximise cultivation potential, hence being functionally independent of one another and dependent only on the adjacent watercourses; or as maintenance constructions intended to facilitate water flow in the longer canals, hence likely constructed on an ad hoc basis. This suggests that upkeep and opportunistic extensions of the system could be undertaken as needed, without requiring renewed large-scale coordination.

Although the systems differ in terms of their soils, vegetation cover, and settlement dynamics, the coexistence of ridge types that require community-level coordination and those feasible at the household scale may echo the types of multiscalar social organisation previously argued for raised fields in Bolivian Amazonia[39]. Yet, given the low labour costs, the different nested organisational scales at La Mojana could still have operated at the site level, and not necessarily across settlements. Previous scholars have noted the dispersed settlement pattern of the region, in which different canal-ridge systems cluster around various groups of housing platforms[6,28,37]. Although our results pertain only to one such agglomeration, they could suggest that other systems throughout the region may have been similarly on a scale manageable by the local inhabitants. This is particularly the case given that the predominant canal-ridge typologies within our study area, in particular Cluster 1 types, correspond to some of the longest formations found across the entire region[14,23], which are also expected to entail the highest construction costs. Together, these patterns suggest construction and upkeep could have been organised internally within each agglomeration of housing platforms and their associated ridges.

Overall, these findings challenge traditional assumptions that these systems represent centralised intervention or oversight. The implications extend to a broader understanding of Zenú socio-political and economic organisation. Our results demonstrate in concrete terms that unsubstantiated assumptions about their labour-intensive and centralised nature are fundamentally flawed, as previously argued for other regions by Erickson[7], Walker[9], and others. Importantly, archaeological discourse has similarly challenged other indicators traditionally taken as proxies of top-down hierarchical power[23–25,31]. Taken together with these discussions, our quantitative findings call for a wider reassessment of the traditional interpretations of the region's past, which have sometimes been based on rather qualitative assessments of what constitutes monumentality or top-down power. Notably, such arguments for centralised, top-down planning, now clearly unsupported by the data, also risk obscuring the agency of local, rural pre-Hispanic populations in creating and managing the systems.

As other scholars have noted, state control may, in fact, result in undesired consequences for large-scale agricultural or water management systems[7]. This is similarly observed in the failure of modern-day dike construction as a water management strategy in La Mojana. The Cara de Gato dike is an emblematic example of the system's inadequacy, having breached on several occasions since 2021, destroying human lives and livelihoods[15,16]. As a result, the Colombian government's proposed strategy is shifting toward ecosystem restoration and natural hydraulic regulation[18]. Canal rehabilitation has also been projected to yield high financial benefit-to-cost ratios, although based upon limited data[17]. Our work has now shown, on much larger scales than previously tested in present-day practice, that self-organised societies could design, build and maintain these systems. This may provide a guide for present-day policy: by overcoming futile attempts to block the water, local populations may engage in collective

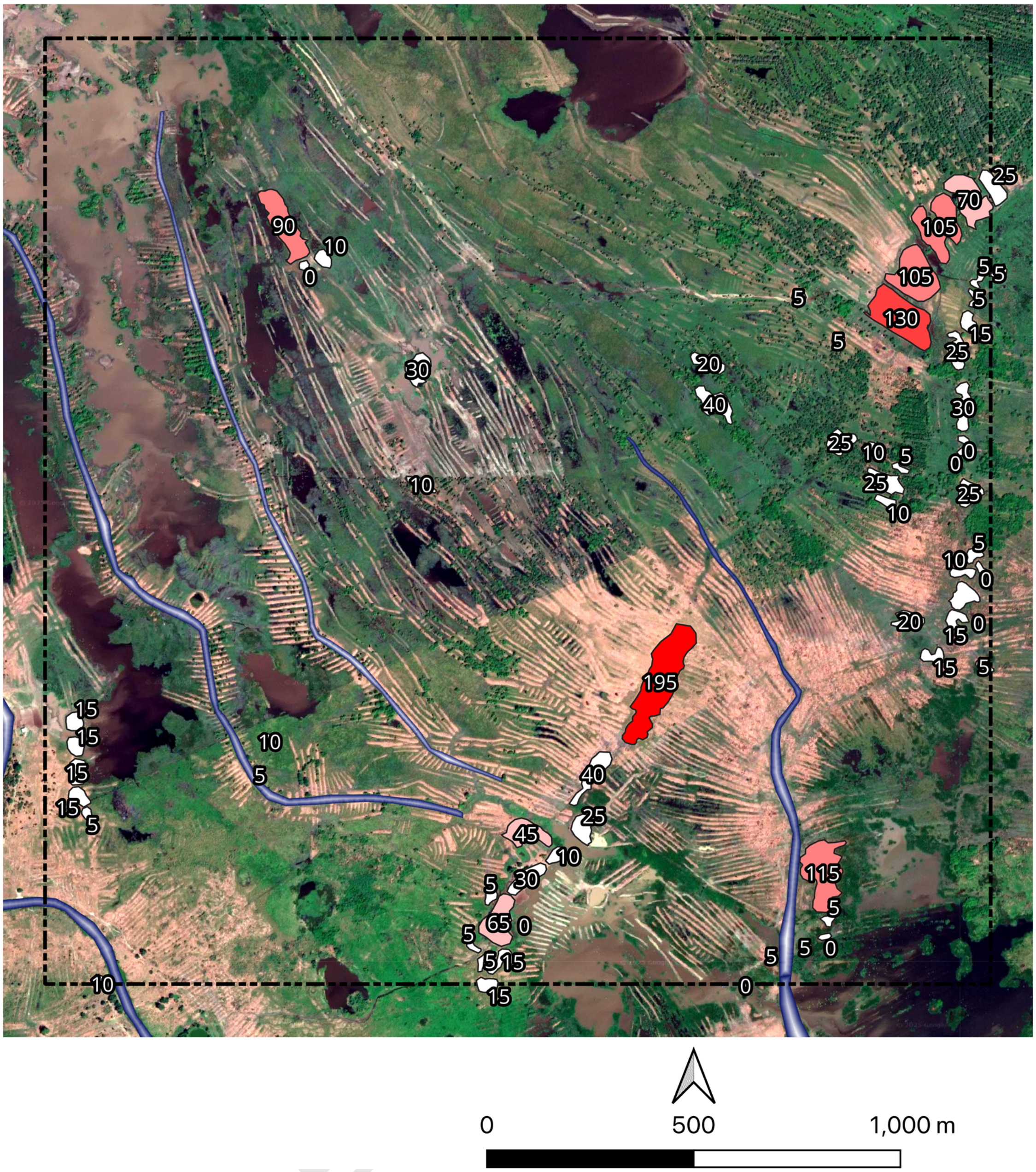

Fig. 6 | Conservative estimates for the number of people housed in each elevated platform identified within the case study area. Satellite imagery: © Google.

action to rebuild and maintain complex raised-field systems with the help of government tools and resources, but without active state intervention.

These inferences also align well with previous characterisations of wetland water management systems as locally functioning and self-organised[10]. Whereas irrigation systems in arid environments can create long-distance interdependencies—and thus could incentivise more centralised management of labour and maintenance, as in the original hydraulic state theories[29]—raised fields in the wetlands tend to distribute water across notably shorter distances. As a result, they are also readily adopted more locally and expanded upon in a modular fashion as necessary.

Unfortunately, given the scarcity of absolute dating evidence, when and for how long particular field groups were in use cannot be reconstructed at present. Evidence from elsewhere in the Bolivian Amazonia may hint at fairly short use phases, between 100-300 years[25–27]. However, the modularity of the systems and the low construction costs witnessed at La Mojana imply that the community could feasibly build, abandon, and rebuild systems as environmental and social circumstances demanded. This renders the modern reintroduction of raised fields viable across a range of scenarios, whether as sporadic, flexible responses to periods of acute environmental stress, or as long-term, sustained solutions to the seasonal flooding and droughts that continue to affect the region today. Future research yielding more absolute dates will allow the available evidence to be contrasted with detailed-scale chronological data, which, together with spatial analyses of the platforms, will also enable us to further refine hypotheses regarding the organisation of household units involved in the construction and adaptation of the canal-ridge system.

Overall, the systems have the potential to benefit present-day local populations by distributing water to and from the settled areas, buffering against drought and flooding during the dry and wet seasons[8]; bringing in fertile soils from the marshes, and enabling cultivation above the water level during inundation; and thus increasing agricultural productivity and crop diversity[19], as witnessed in present-day practice[20,21]. Their large-scale re-adoption can simultaneously promote social cohesion by connecting populations with their ancestral practices through technology[22]. The raised

Table 1 | Summary (min, median, max) of labour costs per ridge type in days

Type	Summary	Volume (m^3)	Person (1)	Family (5)	Community (800)
Cluster 1	Maximum	2248 m^3	450–899	90–180	0.1–0.3
	Median	658 m^3	132–263	26–53	0–0.1
	Minimum	355 m^3	71–142	14–28	0–0
Cluster 2	Maximum	1658 m^3	332–663	66–133	0.1–0.2
	Median	220 m^3	44–88	8.8–18	0–0
	Minimum	17 m^3	3.5–6.9	0.7–1.4	0–0
Cluster 3	Maximum	683 m^3	137–273	27–55	0–0.1
	Median	97 m^3	19–39	3.9–7.8	0–0
	Minimum	1.3 m^3	0.3–0.5	0.1–0.1	0–0
Cluster 4	Maximum	677 m^3	135–271	27–54	0–0.1
	Median	59 m^3	12–23	2.3–4.7	0–0
	Minimum	4.3 m^3	0.9–1.7	0.2–0.3	0–0

Table 2 | Total estimated labour costs for each of the ridge types across the whole study region

Type	Quantity	Combined volume	Unit	Person (1)	Family (5)	Community (800)
Cluster 1	169	127,306 m^3	Days	25,461–50,922	5092–10,184	8–16
			Weeks	3637–7275	727–1455	1–2
			Months	849–1697	170–339	0.3–0.5
Cluster 2	492	122,425 m^3	Days	24,485–48,970	4897–9794	8–15
			Weeks	3,498–6,996	700–1399	1–2
			Months	816–1632	163–326	0.3–0.5
Cluster 3	617	82,690 m^3	Days	16,538–33,076	3308–6615	5–10
			Weeks	2363–4725	473–945	1–1
			Months	551–1103	110–221	0.2–0.3
Cluster 4	322	23,153 m^3	Days	4631–9261	926–1852	1–3
			Weeks	662–1323	132–265	0–0
			Months	154–309	31–62	0.0–0.1
Total	1600	355,574 m^3	Days	71,115–142,229	14,223–28,446	22–44
			Weeks	10,159–20,318	2032–4064	3–6
			Months	2370–4741	474–948	0.7–1.5

fields could also be linked to local markets to provide plant species such as corn, cassava, yams and other species of daily use, while simultaneously promoting sustainable fishing practices by creating movement corridors for fish to be harvested locally (see Fig. 4). Finally, ensuring the sustainability of tropical regions such as La Mojana has broader implications for combatting global climate change[8], with the increased plant diversity enabled by these systems having the potential to offer significant benefits for carbon sequestration compared to current land use predominantly directed at cattle farming.

As to the limitations of our study, it is possible that some of the elevated platforms identified within the case study area did not serve habitational ends, but rather, were used for ceremonial, ritual, storage purposes, or as spaces for other collective use. This, in turn, could imply that the population estimates are somewhat inflated, even though we adopted the lowest estimates of occupation density produced by excavation data (see Section 5.5). Even if the larger platforms were to be excluded from the analysis, the population estimates would still imply community costs of only one or a maximum of two dry seasons of work. We also adopted a fixed ridge–canal height based on a limited number of excavation profiles in our calculations, rather than accounting for the variation observed across different formations in the Digital Elevation Model. However, compared to the actual surviving height of the systems (Supplementary Material S2, Supplementary Figs. 7, 8), which have likely undergone significant erosion over more than a millennium of disuse, the height estimates derived from excavated section profiles were significantly higher. As a result, we are more likely to have inflated the construction costs rather than underestimated them. Finally, our calculations have focused on construction costs alone, without considering the work invested in the actual cultivation of the fields. However, ongoing research by ICANH continues to explore dietary and ecosystem management strategies (see Supplementary Material S1), which will help identify types of cultivars grown in pre-Hispanic La Mojana and inform sustainable cultivation practices for any future applications.

Moreover, whilst the spatial positioning and orientation of Cluster 1 and 2 formations strongly suggest a role in redistributing water and fertile soils across the landscape, these interpretations currently rest on morphological and locational evidence alone. Hydrological modelling would allow these inferences to be tested more rigorously, providing further insight into how water circulation may have been conditioned by the morphology of the canals and their relationship to the movement of water from main watercourses toward marsh areas or platform concentrations.

We are not the first to highlight the potential for the large-scale adoption of sustainable, community-driven approaches to modern water management in La Mojana that draw upon ancestral pre-Hispanic technologies and knowledge (see, e.g., Montejo[10]; Olmos-Severiche et al.[11]). However, our work leverages archaeological data in demonstrating the feasibility and scalability of the approach in concrete terms. The Colombian government is actively looking for solutions to restore the ecosystem's resilience as a water regulator[18]. However, so far, it has not directly explored the adoption of ancestral practices as a large-scale solution. We propose that the most promising role for the state may not be to centralise water control, but rather, to provide the technical, legal and financial frameworks to enable community-driven initiatives making use of pre-Hispanic raised field technologies.

Finally, we would like to highlight that the open-source pipeline presented in this paper can readily be applied to the study of agricultural systems in other regions. It allows for the rapid detection of such systems from satellite imagery (or of any other earthworks clearly delineated from the surrounding landscape by their differing vegetation), their typological classification, as well as the quantification of their dimensions and their associated construction costs. This approach has great potential for cross-cultural comparisons that further our understanding of labour organisation behind past agricultural activities. In the past, raised field infrastructure operated under a variety of environmental, social, and political conditions. The new methods can reveal whether collective labour models are feasible across the board, e.g., whether raised field systems in areas governed by states, e.g. in Mesoamerica or within the confines of the Tiwanaku state, were designed to incur higher investments. In doing so, the methods have much to contribute to broader archaeological debates on the relationship between infrastructural scales and political organisation.

Conclusion

We demonstrated that the impressive scale of the Zenú raised fields does not require explanations of centrally organised, top-down labour management. Rather, their construction is compatible with community-driven organisation, with these inferences grounded in explicit labour estimates and the spatial network structure of their surviving archaeological remains. Even under conservative assumptions, the newly mapped 500-hectare system could have been fully constructed by the local community workforce in approximately 0.7–1.5 months, and fully restored once per generation with only a few days of annual maintenance. Extrapolating these labour estimates to the full extent of the network suggests that these canals and ridge systems could be established in relatively short time spans by small farming communities and subsequently maintained and renewed on a generational basis with minimal labour investment. Thus, low-cost, locally governed solutions to flooding and drought in present-day La Mojana are now not only imaginable, but also archaeologically grounded and technically feasible. Finally, the methods offer significant potential for the study of agricultural systems in other case study areas, both within and beyond La Mojana, enabling future cross-cultural comparisons of past agricultural labour organisation.

Methods

Software and data

To obtain high-resolution satellite imagery across the study area, we used the Google Maps API to download tiles at zoom level = 21 and with a tile size of 640 × 640 pixels, with additional visual comparisons made with Bing satellite imagery. A 1-metre resolution Digital Elevation Model (DEM) based on LiDAR data was provided to us courtesy of Fondo de Adaptación, a Colombian government institution, in 2019.

The spatial analyses were conducted using *QGIS* v.3.30.3-'s-Hertogenbosch[40] with *Python* v.3.9.5[41] and using the *QGIS Python Console*. Projection MAGNA-SIRGAS 3116 was used throughout. The centrality approach was done using the igraph package v.2.1.4[42] through *R* v. 4.5.1[43] and using *RStudio* v. 2025.09.1[44]. *R* and *RStudio* were also used for additional post-processing and graphs for the other analyses. *OpenAI's ChatGPT 5.1* was used for generating or debugging parts of the code.

Cartography

The ridges, which have higher elevations compared to the surrounding landscape and are visible from the satellite imagery for differing in their vegetation cover (Supplementary Fig. S4A), were digitised using a combination of automated and manual polygonisation. The automated polygonisation (Supplementary Fig. S4B), which helped identify major ridge formations, was based on the extraction of blue channel values between 75 and 100 from the RGB satellite imagery, with this found to be the most consistent range for distinguishing the ridge structures from the surrounding landscape. This was followed by manual cleaning as well as the manual digitisation of ridges not captured by the automated approach (Supplementary Fig. S4C). The digitisation of the housing platforms was achieved through fully manual vectorisation based on satellite imagery.

Extracting dimensions

The following procedure was used for extracting the length and width of each ridge, with Fig. 7 showing a schematic illustration of the axes:

1. The centre line along the longest axis of each polygon was calculated for each ridge, extracted from the corresponding polygon using the GRASS GIS *v.voronoi.skeleton* algorithm. The length, *L*, was estimated as the total length of this line.
2. Points were created every 0.5 m along the centre line. The width of lines, *W*, perpendicular to the average angle of the centre line at these points were measured to obtain the width of each 0.5 m polygon segment (Supplementary Fig. S5).

For the original height of the formations, we based our estimations on section profiles from archaeological excavations conducted in 2024[45] (Supplementary Fig. S6). These indicate that accounting for erosion, the typical difference between the highest point of the ridge and the lowest point of the canal was originally c. 1.4 m, which is the value that was adopted and fixed in these calculations.

We also used a 1-metre DEM (Supplementary Fig. S7) to compute the surviving height of the canal-ridge formations in the present-day (Supplementary Fig. S8). However, we decided not to adopt these in the final volume calculations, given they are likely to represent significant erosion and sediment deposition, and therefore would have artificially and notably lowered the estimates of the ridge volumes (Supplementary Material S2).

Cluster analysis

To classify different ridge typologies based on their orientation and total length, unsupervised K-means clustering was performed. These two variables (Supplementary Fig. S1) were chosen for having potential implications for the function of the constructions and their corresponding labour costs. For each ridge, the orientation of its minimum bounding rectangle was computed to capture its predominant direction whilst treating opposite directions as equivalent. To ensure that the algorithm would capture similarities in Euclidean space, the orientation was converted into cosine and sine values prior to cluster analysis. All data was scaled using the median and IQR values of each variable using the *RobustScaler* algorithm, and the optimal number of clusters was estimated through a gain threshold method based on explained variance (stopping when the gain in explained variance becomes ≤ 0.10 for the first time).

Population estimates

We based our population estimates on the typical area occupied by a single dwelling in an elevated platform, against the area of each platform identified within the case study area. Ethnographic parallels indicate these constructions were likely circular houses with a maximum diameter of 10 m. Assuming this diameter ($\pi * r^2 = \pi * 5^2$), each house itself could therefore take up to 80 m^2 of space[46]. Nevertheless, the platforms also housed the associated activity areas located outside of the dwelling itself used, e.g., for food preparation.

We therefore incorporated pre-existing archaeological knowledge to estimate the total area required for each dwelling and its associated activity areas, using data from excavations of a representative housing platform conducted by Fernando Montejo and Sneider Rojas Mora in 2002. Figure 8 shows the plan of the excavated platform, where the areas surrounding the blue highlighted polygons yielded the highest number of excavated ceramics finds, interpreted by the authors to be rubbish pits[46]. The dwellings were

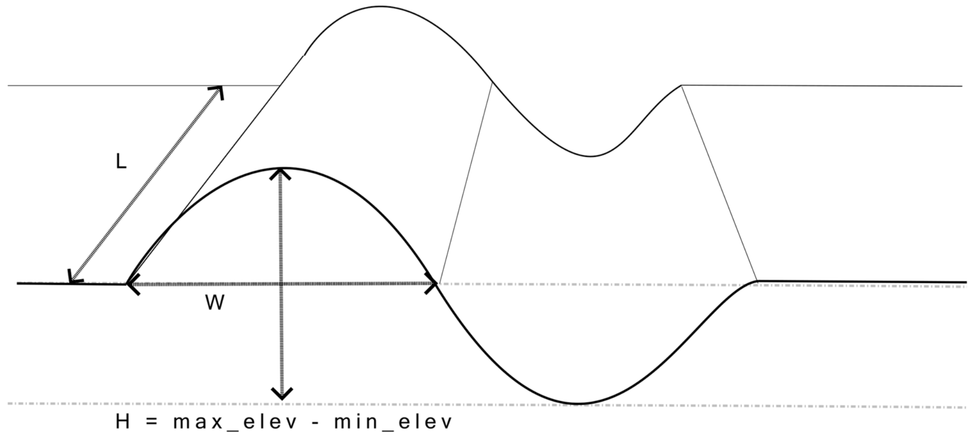

Fig. 7 | Schematic illustration of the axes used to estimate ridge dimensions.

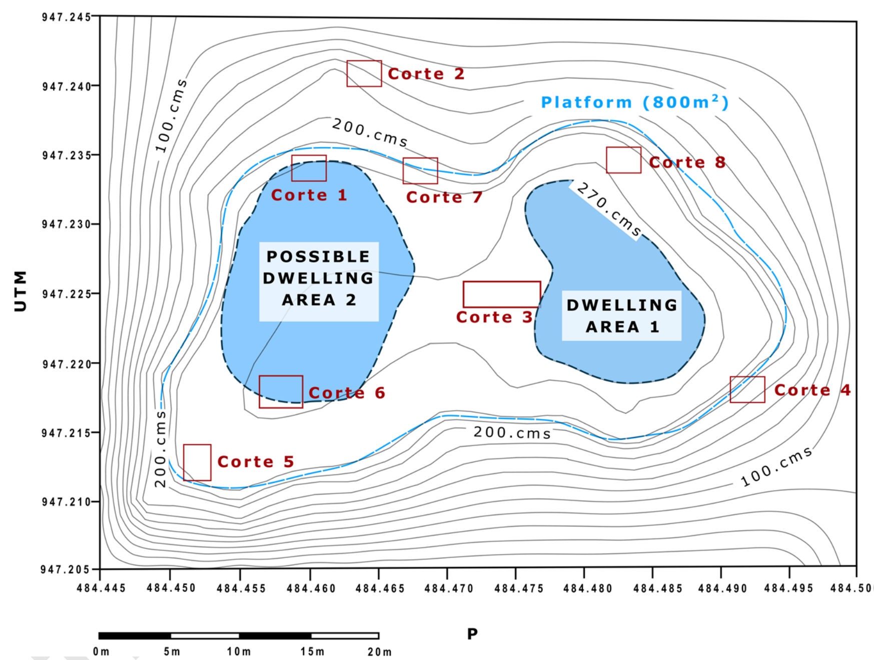

Fig. 8 | The plan of a housing platform excavated in 2002[45]. Areas highlighted in blue indicate the likely locations of the circular houses.

likely located between these, with two identified in the platform as highlighted in blue. The area of dwelling 1 corresponds to ~80.7 m^2 and of dwelling 2–116.2 m^2. In the opinion of Fernando Montejo, the former could house one dwelling only, while the latter could house up to two. This, in turn, suggests an occupation of 10–15 people per 800 m^2 housing platform, assuming a single nuclear family per dwelling.

We adopt two houses per 500 m^2 as a conservative density, which is lower than the density implied by the excavated platform. We therefore divided the area of each platform (Supplementary Fig. S9) by 500 m^2 and floored the results to full integers to obtain the expected number of houses in each platform. This allowed us to estimate the number of people inhabiting each of the 64 platforms, assuming five people per dwelling, or a nuclear family.

Estimating ridge volume

The labour costs of the canal-ridge systems were estimated based on the volume of earth (V) needed to move for their construction. Assuming symmetry between the ridge and the canal, i.e., that the earth removed to create the canal was used for ridge construction, we decided to focus on estimating the ridge volume alone. We based the calculations based on the following formula:

$$V = \frac{2}{3} x \frac{H}{2} WL$$

where H is the difference in the typical estimated height between the highest point of the ridge and the lowest point of the canal (~1.4 m, see Section 5.3), W is the width of the ridge, and L is the length of the ridge along the long axis. Because we assume symmetry, the ridge height here is approximated as $\frac{H}{2}$. The multiplication by 2/3rds was intended to account for the parabolic cross-section, i.e., for the diminished area of each ridge's cross-section towards the top (Fig. 7). The total estimates of area and volume for each ridge was achieved by calculating areas in 0.5 m length segments and summing up the estimates returned for each segment belonging to the same polygon.

Conversion to labour hours

In converting the volume of earth moved to labour hours, we needed to estimate how much earth an individual could move in a set amount of time. The experimental work conducted by Erickson[19,24] at Lake Titicaca, further south in the Andes, provided us with the closest ethnographic analogy to our archaeological case study. His work, focused on replicating the construction of raised field systems using traditional foot ploughs, revealed that a group of three people could move 3 m^3 of soil per hour, with two of these digging the canals and one of them distributing soil. He concluded that each individual could move 5 m^3 of soil in a five-hour workday.

Nevertheless, the soils of the inundated floodplains of the Colombian Caribbean are significantly heavier than those of the Central Andean highlands, being predominantly composed of clay[47], in addition to which there is currently no archaeological knowledge of the types of digging implements that would have been employed in the construction of the pre-Hispanic raised field systems of La Mojana. Given these uncertainties, we incorporated significantly more conservative estimates into our calculations, by halving Erickson's original estimates. We calculated the estimated labour hours as a range, incorporating both the conservative figure of 2.5 m^3 per person per day and his original figure of 5 m^3 pp per day.

We then used these figures to produce estimates of labour costs for one individual and a nuclear family of five, as well as the estimated number of workers who could have contributed to constructive efforts in the area. The community figure was conservatively set at half the population estimate obtained in step 5.5. In pre-industrial societies, almost all able-bodied adults and children likely contributed to labour[38], and the agricultural workforce is consistently estimated to be above 50% of the population[48].

Network centrality analysis

Network centrality can be used to measure the degree to which an entity is central to a network[49,50]. In our case, to analyse the organisation of the ridge network system we implemented a centrality analysis based on a graph-theoretical representation of the spatial ridge network.

Each ridge vector was decomposed into coordinates, which were transformed into an undirected graph G = (V, E)

where nodes *V* are the coordinate points, and edges *E* capture the linear connectivity between the closer points along the individual vectors of ridges. From here, three centrality metrics were derived[43], to evaluate different aspects of topological prominence within the ridge network:

a) the degree centrality (DC), a measure of nodes in relation to the number of direct connections. DC shows the local connectivity; in the case of a ridge network, the high degree nodes could be considered as articulation points in the hydraulic network.
b) the betweenness centrality (BC): BC measures the number of times a node is on the shortest path between each pair of nodes in the network. More formally, for each node v ∈ V, we shall define betweenness as:

$$\mathrm{CB}(v) = \sum\_\{s\neq v\neq t\}(\sigma\_st(v)/\sigma\_st),$$

where *σ_st* is the total number of paths from node *s* to node *t*, and *σ_st(v)* is the subset that passes through *v*. A high BC indicates which nodes propose topological bottlenecks or bridges of flows (e.g., water, materials, labour) through the system.

closeness centrality (CC), is the inverse of the average shortest-path length from a node to all other nodes in the network:

$$\mathrm{CC}(v) = 1/\sum\{u\neq v\}d(v, u),$$

where *d(v, u)* is the shortest-path distance between *v* and *u*. This metric conveys the accessibility of a node in the global network structure and can also be interpreted as the efficiency of transferring resources from that node.

We focus our analysis on betweenness centrality (Fig. 5), as it identifies nodes that have structural significance, defined as those belonging to the 90th percentile of the betweenness distribution. Closeness centrality was also calculated for comparison (Supplementary Fig. S3) using the same 90th percentile threshold. High-centrality nodes can be interpreted as focal points in the network, due to their conveyance of the connections within the ridges network. The spatial distribution of those nodes enables us to hypothesise about potential activities within the ridges system. A centrality-based approach like the one defined here allowed for the comparative assessment of significance across the hydraulic landscapes and provided quantitative evidence for interpretations of spatial organisation, labour coordination and environmental social adaptations visible in the spatial arrangement of the ridges network.

Data availability

All data used in and generated by this research are publicly available in a dedicated GitHub repository (https://github.com/jmkvieri/mojana-fields) and archived in Zenodo (https://doi.org/10.5281/zenodo.20159251)[51], under CC-BY4.0.

Code availability

This research has been done using open-source reproducible software to ensure the reproducibility and replicability of the methods and results. We used *R* v. 4.5.1[35] using *RStudio* v. 2025.09.1[36], and *Python* v.3.9.5[33] using the *QGIS Python Console*, with assistance from Large Language Models (LLMs) for coding (Open AI's ChatGPT v. 5.2). The scripts for reproducing all data collection and the analyses in this research are publicly available in GitHub for collaborative work (https://github.com/jmkvieri/mojana-fields), under the MIT license, and archived in Zenodo (https://doi.org/10.5281/zenodo.20159251)[51].

Received: 3 March 2026; Accepted: 21 July 2026;
Published online: xx xxx 2026

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Acknowledgements

We are very grateful to our friends and colleagues at the Museo del Oro, a division of the Subgerencia Cultural of the Banco de la República de Colombia, who generously facilitated background knowledge and introductions. We are also grateful to Rosie Rhianna Crawford, who undertook the manual vectorisation step for the ridge polygonisation. We would also like to thank Paula Gallego for referring us to the AGROPAPUR initiative.

Author contributions

All authors contributed to the research design and methodology. J.V. carried out the formal analysis, including programming and visualisation, for the cartography, ridge dimensions, cluster analysis, population estimates, ridge volumes, and labour hours; M.C.P. performed the equivalent work for the network centrality analysis. Data curation was undertaken by J.V. F.M. provided resources and regional archaeological expertise on the background context. All authors contributed to the archaeological interpretation of the results and to writing the manuscript, under J.V.'s lead. M.M.T., as PI of the REVERSEACTION project, was responsible for funding acquisition, project administration, and supervision.

Funding

MMT discloses support for the research of this work from the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 101021480, REVERSEACTION project).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44458-026-00128-5.

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Peer review information *Communications Sustainability* thanks Carla James Betancourt and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Ana Ochoa-Sanchez and Nicola Colombo. A peer review file is available.