Archetypes and Drivers of Deforestation in Central America's Tropical Moist Forest Frontiers

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Abstract

Deforestation assessments still treat tropical moist forest loss as a uniform process, and do not distinguish the frontier dynamics that shape where and how forests are lost and the drivers associated with them. Here, we develop a regional spatially explicit frontier classification for Central America's tropical moist forest by combining annual 30-m forest-change data (1990-2023) with a frontier-metrics framework aggregated to 1.5-km cells. We derive three frontier typologies and five archetypes from six metrics. We then move beyond descriptive frontier mapping by using non-parametric contrasts and a Bayesian multinomial logit model to understand the drivers associated with different frontier archetypes. Region-wide, Consolidated (19.4%) accounts for the largest share, but active-edge frontier types remain extensive (Critical 11.1%, Developing 9.2%) alongside Fragmented (12.9%) and Dormant (11.7%) frontiers. The multivariate results show that Critical, Developing and Dormant frontiers are systematically in more remote undisturbed forest when compared to Consolidated and Fragmented frontiers. Protected-area associations differ by archetype, with Critical less and Dormant more associated with protected areas. Our findings demonstrate that deforestation drivers are frontier-process specific, and provide an actionable framework for targeting archetype-specific conservation interventions rather than relying on general regional strategies.

Introduction

Tropical forests are important in sustaining livelihoods, mitigating climate change, and preserving biodiversity, yet they continue to be deforested and degraded. The majority of forest loss occurs in frontier areas. In these areas extractive industries and agricultural expansion encroach on the remaining forest, creating trade-off between conservation and economic development [1-3]. In these regions, land use decisions, commodity markets and governance regimes influence the spatiotemporal processes of deforestation and degradation [4-7]. Therefore, a comprehensive understanding of these processes across frontier regions is essential for designing policies that can protect forest, promote inclusive conservation and development.

Frontier areas are defined as “places experiencing marked transformations owing to rapid resource exploitation,” highlighting their distinct social-ecological changes and persistent inequalities [2,4]. These transformations are driven by complex interactions among smallholders, agribusinesses, and state actors, which often overlap with historical and ongoing processes such as waves of colonization, land speculation and infrastructure investment [6,8]. However, only recently has frontier theory been operationalized in spatially explicit frameworks. This operationalization is crucial, as it allows for the precise identification of frontier archetypes and the specific conditions that pose the greatest risks to both local communities and forest integrity [9-12].

The reconstruction of land-cover change across entire continents and biomes at high spatial and temporal resolution has been made possible by recent advances in remote sensing and time-series analysis. Several studies have developed frontier metrics using these spatial datasets to measure important aspects of frontier processes, including baseline forest cover, cumulative forest loss, remaining forest, the speed and activity of deforestation and degradation, and post-deforestation land use [9,11,13]. These metrics, which summarize the severity, spatiotemporal pattern, and development stage of forest conversion, are used by archetype-based methods to classify landscapes into recurrent frontier types, such as consolidated, degraded, or rampant frontiers [10]. These studies show that frontier metrics provide a diagnostic framework for identifying the variety of deforestation processes and informing spatially targeted governance [14].

With only recent extensions to tropical moist forests (TMF) in Amazonian [11], empirical applications of frontier metrics and archetypes have mostly concentrated on tropical dry forest and woodland frontiers particularly in South America Chaco, the Cerrado and other dry-forest regions in South America, Africa and Southeast Asia [9,10] These studies provide detailed descriptions of frontier patterns and their overlap with protected areas or conservation-priority layers, and qualitatively discuss how archetypes relate to colonization history, agricultural suitability and governance. However, a significant gap remains frontier-metric applications have largely remained descriptive, and no study has explicitly quantified how classic deforestation drivers jointly shift the probability that a location belongs to one frontier archetype rather than another. Moving toward such a process-oriented analysis is essential for identifying the specific driver combinations of each frontier state, which in turn is crucial for designing effective conservation strategies [2,4,5].

Despite decades of conservation efforts, Central America has experienced substantial TMF deforestation as a result of agricultural intensification, land reforms, migration, and global market integration [15,16]. Protected areas (PAs) and community-based conservation initiatives have emerged as regional strategies to halt deforestation and preserve remaining forests [17-19]. Nonetheless, deforestation has advanced into protected and unprotected TMF in northern Guatemala and Belize, the Mosquitia region of Honduras and Nicaragua, and the Darién of eastern Panama, caused by a mixture of cattle ranching, commercial agriculture, smallholder settlement and associated road building [20-24]. In these frontier regions, deforestation and degradation are closely tied to land tenure insecurity, speculative clearing and conflicts between colonists and indigenous communities, as well as uneven enforcement of conservation rules [20,23,25,26]. Collectively, these diverse pressures create highly heterogeneous frontier dynamics that challenge standardized conservation approaches and demand a more nuanced, archetype-based understanding of the region.

Despite these frontier dynamics, regional assessments for Central America are lacking. Most studies continue to describe forest change using aggregate deforestation rates, simple forest/non-forest transitions [27] or classic landscape metrics [22,28], rather than multi-dimensional frontier archetypes. For instance, early remote-sensing analyses in Honduras, Guatemala and Belize assessed forest fragmentation and edge expansion in specific parks and buffer zones using patch-based metrics, identifying roads and settlements as strong drivers of deforestation [29-31]. Later research advances linked deforestation with environmental and socioeconomic factors by combining remote sensing and household surveys [32,33]. More recent research has applied emerging hotspot and time-series clustering methods to identify deforestation in protected-area systems, for instance, in the Selva Maya and the Usumacinta watershed [17,34]. However, while recent analysis is shifting toward time-series data, these approaches still fail to integrate multiple aspects of frontier dynamics to develop a clear set of archetypes that can be compared across countries and governance regimes. Consequently, this lack of a typological framework limits the capacity to identify specific frontier states and prioritize appropriate policy tools like strict protection, community forestry or sustainable intensification [35].

Based on the preceding review four gaps emerge. First, there has been no regional, assessment of deforestation frontiers in Central America. Second, most analyses characterize deforestation in TMF either through aggregate rates or classic landscape metrics, without jointly integrating the severity of forest loss, the spatial configuration of disturbance and the temporal stage or activeness of the frontier, despite evidence from tropical dry woodland studies that these dimensions strongly condition ecological impacts and governance options [10]. Third, and most importantly, emerging frontier-metric applications have yet to perform an explicit, multivariate analysis of how different frontier archetypes are conditioned by classic deforestation drivers. While some studies qualitatively interpret how archetypes relate to accessibility, agricultural suitability or governance, they do not model how these covariates jointly shift the odds of belonging to one archetype versus another [9-11]. Fourth, the alignment between TMF frontier archetypes and conservation instruments remains poorly understood. Specifically, there is limited information on how different IUCN management categories, indigenous territories and other tenure regimes intersect with different TMF frontier archetypes, despite the importance of such data for the debate of management and the future of the forest frontier in TMF regions.

We address these gaps by developing and applying a frontier-metric approach specifically tailored for Central America's tropical moist forests. Using the EU-TMF dataset, we derive six process-based metrics: baseline forest, forest loss, loss speed, fragmentation, activity timing and remaining forest. These metrics are calculated at a 1.5-km resolution across Belize, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica and Panama. We then combined these metrics into three typologies (severity, spatio-temporal pattern, development stage) which were further grouped into five deforestation frontier archetypes: Consolidated, Critical, Developing, Dormant and Fragmented. Beyond providing the first regional, quantitative classification of TMF frontiers in Central America, our study provides an explicit multivariate framework that links archetype membership to classic deforestation drivers. We used non-parametric statistics and an association-focused Bayesian multinomial logit model to quantify how biophysical, accessibility, protection status and land-use factors influence each archetype. In doing so, we show not only where frontier archetypes occur, but also what differentiates them and how they align with existing conservation regimes.

Results

Across Central America, the three landscape typologies indicate a consistent west-to-east gradient, transitioning from long-settled, Fragmented landscapes on the Pacific slope to rapidly shifting frontiers along the Caribbean lowlands. The spatiotemporal pattern typology characterizes the Pacific regions, from Guatemala to Panama, as areas of high fragmentation but slow forest loss (Fig. 1a). In contrast, the Caribbean flank is dominated by medium-to-fast loss with medium-high fragmentation. Specific hotspots of intense, fast, and highly fragmented loss are identified in the Petén basin (Guatemala), the Caribbean coasts of Honduras and Nicaragua, and the Darién region of Panama.

The development-stage typology distinguishes Old fronts with low remaining forest, which prevail in the Pacific and central regions, from Active and Emerging fronts (Fig. 1b). Active and Emerging fronts with medium-to-high forest retention are concentrated along the Caribbean side of Honduras, Nicaragua, and central-eastern Panama. Nicaragua provides a distinct spatial progression beginning with Old fronts on the Pacific, transitioning through a central belt of Active fronts, and culminating in Emerging fronts at the northern and the Caribbean edges.

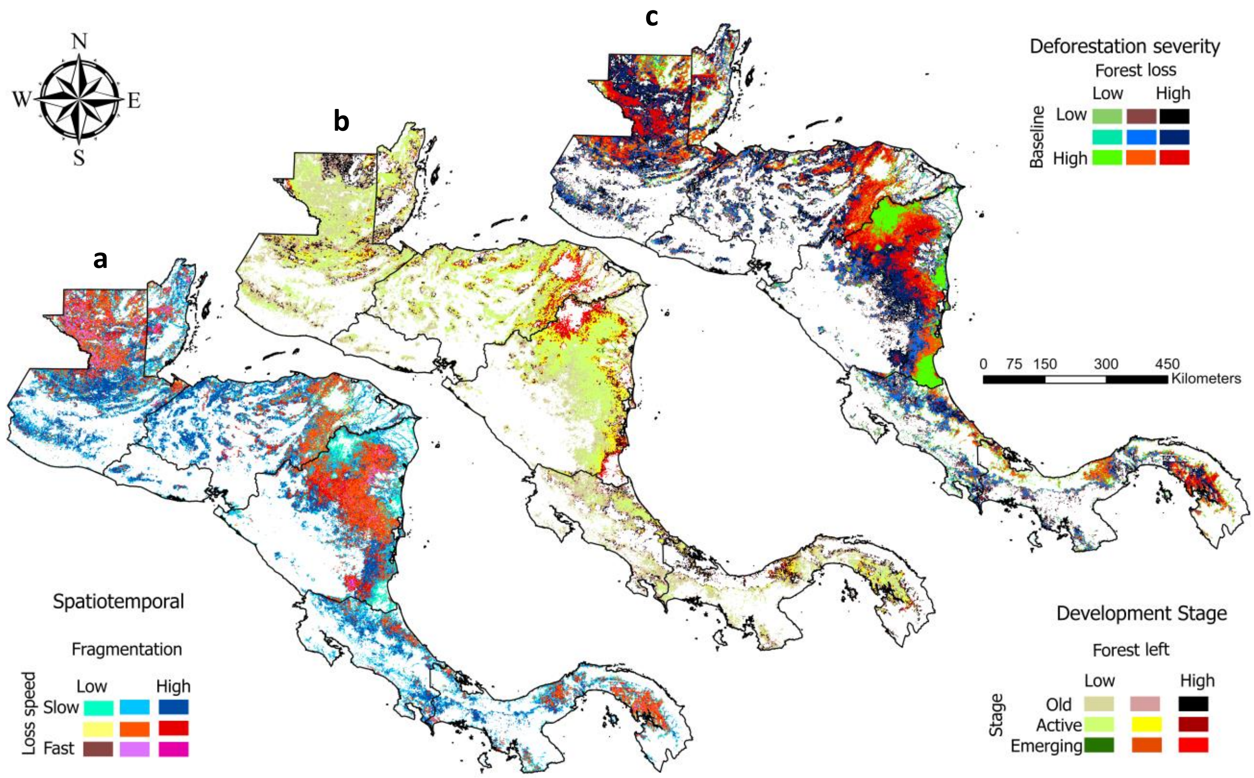

Fig. 1| Spatial patterns of three deforestation-frontier typologies across Central America (1990–2023). *(a) Spatiotemporal typology, combining loss speed (slow → fast) and fragmentation (low → high). (b) Development-stage typology, combining stage (emerging → active → old) and forest left (low → high). (c) Deforestation-severity typology, combining baseline condition (low → high) and forest loss (low → high). Each pixel is assigned to one of the nine class combinations per typology.*

Finally, the deforestation severity typology pinpoints critical hotspots distinguished by high baseline forest cover and high subsequent loss (Fig. 1c). These clusters correspond to Active frontier zones, particularly in the Petén, eastern Honduras, and the Darién. These severe-loss areas are frequently bordered by expanding edges of high-baseline medium-loss areas, contrasting the high-forest low loss areas found in Nicaragua.

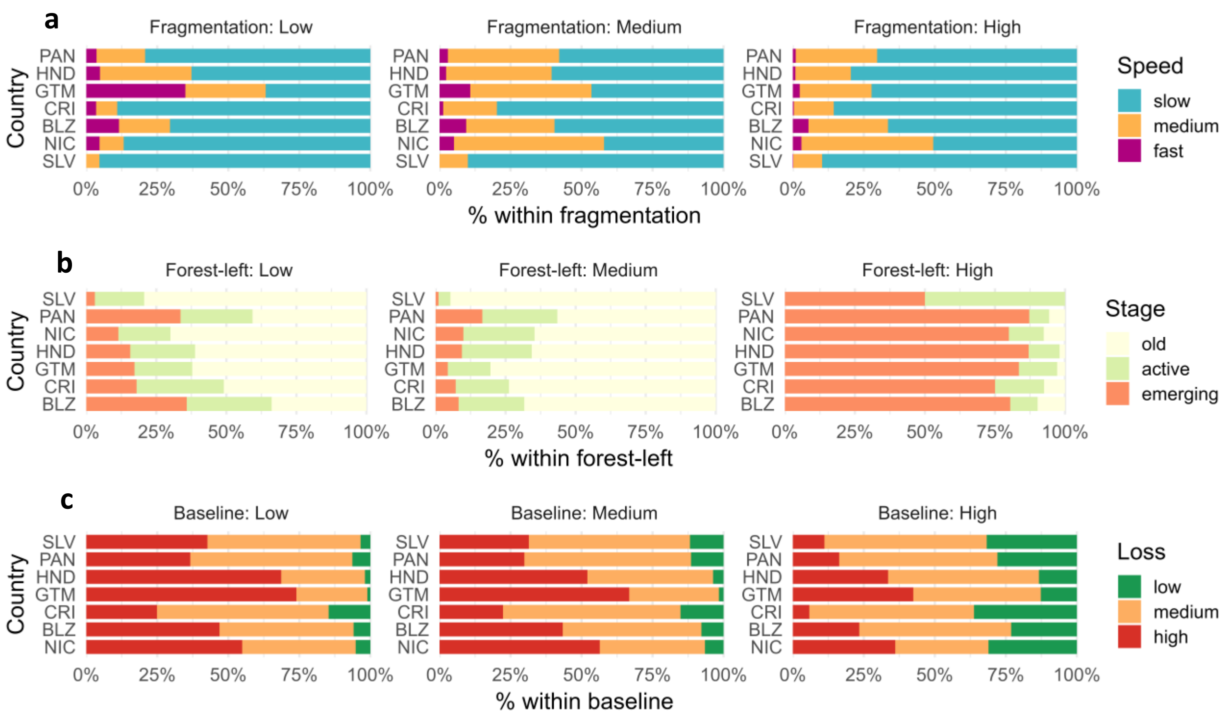

Fig. 2| Country-level composition of deforestation frontier typologies across Central America. *Panels show (a) the spatiotemporal typology (loss speed) stratified by fragmentation class, (b) the development-stage typology (frontier stage) stratified by forest-left class, and (c) the severity typology (forest loss) stratified by baseline class. Stacked bars indicate the percentage share within each stratifying class for each country (i.e., bars sum to 100% within each fragmentation, forest-left or baseline tier).*

At the Central American scale, the spatiotemporal typology is dominated by slow loss, accounting for 59.8% of all loss, with medium loss as a consistent secondary mode (35.3%) and fast loss comprising a small fraction (4.9%) (Table S4). Under high fragmentation (31.2% of all loss), slow loss overwhelmingly prevails in most countries, such as Costa Rica (CRI, 85.6%). The clear exception is Nicaragua (NIC), where slow loss (50.6%) and medium loss (46.4%) are nearly equal (Fig. 2a). In the medium-fragmentation stratum (the largest, accounting for 60.9% of all loss), patterns diverge. While Costa Rica (79.8%) remains strongly slow-loss dominated, medium loss becomes the single largest category in Nicaragua (NIC, 52.8%). It is also highly prominent in Guatemala (GTM, 42.7%) and Honduras (HND, 37.2%). The low-fragmentation frontiers (7.9% of all loss) show the greatest contrast. Guatemala (GTM) has a considerable fast-loss component (34.9%). Most other countries, including Costa Rica (89.1%), and Nicaragua (86.8%), remain strongly slow-loss dominated. In this stratum, the most substantial medium-loss shares can be seen in Honduras (32.2%) and Guatemala (28.3%).

Across Central America, the Development-stage typology is dominated by Old fronts (61.1% of all area), followed by Active (22.6%) and Emerging (16.3%) fronts (Table S5). The landscape is almost evenly split between low (47.8%) and medium (49.0%) forest-left strata, with high forest-left areas being exceedingly rare (only 3.2% of the total area). The high forest-left stratum is predominantly dominated by Emerging fronts, which cover 82.8% of its area. The medium forest-left stratum is predominantly Old (68.6% of its area) with Active and Emerging fronts accounting for 22.6% and 8.8% respectively. The low-forest-left stratum is dominated by Old fronts (57.2%), with Active (23.3%) and Emerging (19.4%) fronts persisting as smaller, secondary components. At the country level, for example, in Costa Rica the high-forest-left stratum is three-quarters Emerging (75.0%), with 17.5% Active and just 7.5% Old; the medium-forest stratum is 73.81% Old, 19.01% Active and 7.18% Emerging; and the low-forest stratum is split between Old (50.91%), Active (31.14%) and Emerging (17.94%) (Fig. 2b). Guatemala exhibits the same pattern even more strongly: the high-forest-left stratum is 83.52% Emerging (13.64% Active; 2.84% Old), the medium-forest stratum is 80.43% Old (15.20% Active; 4.36% Emerging) and the low-forest stratum 62.19% Old (20.61% Active; 17.20% Emerging).

At the regional level, the severity typology reveals that loss is predominantly medium (42.2%) or high (44.9%). These most prevalent areas had high baseline forest cover (42.4% of the region) followed by medium baseline forest cover (32.18%), with the single largest combination being high baseline, medium loss (18.9%) (Table S6). Notably, low loss is rare, accounting for only 12.8% of the total area. Country-level analysis reveals individual regimes. Belize (25.9%), Honduras (21.1%) and Panama (26.8%) are characterized by a high baseline and medium loss pattern. Costa Rica (26.5%), Guatemala (24%) and Nicaragua (18%) are characterized by medium baseline-medium loss, medium baseline -high loss and high baseline-high loss, respectively. Within low-baseline strata, high-loss is overwhelmingly dominant for Guatemala (73.9%), Honduras (68.6%) and Nicaragua (54.8%) (Fig. 2c). A similar pattern is observed in the medium-baseline strata for these countries where high loss exceeds 50%. In contrast, in the high-baseline strata high loss is below 50% for all countries. Honduras and Guatemala show the strongest high-baseline loss profiles, with medium-to-high loss jointly accounting for 86.1% and 87.2% of their high-baseline strata, respectively. This pattern is mirrored in Belize, where medium-to-high loss is the dominant category within its extensive high-baseline stratum (53.1% and 53.4%, respectively). However, this pattern is less pronounced in Costa Rica which exhibits 36.2% of slow loss and only 5.8 % of high loss.

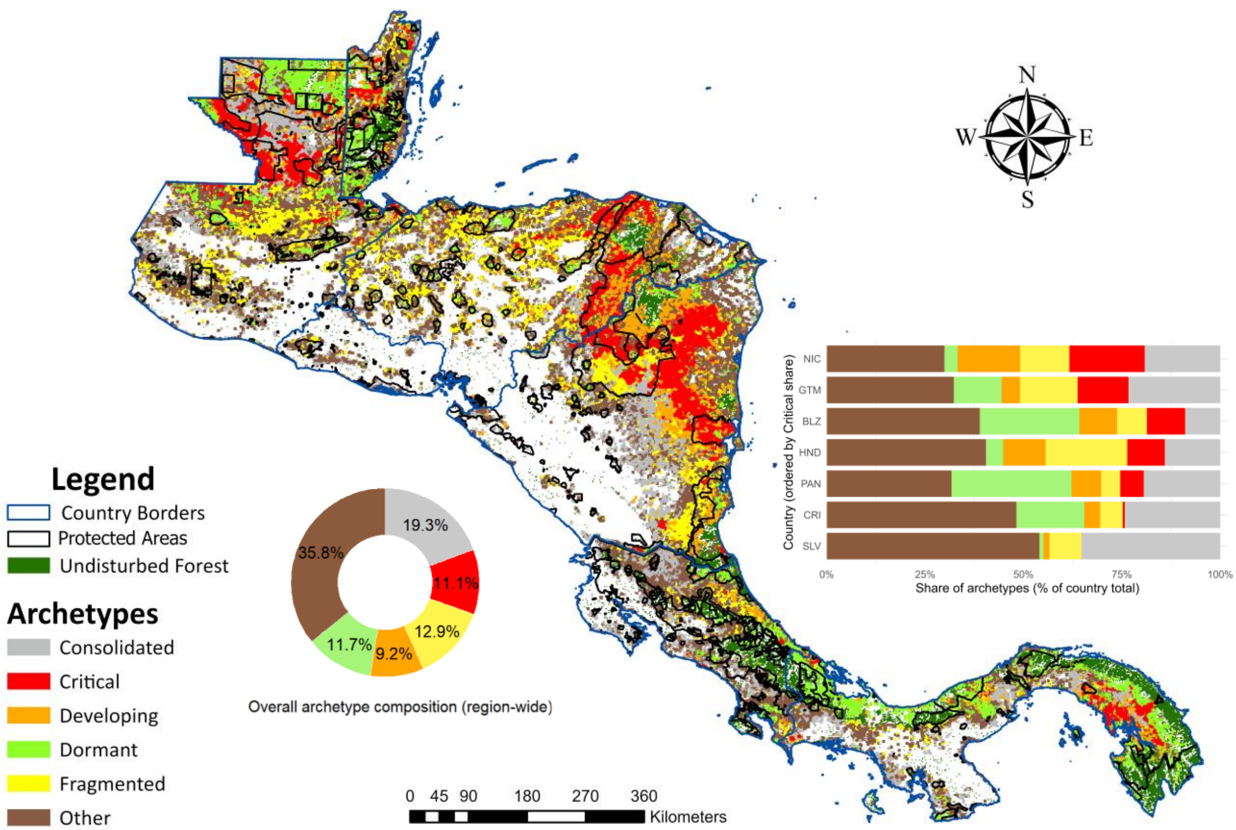

Fig. 3| Frontier archetypes across Central America and country-level composition. *The donut chart summarizes the region-wide archetype composition. The stacked bars show within-country archetype shares (percentage of each country's total archetype area; bars sum to 100%) and countries are ordered by the share of the Critical archetype.*

Regionally, the archetype mosaic shows a coherent progression from intact cores to post-frontier landscapes. Quantitatively, the Other category accounts for the largest share of mapped area (35.8%), followed by Consolidated post-frontier landscapes (19.4%), Fragmented frontiers (12.9%), Dormant frontiers (11.7%), Critical frontiers (11.1%), and Developing frontiers (9.2%) (Fig. 3). The map reveals that Developing frontiers form semi-continuous belts at the edges of remaining intact forest, most prominently along the Mosquitia-Caribbean flank of Honduras-Nicaragua and across south-western Petén in Guatemala with extensions into central Belize. These belts border Critical frontiers, producing the expected sequence of active conversion that attenuates into fragmented mosaics and then consolidated interiors. Dormant frontiers appear as enclaves where clearing has slowed but substantial forest remains.

Country profiles mirror this continental gradient. Ordering countries by the proportion of Critical area Nicaragua ranks highest, followed by Guatemala and Belize, then Honduras and Panama, with Costa Rica and El Salvador ranking lowest. In Nicaragua, a broad Critical corridor runs from the North Caribbean Autonomous Region into the central–eastern lowlands, with adjacent Developing and Fragmented frontiers extending westward. Guatemala features a notable Critical belt along southwest Petén; with consolidated areas in the middle and Dormant classes northeast. In Belize, Critical and Developing frontiers cluster along the northern lowlands, while Dormant pockets persist toward the Maya Mountains. Honduras shows a mixed portfolio: Critical and Developing along the Caribbean, Fragmented interiors across valley bottoms, and localized Dormant areas in the montane reserves. Panama's Critical frontiers concentrate in Darién, with an extensive Dormant belt that extends to Costa Rica. By contrast, El Salvador is dominated by Consolidated and Other classes, reflecting long-standing settlement, limited remaining intact cores, and widespread post-frontier land systems. This stratified view identifies where pressure is currently greatest, where it is expanding into Fragmented frontiers, and where the frontier has largely transitioned to post-frontier types.

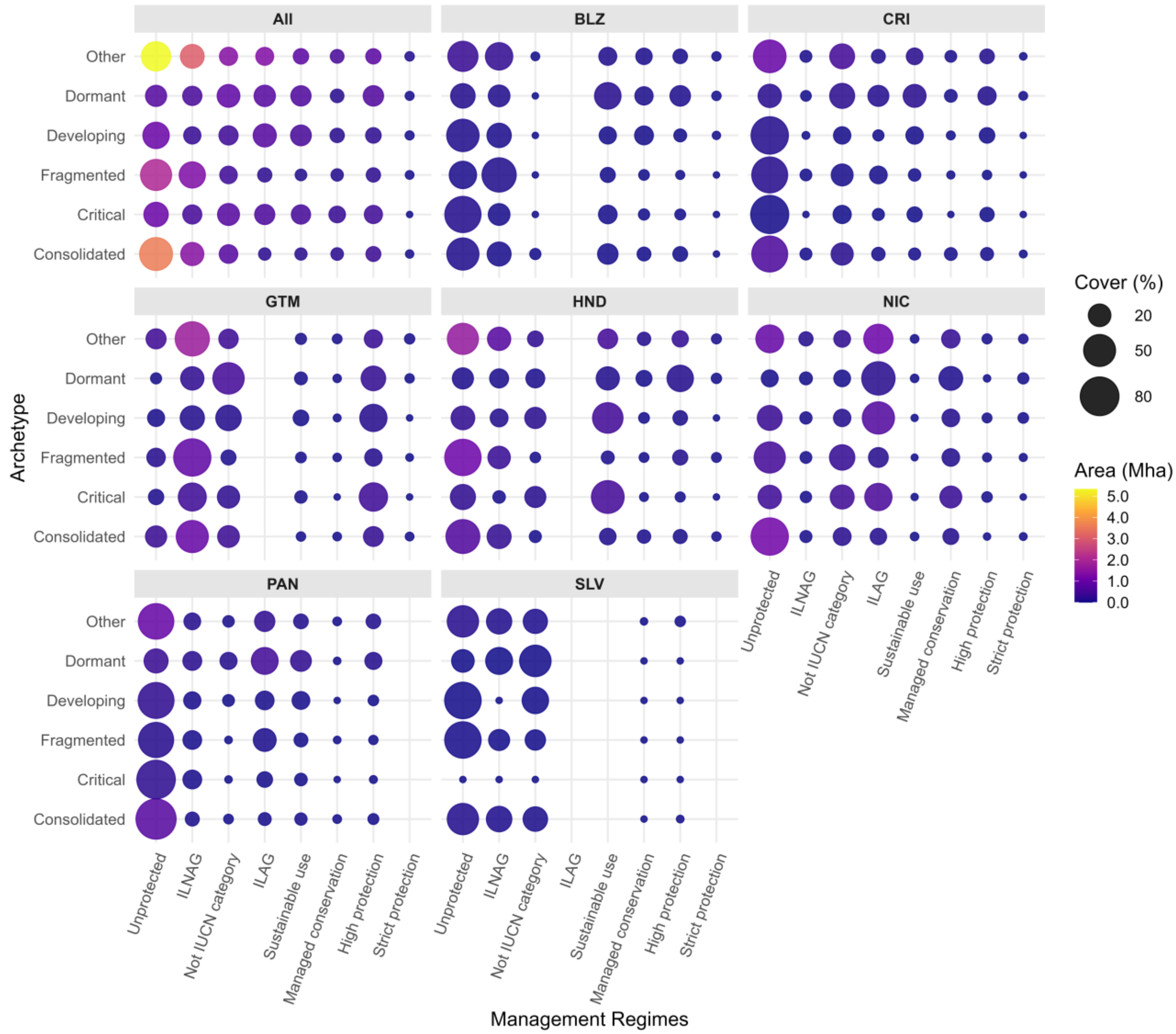

Fig. 4| Distribution of deforestation archetypes across management regime classes to all Central America (all) and by country. *Bubble size represents the cover (%) share of archetype area that falls into each protection class per country (i.e., for a given country and archetype row, percentages across protection classes sum to 100%). Bubble color represents the absolute areas of each country-archetype-protection combination expressed in million hectares (Mha).*

At the regional scale, the archetype areas are concentrated in unprotected and low-protection classes. For Central America, the largest within-archetype shares (bubble size) and the greatest absolute areas (color intensity) occur in unprotected lands for most archetypes, with ILNAG and not-IUCN category also accounting for substantial fractions (Fig. 4). By contrast, the strictest categories shown here contain only a small share of most archetypes at the regional scale (e.g., 10% of Critical and 7% of Developing), showing that active frontier types are generally not embedded within strictly protected cores. Multiple-use categories (ILAG, sustainable use) include frontier types, but their importance varies widely by country. Country panels reveal distinct governance intersections. Guatemala is an exception to the regional pattern, with large shares of Critical (37%) and Developing (33%) occurring in highly protected areas. Honduras concentrates a large share of active frontier types in sustainable use (Critical 53%, Developing 44%), while Nicaragua shows a strong intersection with ILAG areas (Developing 51%; Dormant 55%). Panama and Costa Rica are dominated by unprotected or low-protection classes overall, while Belize shows visible shares of Fragmented, Critical and Developing archetypes across unprotected and ILNAG. El Salvador is almost entirely confined to the least-protected classes in this TMF-based domain, with negligible representation in the strictest categories.

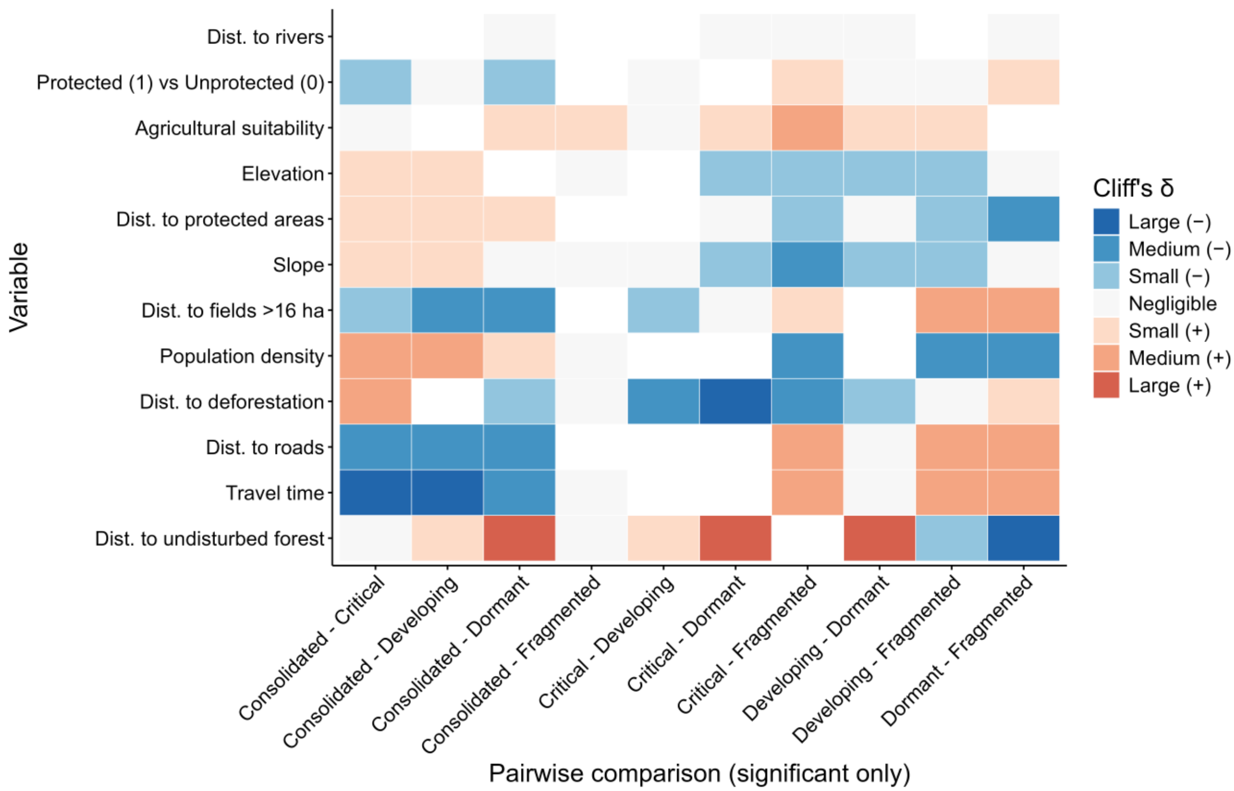

Fig. 5| Effect-size heatmap (Cliff's δ) for significant pairwise differences in drivers across frontier archetypes. *Rows show standardized predictors and columns show pairwise archetype contrasts labeled as Group1 – Group2 (Group1 appears to the left of the dash; Group2 to the right). Each cell reports Cliff's delta (δ) for the predictor between the two archetypes and is shown only for contrasts that are significant in Dunn's post-hoc tests following a Kruskal–Wallis* *screen (FDR-adjusted $p \leq 0.05$). Colors encode both direction and magnitude: warm colors ($\delta > 0$) indicate higher predictor values in Group1 than Group2, whereas cool colors ($\delta < 0$) indicate higher values in Group2 than Group1. Color intensity reflects effect-size class (negligible, small, medium, large). For binary predictors (e.g., Protected = 1 vs Unprotected = 0), $\delta > 0$ indicates a higher probability of the value "1" in Group1 relative to Group2.*

We summarized differences in covariates across archetypes using Cliff's δ (Fig. 5), masking cells that were not significant after Benjamini–Hochberg correction (α=0.05) (Fig. S1). Positive values indicate larger covariate values in the first archetype of each contrast, while negative values indicate the opposite. Across variables, the clearest, most consistent separations are observed along accessibility gradients and forest-edge proximity. Consolidated areas are more accessible than any other class. They have substantially shorter travel times and smaller distances to roads than Critical, Developing and Dormant. They also lie closer to large fields (>16 ha) while hosting higher population densities. At the same time, Consolidated pixels tend to be farther from undisturbed forest than Developing and Dormant pixels and farther from protected areas. Critical frontiers, in contrast, are closer to deforestation areas than all the other frontiers. Agricultural suitability is generally higher for Critical than for Dormant and Fragmented and Critical frontiers also occur at lower slopes and elevations. Dormant frontiers differ from Critical frontiers most strongly by proximity to undisturbed forest (and, similarly, by greater distance from prior deforestation), whereas Developing differs from Critical primarily by proximity to prior deforestation (with smaller differences in distance to undisturbed forest). Fragmented frontiers in general resemble Consolidated frontiers, except that agriculture suitability is higher for Consolidates frontiers.

Table 1| Bayesian multinomial logit associations between covariates and archetype membership

Predictor	Critical	Developing	Dormant	Fragmented
Fixed Effects	Est. [95% CI]	Est. [95% CI]	Est. [95% CI]	Est. [95% CI]
Intercept	-0.81 [-1.83, 0.16]	-0.39 [-1.45, 0.62]	-1.19 [-2.47, 0.26]	-0.17 [-1.09, 0.74]
Elevation (z)	**-0.36 (-0.62, -0.12)**	**-0.37 (-0.58, -0.16)**	-0.00 (-0.18, 0.18)	-0.12 (-0.24, 0.01)
Slope (z)	**-0.40 (-0.59, -0.22)**	**-0.18 (-0.34, -0.02)**	0.12 (-0.04, 0.27)	-0.09 (-0.20, 0.02)

Travel time (log1p, z)	**1.18 (0.99, 1.37)**	**0.92 (0.74, 1.10)**	**1.09 (0.89, 1.30)**	**0.14 (0.01, 0.26)**
Dist. to roads (log1p, z)	**0.20 (0.08, 0.32)**	0.05 (-0.06, 0.16)	**0.19 (0.05, 0.34)**	-0.08 (-0.16, 0.00)
Population (log1p, z)	0.18 (-0.03, 0.39)	**0.27 (0.08, 0.45)**	0.13 (-0.08, 0.34)	**0.26 (0.12, 0.41)**
Agricultural suitability (z)	**-0.28 (-0.41, -0.15)**	**-0.25 (-0.37, -0.12)**	**-0.32 (-0.47, -0.16)**	**-0.28 (-0.40, -0.17)**
Dist. to PAs (log1p, z)	**-0.31 (-0.46, -0.16)**	**-0.21 (-0.35, -0.06)**	**-0.23 (-0.41, -0.06)**	0.03 (-0.10, 0.16)
Dist. to prior defor. 1990–2010 (log1p, z)	**-0.66 (-0.74, -0.58)**	**-0.11 (-0.20, -0.02)**	**0.31 (0.17, 0.45)**	**-0.12 (-0.21, -0.04)**
Dist. to undisturbed forest 2023 (log1p, z)	**-0.20 (-0.34, -0.06)**	**-0.67 (-0.79, -0.55)**	**-1.23 (-1.36, -1.11)**	**-0.27 (-0.39, -0.14)**
Dist. to fields >16 ha (log1p, z)	**0.14 (0.01, 0.26)**	**0.30 (0.18, 0.43)**	**0.30 (0.14, 0.46)**	0.07 (-0.02, 0.16)
Protected (1) vs Unprotected (0)	**-0.37 (-0.71, -0.05)**	-0.02 (-0.33, 0.28)	**0.49 (0.12, 0.87)**	0.17 (-0.08, 0.43)

The table presents the posterior mean estimates and 95% Credible Intervals (CIs). Estimated for which the 95% CI excludes zero (indicating strong evidence of an effect) are highlighted in bold

The multinomial logit model (reference = Consolidated) corroborates and sharpens the distributional patterns seen with Cliff's δ by quantifying how accessibility, edge context, and land-use setting shift the odds of each frontier state. Accessibility appears as the dominant separator. A one standard deviation increase in travel time multiplies the odds of Critical by 3.3 (log-odds 1.18, 95% CrI 0.99-1.37), Developing by 2.5 (0.92, 0.74-1.10), and Dormant by 3.0 (1.09, 0.89-1.30) relative to Consolidated. Distances to roads show a similar (though smaller) pattern, increasing the odds of Critical (0.20, 0.08-0.32) and Dormant (0.19, 0.05-0.34), while being indistinguishable from zero for Developing and Fragmented (Table 1). Furthermore, population density shifts the odds away from Consolidated frontiers toward Developing (0.27, 0.08-0.45) and to Fragmented (0.26, 0.12-0.41).

Deforestation shows strong, coherent signals. Greater distance from prior (1990-2010) deforestation sharply lowers the odds of Critical (-0.66, -0.74 to -0.58; OR 0.52) and Fragmented (-0.12, -0.21 to -0.04), while increasing the odds of Dormant (0.31, 0.17-0.45), aligning with a legacy-clearing footprint around active fronts and waning pressure in older fronts. In contrast, a greater distance from undisturbed forest strongly lowers the odds of Developing (-0.67, -0.79 to -0.55; OR 0.51) and especially Dormant (-1.23, -1.36 to -1.11; OR 0.29), situating both along or immediately exterior to remaining intact cores. More broadly, distance to undisturbed forest is negative for all non-Consolidated classes (Critical -0.20, Fragmented -0.27), indicating that these frontier types tend to occur closer to intact forest than the Consolidated reference, with the strongest proximity signal for Dormant. These associations fit together with the effect-size results where Critical concentrates near recent clearing, while Developing and Dormant border intact-forest edges.

Signals tied to land-use intensity also differentiate types. Greater distance from large fields (>16 ha) increases the odds of Developing and Dormant (both 0.30), indicating that these types are more prevalent away from large-field agriculture relative to Consolidated, whereas Fragmented shows no clear contrast with Consolidated. Agricultural suitability is lower in all non-Consolidated types (Critical -0.28, -0.41 to -0.15; Developing -0.25, -0.37 to -0.12; Dormant -0.32, -0.47 to -0.16; Fragmented -0.28, -0.40 to -0.17), supporting the Cliff's δ pattern that high-suitability areas are more often Consolidated or already converted. Protection status exhibits asymmetric associations. Pixels in protected areas have lower odds of being Critical versus Consolidated (-0.37, -0.71 to -0.05; OR 0.69), but higher odds of being Dormant (0.49, 0.12-0.87; OR 1.63), consistent with slowed but not absent frontier activity within protected areas.

Discussion

Interpretation of frontier metrics in Central America

Our frontier metrics reveal a multi-dimensional gradient of tropical moist forest change across Central America. This framework captures, with distinct combinations of how much forest has been lost (severity), how loss unfolds in space (spatiotemporal pattern), and where landscapes sit along a pre- to post-frontier trajectory (development stage). Collectively, these metrics demonstrate variability in accessibility, land-use intensity, and governance context. This multi-dimensional approach aligns with recent advances in defining diverse frontier typologies in other global deforestation hotspots, such as the South American Chaco [9] and the dry woodlands of the tropics [10].

At the regional scale, deforestation severity is dominated by medium-to-high cumulative loss occurring in areas that initially had high baseline forest cover, while low-loss frontiers are comparatively rare. This indicates that much of the multi-decadal conversion has occurred in once-intact, high-biomass forest landscapes rather than being confined to already-open, heavily modified mosaics. This finding is consistent with continent-scale evidence that recent tropical forest loss has disproportionately affected remaining high-cover forest [36,37].

The development-stage typology further clarifies that Central America is not defined by a single frontier, but by the coexistence of long-established (Old) frontier landscapes, ongoing (Active) conversion zones, and a distinct leading edge of Emerging frontiers. These Emerging frontiers are probably caused by actors looking for new areas to establish themselves, a dynamic observed in frontier emergence globally[4]. Notably, Emerging fronts cluster along the Caribbean-facing escarpments and lowlands of Guatemala, Honduras and Nicaragua and in eastern Panama, indicating that the contemporary expansion front is concentrated where relatively continuous moist forest still remains.

The spatiotemporal typology indicates that the bulk of historical clearing has been relatively slow but highly fragmented, consistent with land-use change dominated by smallholders and gradual road extension, rather than by very large, abrupt clear-cuts alone [21,38,39]. However, our metrics also capture pockets where loss is both fast and spatially aggregated especially within Critical frontiers in northern Guatemala, the Honduran-Nicaraguan Mosquitia and Darién. These findings show recent accelerations in commodity-driven or road-facilitated expansion [38,40,41].

While our model did not explicitly test for illicit drivers, the spatial coincidence of these Critical fast-loss clusters with known trafficking corridors strongly suggests a link to illicit capitalization and narco-deforestation dynamics documented in these specific sub-regions [42,43]. As opposed to traditional smallholder-driven deforestation, such processes are frequently characterized by uncharacteristic capital injections that fuel rapid land clearing for territory control and money laundering rather than productive agriculture alone. This phenomenon is becoming more widely acknowledged in landscape suitability models for trafficking throughout the region [44].

The distribution of frontier types throughout the region and their relationship to the gradient from intact cores to post-frontier landscapes can be concisely understood by combining the three typologies into archetypes[9,11]. The regional mosaic is characterized by extensive Other and Consolidated landscapes, with Fragmented frontiers widespread across long-settled agricultural regions, consistent with Central America's long history of frontier expansion and in some areas movement toward post-frontier transition dynamics [45,46]. Dormant and Developing frontiers frequently cluster near remaining forests, while Critical frontiers occur at the frontier edge of forest-rich landscapes. This spatial edge-mediated pattern is consistent with frontier expansion driven by improved access, land speculation and the progressive outward expansion of cattle [20,47]. Country profiles show that the frontier gradient differs markedly among countries, likely reflecting distinctions in remaining forest extent and wider national land-use and governance contexts. Nicaragua and Guatemala contain the largest proportions of Critical frontiers [15,48], while Panama, Belize, and Costa Rica have substantial shares of Dormant frontiers [49,50]. By contrast, Honduras has comparatively large Fragmented frontiers, consistent with a more pervasive network of long-settled agricultural landscapes alongside ongoing edge-mediated expansion [15]. These archetypes highlight how divergent national trajectories have produced distinct patterns of forest loss across Central America.

Accessibility, edge dynamics, and protection shape frontier archetypes

The covariate contrasts and multinomial logit model suggest that accessibility is the strongest separator among frontier types relative to Consolidated, Critical, Developing, and Dormant frontiers. Critical and Dormant frontiers are systematically more remote showing higher travel times and further from roads. This is consistent with global mappings of travel time which highlight how accessibility stratifies economic opportunity and human activity [51], and with long-standing evidence that transport costs are among the most robust proximate predictors of tropical deforestation [21]. The most accessible areas tend to be cleared earlier, leaving later frontier activity concentrated in remaining forest margins and newly accessible peripheries. The proximity of Critical frontiers to prior deforestation footprints is consistent with stepwise, edge-mediated expansion, in which earlier clearing creates local access, land markets, and spatial contagion effects that increase the likelihood of subsequent clearing nearby [52] and are theorized as a key mechanism of frontier emergence globally[4]. Developing frontiers are also more likely to be closer to prior deforestation and to remaining undisturbed forest, consistent with active expansion along existing forest-edge interfaces. In contrast, Dormant frontiers are concentrated near undisturbed forest yet occur farther from historical deforestation footprints, aligning with potential pioneer efforts. More broadly, distance to undisturbed forest is negatively associated with all non-Consolidated frontier types (with the strongest effect in Dormant).

The land-use intensity proxies further suggest that Central American frontiers are determined by interactions between smallholder mosaics, and more capitalized agriculture. Greater distance from large fields (>16 ha) is associated with higher odds of Critical, Developing and Dormant relative to Consolidated, implying that large-field, capital-intensive agriculture is most characteristic of consolidated landscapes. This pattern is consistent with the idea that much of the remaining Active frontier in Central America is unfolding away from established mechanized-agriculture cores, in more remote forest margins and mixed-use landscapes. It also suggests that large-field expansion may be more characteristic of later-stage consolidation than of the leading edge captured by our Critical and Emerging fronts. This stands in contrast to several South American frontiers, where rapid large-scale expansion often occurs at much earlier stages of frontier advance[9]. At the same time, agricultural suitability is lower in all non-Consolidated types relative to Consolidated, implying that the highest-suitability lowlands have already been disproportionately converted, while remaining frontier advance is increasingly pushed into less favorable or more weakly governed settings [53].

Protection status shows an asymmetric association, protected pixels are less likely to be Critical than Consolidated, but more likely to be Dormant. This is consistent with the interpretation that protection often slows frontier advance without necessarily eliminating pressure, and that protected landscapes may include substantial areas where conversion is reduced or displaced toward edges rather than absent altogether[54]. Several frontier states are notably situated in proximity to protected areas, indicating a tendency to cluster around protected-area boundaries, even in regions where critical conversion is less probable within protected lands. This pattern aligns with evidence indicating that the effects of protected areas are heterogeneous, influenced not only by formal designation but also by location, accessibility, and local enforcement capacity [55,56]. It also implies that varying results throughout the region may indicate disparities in the intensity of underlying frontier pressures rather than solely differences in management. In the

Costa Rican context, PAs have reduced deforestation largely due to long-standing state policies and institutionalized conservation programs [57,58] and the placement of PAs in lower-pressure areas [55]. In Guatemala, on the other hand, protected areas have been heavily encroached upon as a result of colonization, land speculation, illegal cattle ranching, and drug-trafficking-linked land use change [47,59,60]. However, in Guatemala's Maya Biosphere Reserve, community-managed concessions have historically outperformed strictly protected areas in limiting forest loss [61,62]. This indicates that in some Active frontiers, well-secured and enforceable community tenure can be highly effective, but the persistence of Critical and Developing frontiers in ILAG areas (e.g. Nicaragua) indicates that tenure recognition alone does not guarantee protection.

Relevance to conservation and land-use policy

Our archetypes indicate that the region's highest near-term leverage for avoided deforestation lies in Critical and Developing frontier belts that are still forest-rich yet comparatively more remote and close to remaining intact forest. In these settings, relatively small changes in access (e.g., road upgrading and travel-time reductions) and land-market dynamics can trigger rapid, edge-mediated expansion, implying high additionality for interventions that strengthen tenure security, reduce incentives for speculative clearing and anticipate and manage new access before forest loss accelerates [5].

Most Critical and Developing frontiers lie outside the strictest categories. However, this pattern is not uniform. For example, Guatemala is a clear exception, where a substantial fraction of Critical and Developing frontiers occurs within high-protection categories, alongside large shares in ILNAG and non-IUCN category. Across the region, strict categories contain a higher relative representation of Dormant than Developing, but also a non-trivial Critical area in specific national contexts. Importantly, this overlap analysis is not a counterfactual estimate of protected-area effectiveness; rather, it is consistent with evaluation evidence that protected-area outcomes vary with placement and management capacity. Country contrasts suggest different policy entry points for similar frontier types. In Guatemala, the prominence of Critical and Developing archetypes within strict protection categories aligns with concerns about encroachment pressures in parts of the protected-area system [47]. In Nicaragua, Active frontier archetypes show a strong intersection with the ILAG category, consistent with the central role of tenure and governance dynamics in frontier expansion [20]. Honduras, by contrast, concentrates much of its Critical and Developing frontier signals in sustainable use and unprotected areas, highlighting multi-use landscapes as key arenas for managing frontier advance. Finally, in Costa Rica most frontier archetypes intersect with unprotected areas with the exception of Dormant, consistent with the country's longstanding focus on environmental protection measures.

These results imply that a single frontier response, such as simply expanding protected area coverage, will be insufficient. Instead, an archetype-informed strategy suggests different instrument mixes. In Critical frontiers, the priority is speed and credibility because the land system is changing quickly and local environmental governance is being outpaced. These areas are located in the Caribbean-facing frontier belts (e.g. Honduras and Nicaragua) where loss is relatively fast and increasingly fragmented. In these areas mitigation cannot be limited to a new plan on paper. These areas require near real-time monitoring tied to rapid-response enforcement and very practical tenure actions such as accelerating titling or co-titling in places where land claims are being contested, particularly to secure and protect Indigenous peoples' land rights. Developing frontiers, in contrast, are found where conversion pressure is expanding outward from an already active edge into adjacent higher forested areas. That pattern is visible in zones around remaining intact cores, where medium-to-fast loss is present but not yet fully converted into a high-fragmentation end state. These areas are where supply-chain and land-use planning tools can be effective. For instance, targeted zero-deforestation procurement, zoning that explicitly sets no use buffers around the intact core, and road planning that treats new access as a land-use decision rather than a neutral infrastructure upgrade may be especially valuable.

Dormant frontiers in our results look more like landscapes where clearing has slowed and the pattern is comparatively stable, often away from the main expansion front. These areas offer opportunities for ensuring forest stability. In these areas, co-management agreements, restoration incentives, and community-based governance can be used to prevent re-acceleration when commodity prices rise or a new access route appears. For example, this could include restoration payments to verifiable regeneration in previously disturbed zones, along with empowering local enforcement authorities with genuine jurisdictional power and resources (for example, allowing community forest guards to issue legally binding citations), rather than just assigning them monitoring responsibilities without the legal backing to act.

In Fragmented mosaics, which are prominent in the long-settled Pacific-slope landscapes, the problem is less the presence of a single advancing edge and more the slow advancement of degradation and connectivity loss. Therefore, the intervention logic shifts toward landscape-scale design. For instance, priorities include maintaining functional corridors between remnant patches, reducing chronic degradation, and making regeneration financially rational inside these landscapes. This is where strategies such as riparian buffer enforcement, agroforestry incentives, and corridor-focused restoration are needed because connectivity is already the scarce resource.

Finally, Consolidated interiors are areas where most conversion is already historical. Therefore, the remaining leverage here is about how production systems operate and how restoration is targeted. In these landscapes, prevention is no longer the main policy margin. The more realistic strategy is long-term. For example, it may involve sustainable intensification where agriculture is entrenched, restoration corridors that reconnect higher-value patches, and demand-side policies that reduce incentives for land-intensive production.

Limitations and future research

Several limitations qualify our findings. First, all frontier metrics ultimately inherit the uncertainties of the underlying TMF dataset. While we partially mitigate this by focusing on broad tiers (low/medium/high) and by interpreting patterns at 1.5-km resolution, some fine-scale mosaics and smallholder dynamics will be under-represented. Second, our typology is static over the analysis period each pixel is assigned to a single archetype summarizing its 1990-2023 trajectory. This is appropriate for identifying long-term frontier types, but it cannot capture within-class dynamics such as transitions from Developing to Critical or from Fragmented towards Consolidated. Third, the covariates we analyze are predominantly biophysical and infrastructural proxies. We do not explicitly model actor types, commodity supply networks or land-tenure categories, which are known to be decisive for frontier behavior in Latin America. Nor do we consider telecoupled feedbacks whereby policies or market shocks in one country displace deforestation to another. Finally, our governance analysis simplifies the diversity of protection status into seven classes and does not explicitly consider management effectiveness, enforcement capacity or Indigenous and community land rights beyond the ILAG and ILNAG categories. However, comparative research suggests that official protection status is often a poor proxy for actual conservation outcomes [63]. In many cases, Indigenous territories provide robust forest safeguards that equal or exceed those of formal IUCN-designated areas, although they may lack a legal conservation mandate [64,65].

Future work could address these limitations in several ways. Temporal archetype analysis or Markov models could capture path dependencies more explicitly by tracing shifts between frontier types over time. Integrating actor-specific data, such as cattle versus oil-palm expansion or smallholder versus agribusiness clearing, would sharpen the policy relevance of particular archetypes and help distinguish national from transnational drivers. Research could also examine telecoupled feedbacks, where policies or market shocks in one country displace deforestation to another. A further priority is to connect our frontier typology to independent indicators of governance quality and formal rights recognition, which would better reflect the realities of forest conservation on the ground.

Conclusion

This study moves beyond aggregate deforestation rates to reveal, in a process-based and spatially explicit way, how tropical moist forest frontiers unfold across Central America. Using frontier metrics, archetype classification, and multivariate modeling, we provide the first regional quantitative framework that maps where frontier types occur and identify the combinations of drivers associated with each frontier type. The results show that Central American deforestation is not a single regional process, but a mosaic of distinct frontier types distributed along a broad west to east gradient, from long-settled, Fragmented and Consolidated Pacific landscapes to active, forest-rich frontier belts concentrated in Petén, central Belize, the Mosquitia corridor, and Darién. These Active frontiers remain extensive and are systematically more remote, closer to undisturbed forest, and more tightly linked to frontier-edge expansion than Consolidated post-frontier landscapes. Our findings also show that frontier drivers and governance relationships are archetype specific. By identifying where different frontier processes occur and what distinguishes them, our study provides an actionable basis for targeting conservation policy where it can have the greatest ecological and governance impact.

Methods

Study Region

Our study centers on the tropical moist forest (TMF) of Central America, spanning Belize, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica and Panama (Fig. 6), where TMF is defined as closed forests in the humid tropics, including tropical rain forests, moist deciduous forest, and mangroves. In this region, TMF extends from the Selva Maya and lowland Petén basin in the north through the Honduran and Nicaraguan Caribbean lowlands to the Darién in eastern Panama, with fragmented TMF on the Pacific slope and interior uplands. The TMF in Mesoamerica is a biodiversity hotspot and forms a corridor between the tropical forests of southern Mexico and north-western South America providing critical habitat connectivity and protecting biodiversity [15]. Climatically, the region is characterized by humid tropical conditions, with annual rainfall exceeding 2,000 mm on the Caribbean coast and declining toward the Pacific [66]. The steep changes in elevation caused by terrain create mosaics of lowland, premontane and montane forest formations, interspersed with mangroves and riparian systems along both coasts [67].

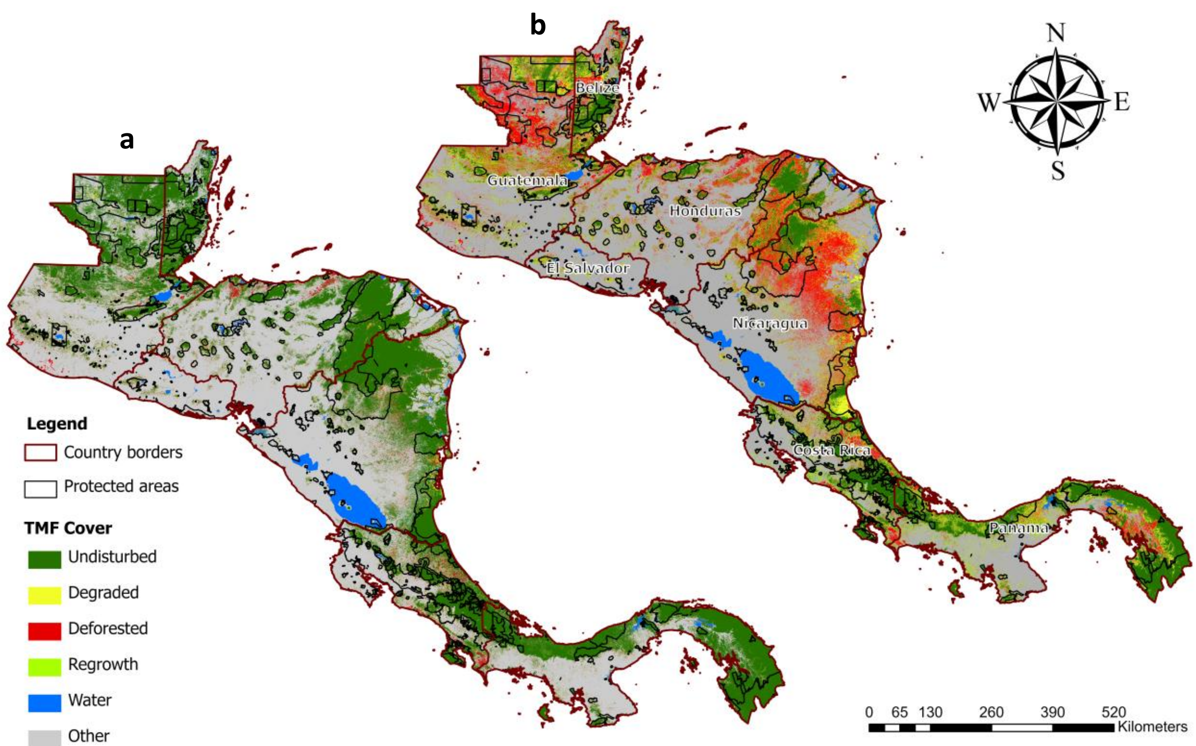

Fig. 6 | Central America’s Tropical Moist Forest Cover (a) 1990 and (b) 2023

Central America’s TMFs have undergone rapid and spatially heterogeneous changes over the past four decades. Land-use frontiers have advanced into lowland moist forests in northern Guatemala and Belize, across the Mosquitia of Honduras and Nicaragua, and into the Darién of eastern Panama. These shifts are driven by a dynamic combination of cattle ranching, commercial crops, smallholder colonization, road building and, in some areas, extractive and illicit economies [20,43,68]. Deforestation continues in Petén and Belize where land speculation, and agricultural expansion have turned forested areas into pasture and cropland [22,31,41]. In Honduras and Nicaragua, deforestation increasingly affects Indigenous territories and community lands. For example, in the Caribbean region, land tenure disputes and speculative clearing interact with unequal access to infrastructure and markets [20,69]. Furthermore although, deforestation has decreased nationally, mature forests in Panama are still being cleared along road corridors and within frontier municipalities, most notably in Darién [63,70].

The rural communities in this region are reliant on land and forest-based livelihoods. However, deforestation has impacted their well-being, by reducing ecosystem services and endangering biodiversity. Significant differences in human development and governance capacity, both between countries and among subnational units, exacerbate these pressures [15,71]. As a result, the region has implemented governance regimes such as community forests and protected areas to address deforestation and improve livelihoods. Nevertheless, the implementation of these governance regimes varies spatially. For example, community territories are important in the northern Guatemalan lowlands and the Caribbean regions of Honduras and Nicaragua, whereas in Costa Rica, Belize, and parts of Guatemala and Panama protected-area networks are more prevalent [19,20,72]. Despite these efforts, research shows ongoing deforestation and degradation in buffer zones, isolated border interiors, and the margins of protected areas. These processes are frequently linked to weak enforcement, insecure tenure, cattle ranching, logging and drug-trafficking interests.

Frontier delineation, metric derivation, and archetype classification from the Tropical Moist Forest dataset

We used the Tropical Moist Forests dataset TMF v2024 (1990-2023, 30 m resolution, with an overall accuracy of 91.4%) [73]. This dataset maps tropical rainforest and tropical moist deciduous forest characterized by low annual temperature variability and high rainfall (>200 cm yr^{-1}). TMF labels each 30 m pixel as undisturbed forest, degraded forest, deforested, regrowth, water, or other land cover**.** In this dataset, undisturbed forest is described as closed evergreen or semi-evergreen forest with no observed disturbance across the Landsat record and degradation is defined as short-duration canopy disturbance (<2.5 years) after which the pixel remains forested. The TMF dataset does not attribute drivers or disturbance intensity, therefore we defined baseline forest as the combination of undisturbed and degraded TMF in 1990. Using Google Earth Engine, we extracted two layers for Central America the annual change collection between 1990 and 2023 and the deforestation year layer between 1991 and 2023. We then aggregated baseline forest and the annual deforestation time series from 30 m to **a** 1.5 × 1.5 km grid. In order to identify frontier cells, we excluded grid cells with less than 10% baseline forest, eliminating areas with little initial forest. Next, we selected cells that had an average annual loss of at least 0.5% over any consecutive 5-year interval between 1990 and 2023 [10]. This process defines frontiers as areas where forest loss is persistent and significant.

Following Buchadas et al. (2022), we computed six metrics for every 1.5 km cell: (a) baseline forest; (b) forest loss; (c) speed; (d) fragmentation; (e) activeness; and (f) forest left (Table 2). To ensure that the classification was appropriate for tropical moist forests in Central America, metric thresholds were adapted from Buchadas et al. (2022) and adjusted to the distribution of values observed in our dataset, while maintaining the conceptual interpretation of each metric.

Table 2| Definition and Classification for the six land-cover metrics

Metric	Definition	Classification
Baseline forest	Forest area in 1990 within each 1.5 km cell	Low: <0.68 km^2; Medium: 0.68–1.58 km^2; High: >1.58 km^2
Forest loss	Cumulative forest loss relative to the 1990 baseline	Low: <10% of baseline; Medium: 10–50%; High: >50%
Speed	Maximum annual rate of forest loss over 1990–2023, estimated as the peak first derivative of a LOESS fit to the annual loss time series	Slow: <0.03 $km^2\ yr^{-1}$; Medium: 0.03–0.12 $km^2\ yr^{-1}$; Fast: >0.12 $km^2\ yr^{-1}$

Fragmentation	Maximum edge density of the evolving forest-loss pattern across the study period, computed from yearly cumulative loss maps	Low: <23 m m^{-2}; Medium: 23–45 m m^{-2}; High: >45 m m^{-2}
Activeness	Timing of frontier activity within 1990–2023, derived from five-year rolling means of annual loss rates using a ≥0.5% yr^{-1} threshold	Old: activity only in early windows (1991–2016); Emerging: activity only in recent windows (2018–2023); Active: activity in both early and late windows, or concentrated in mid-period windows
Forest left	Forest area remaining in 2023 within each 1.5 km cell	Low: <0.75 km^2; Medium: 0.75–1.5 km^2; High: >1.5 km^2

These pairs of metrics were then combined to form three 3×3 typologies: Deforestation Severity (Baseline × Loss), Spatiotemporal Pattern (Speed × Fragmentation), and Development Stage (Activeness × Forest-left), resulting in nine classes in each typology which represent, respectively, accumulated pressure, spatial progression mode, and development stage along a pre- to post-frontier gradient. Finally, we consolidated selected type combinations into six archetype categories (Tables S1): Consolidated, Critical, Developing, Dormant, Fragmented and Other based on the most prevalent patterns and on combinations that offered particular analytical insight, potentially reflecting distinct mechanisms of frontier development consistent with theory-driven typology construction [10].

Spatial covariates, data preprocessing, and archetype comparisons

Based on the deforestation literature in Central America [21,30,46,48,74,75], we identified the region's main deforestation drivers. We represented terrain using slope and elevation (DEM), which influence accessibility and cultivation costs. In Costa Rica and Panama, for instance, steeper slopes have been shown to significantly deter clearing due to their low suitability for mechanized agriculture [49,56]. We used distance to roads and travel time to cities as proxies for landscape accessibility. Roads are the primary channel for deforestation frontiers in Petén (Guatemala) and Bosawás (Nicaragua), facilitating the influx of colonists and cattle [20,47]. Prior deforestation (1990-2010) was included as a legacy indicator of land-use pressure and edge creation, highlighting places where clearing has already occurred and may propagate. Additionally, since frontiers nearer perennial water often experience higher levels of human use and in-forest mobility, we used distance to streams to capture proximity to water and riparian corridors.

Distance to undisturbed forest (2023) measures edge effects, shorter distances indicate areas where spillover clearing can advance more easily into the undisturbed forest. In situations where other constraints are minimal, population density frequently increases conversion risk because it reflects both local human pressure and market demand. Agricultural suitability (agro-climatic potential) serves as a proxy for expected agricultural returns, with higher suitability generally increasing the opportunity cost of forest retention. We used protected areas as a proxy for governance. Their performance varies by region. For example, they are relatively effective in Costa Rica [55], PAs commonly experience encroachment in Guatemala and Honduras [48,59]. Finally, we used distance to large fields (>16 ha) as a proxy for adjacency to capital-intensive, mechanized agriculture. Shorter distances indicate exposure to commodity-driven frontiers which can facilitate further expansion.

All covariates were resampled to 1.5 km to match the analysis grid. Elevation and slope were derived from SRTM. Roads and streams were derived from OpenStreetMap, and travel time to cities was obtained from the European Commission global accessibility surface [51]. Population density (2020) was sourced from CIESIN. Protected areas were obtained from the World Database on Protected Areas (WDPA), while Indigenous lands (Indicative indigenous areas not acknowledged by government (ILNAG) and Indigenous territories acknowledged by government (ILAG)) were obtained from the LandMark database. Prior deforestation was the aggregated area of TMF deforestation from 1990–2010, and undisturbed forest was the remaining TMF forest in 2023. Agricultural suitability was taken from GAEZ v4.0 (summed agro-climatic potential for low-input, rain-fed crops/commodities). Large field size was obtained from Lesiv, M. *et al.* *(2019)*[76]. For all distance-to variables (roads, protected areas, prior deforestation, undisturbed forest, large fields, streams), we computed Euclidean distance rasters.

Cell-level covariates were extracted for the six archetypes (n = 105,045), and records with missing attributes were removed (remaining: n = 104,213). We also excluded the category Other from the analysis (remaining n = 73,705) and all archetypes cells in El Salvador (remaining: n = 67,746), due to the low frequency of some archetype categories in that region. To stabilize scales and comparability, distance variables were log1p-transformed, and all continuous predictors were z-standardized (mean = 0, s.d. = 1). The binary factor (unprotected vs protected) was coded as 0–1.

We applied a two-stage collinearity screen to the z-standardized covariates to limit redundancy and unstable estimates. First, we computed the Pearson correlation matrix and then performed iterative correlation pruning when a pair exceeded $|r|>0.85$, we removed the covariate with the larger mean absolute correlation to all other variables and recomputed correlations. This process was repeated until no pairs exceeded the threshold. Second, on the remaining set we calculated variance inflation factors (VIFs) using auxiliary OLS regressions and dropped variables with VIF > 8**,** recalculating VIFs after each removal (Table S2). Finally, a stratified sample (by country and archetype), representing 10% of sample of the filtered dataset (n = 6,762) was used for the non-parametric characterization and for the Bayesian model.

We applied non-parametric contrasts to the dataset to characterize distributional differences in covariates across frontier archetypes. For each covariate we ran a Kruskal–Wallis (KW) test across the five remaining archetype categories. When the KW test indicated significant heterogeneity, we conducted Dunn's post-hoc pairwise comparisons with Benjamini–Hochberg false-discovery-rate control across predictors and pairs [77] (Fig. S1). To convey magnitude and direction rather than p-values alone, we computed Cliff's δ for each archetype pair and variable, retaining the sign (indicating which group tends to be higher) and classifying |δ| as *negligible* (<0.147), *small* (0.147–0.33), *medium* (0.33–0.474) or *large* (≥0.474) [78]. These KW/Dunn results are reported as descriptive distributional fingerprints of the archetypes; they were not used to select predictors for the multivariate model.

Bayesian multinomial analysis of archetype covariate associations, model diagnostics, and prior sensitivity

We quantified adjusted associations between spatial covariates and frontier archetype using an association-focused Bayesian multinomial logit model (fitted via brms with the cmdstanr/Stan backend) [79]. The outcome was the five-level archetype factor, including Critical (n = 1,396), Developing (n = 1,198), Dormant (n = 967), Fragmented (n = 1,565), Consolidated (n = 1,636)) as the reference category. Continuous covariates were entered in their pre-processed form distance-like variables were log1p-transformed and all continuous predictors were z-standardized (mean 0, s.d. 1). To absorb contextual heterogeneity, we included a country-level random intercept, and to capture broad residual spatial structure we added a bivariate thin-plate spline over scaled coordinates, s(x_z, y_z; k = 30), with x_z and y_z expressed in kilometers and z-scaled. To mitigate pseudoreplication and keep computation tractable for intensive diagnostics, the model was estimated on the stratified 10% sample (n = 6,762).

We ran four chains (4,000 iterations per chain; 1,500 warm-up) with adapt_delta = 0.995 and max_treedepth = 15. For the primary model we used brms defaults flat priors: flat priors for fixed-effect slopes (class "b"), Student-t (3, 0, 2.5) for category-specific intercepts, and half-Student-t (3, 0, 2.5) for standard deviation parameters (country-level random-effect SDs and spline SDs). We compared $k \in \{10, 30, 50\}$ using PSIS-LOO. Both spatial models (k = 10 and k = 30) substantially out-performed the non-spatial baseline, and k = 50 yielded the highest ELPD overall. However, the k = 50 fit exhibited a persistent influential observation (Pareto-k > 0.7) even after moment matching, whereas k = 30 had all Pareto-k < 0.7 and provided a strong improvement over k = 10. We therefore retained k = 30. Convergence and sampler behavior were assessed via split-$\hat{R}$ (< 1.01), effective sample sizes, absence of divergent transitions, and no treedepth saturation. Posterior predictive checks (overall bars and country-grouped bars) indicated good reproduction of observed class frequencies.

Model adequacy and comparisons relied on leave-one-out cross validation (PSIS-LOO) with Pareto-k diagnostics; for k = 30 all k < 0.7. As a prior-sensitivity check, we refit the k = 30 spatial model with stronger regularizing priors (Normal (0,1) on slopes; Student-t (3,0,2.5) on intercepts; Exponential (1) on country and spline SDs). Out-of-sample fit was worse relative to the default-prior model (ΔELPD = −15.5, SE = 6.0); thus, the default priors were used. Even though our model is association-focused rather than predictive, we summarized classification using overall accuracy (0.54), balanced accuracy (0.545), macro-F1 (0.537) and macro-AUC (0.824), computed from posterior mean class probabilities. Fixed-effect coefficients of the selected model are presented as odds ratios (OR) with 95% credible intervals (CrI); we consider evidence strong when the 95% CrI excludes zero.

Protected area and Indigenous land overlap analysis

We quantified the overlap between frontier archetype classes, protected area IUCN management categories (PIUCN) and indigenous lands (IL) using the tabulate area tool in ArcGIS Pro (Esri). For each country, we ran a tabulate area with the PIUCN and IL layer as the zone dataset and the categorical archetype raster as the class dataset. We calculated the area of overlap between archetypes, PIUCN and IL, and the area of the country overlapped by PIUCN and IL. We harmonized PIUCN categories into five analytical classes based on similarities in IUCN management objectives (Table S3): Strict protection (Ia/Ib), High protection (II/III), Managed conservation (IV), Sustainable use (V/VI), and Not an IUCN category. We separately classified LandMark Indigenous and community lands by recognition status as acknowledged by government (ILAG) or not acknowledged by government (ILNAG), following LandMark's definitions of formal state recognition. Finally, we mapped archetype for each country, PIUCN and IL class, and computed: (1) the percentage cover % within each country, (2) the archetype's share of its total archetype area that falls into each protection class and (3) the absolute area of that country-archetype protection combination.

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Data availability

The tropical moist forest data used to derive baseline forest, prior deforestation (1990–2010), and undisturbed forest (2023) were obtained from the European Commission Joint Research Centre Tropical Moist Forest product, available at https://forobs.jrc.ec.europa.eu/TMF. Elevation data used to derive elevation and slope were obtained from the Shuttle Radar Topography Mission (SRTM), available via EarthExplorer at https://earthexplorer.usgs.gov/. Road and stream layers were derived from OpenStreetMap data, available from https://planet.openstreetmap.org/. Travel time to cities was obtained from the European Commission Global Accessibility Map, available at https://forobs.jrc.ec.europa.eu/gam. Population density (2020) was obtained from the Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11, distributed by the

NASA Socioeconomic Data and Applications Center (SEDAC), available at https://www.earthdata.nasa.gov/data/catalog/sedac-ciesin-sedac-gpwv4-popdens-r11-4.11. Protected areas were obtained from the World Database on Protected Areas (WDPA) via Protected Planet, available at https://www.protectedplanet.net/en/thematic-areas/wdpa. Indigenous lands were obtained from the LandMark global platform, available at https://www.landmarkmap.org/. Agricultural suitability was obtained from the Global Agro-Ecological Zoning (GAEZ) v4 data portal, available at https://gaez.fao.org/pages/data-access-download. The global field-size layer used to identify large fields (>16 ha) was obtained from the Geo-Wiki agricultural field-size dataset, available from IIASA at https://iiasa.ac.at/models-tools-data/data-from-geo-wiki-campaigns-on-agricultural-field-size.

Code availability

The workflow used to generate the frontier metrics, typologies, and archetypes for Central America was adapted, see methods, from the Frontiermetrics_Code archived by Buchadas et al., available on Zenodo at https://doi.org/10.5281/zenodo.6141799. The derived typologies and archetypes for Central America are available on Zenodo at https://doi.org/10.5281/zenodo.19103981

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Author contributions

S.D.C. conceived the study, designed the methodology, compiled and processed the data, implemented the analysis, interpreted the results, and wrote the first draft of the manuscript. N.M. supervised the research, interpretation of the results, and manuscript revision. A.B. and M.B contributed to the adaptation of the frontier-metrics framework and to interpretation of the results. H.X.B., S.H., J.G., T.O., J.G.V., and K.T.W.K. contributed to interpretation of the results, discussion of the findings, and improvement of the manuscript.

Competing interests

The authors declare no competing interests.