Uncovering major types of deforestation frontiers across the world’s tropical dry woodlands

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Tropical dry woodlands are rapidly being lost to agricultural expansion, but how deforestation dynamics play out in these woodlands remains poorly understood. We have developed an approach to detect and map high-level patterns of deforestation frontiers, that is, the expansion of woodland loss across continents in unprecedented spatio-temporal detail. Deforestation in tropical dry woodlands is pervasive, with over 71 Mha lost since 2000 and one-third of wooded areas located in deforestation frontiers. Over 24.3 Mha of deforestation frontiers fall into what we term ‘rampant frontiers’. These are characterized by drastic woodland loss and conditions favourable for capital-intensive agriculture, as seen in the South American Chaco and Southeast Asia. We have found many active and emerging frontiers (~59% of all frontiers), mostly in the understudied dry woodlands of Africa and Asia, where greater frontier monitoring is needed. Our approach enables consistent, repeatable frontier monitoring, and our global frontier typology fosters comparative research and context-specific policymaking.

Deforestation frontiers, in particular, are poorly understood in the world’s tropical woodlands (defined in our manuscript as including tropical dry forests, shrublands and wooded savannas with more than 10% tree cover). When compared with humid forests, these woodlands are overlooked by researchers, policymakers and the general public. Yet these ecosystems harbour unique biodiversity, including many endemic species, and are some of the last refuges for iconic megafauna. Tropical dry woodlands provide important ecosystem services that sustain hundreds of millions of people and store globally relevant amounts of carbon.

Three factors have contributed to this knowledge gap. First, there are major geographical research biases towards a few specific regions, while many others remain entirely overlooked. Second, research on deforestation frontiers has typically focused on investigating dynamics within certain places or regions, such as in Amazonia, Indonesia or the Congo Basin, but there is a clear lack of cross-regional and comparative assessments. Third, global satellite-based time-series products describing forest and woodland loss at high spatial resolution have only recently become available. These data could provide deep insights into how deforestation frontiers advance and help to identify typical, recurrent patterns of deforestation frontiers. Recently, detecting and assessing such archetypical human–environment interactions has become a major focus in sustainability science, including for identifying static land systems or driver/outcome constellations. In this study, we have pioneered the use of archetypal analyses to identify the major, recurring patterns in global deforestation frontiers.
then used in step 3 to develop three thematic typologies describing the severity, spatio-temporal patterns and development stage of the frontiers. Finally, in step 4, we grouped these thematic types into frontier archetypes.

Applying this framework across the world’s tropical dry woodlands, according to our definition (Supplementary Fig. 1), revealed that woodland grid cells occupied 1,884.97 Mha and contained about 1,044.13 Mha of woodland in the year 2000. We identified 577.36 Mha of woodland cells undergoing substantial deforestation processes from 2001 to 2020 (~31% of woodland cells in 2000), accounting for around 71.7 Mha of woodlands loss (92% of total loss). Of the frontier area, three-quarters (76.5%) is in the tropical and subtropical grasslands, savannas and shrublands biome, highlighting the importance for considering this biome when assessing woodland loss, with the remaining quarter (23.5%) in the tropical and subtropical dry broad-leaved forests biome. Deforestation frontiers occurred across the globe, with the highest prevalence in South America (46.2% of total frontier area in tropical dry woodlands) followed by Africa (43.8%), Asia (5.0%), North America (3.9%) and Australia (1.1%).

Three typologies of deforestation frontiers. In step 3, we combined the frontier metrics from step 2 that described how deforestation progressed in space and time. This resulted in our thematic frontier typologies (see Methods, Supplementary Text 1 and Supplementary Figs. 2 and 3). We combined metrics pairwise to yield three typologies describing the severity, spatio-temporal patterns and development stage of frontiers. We classified each metric into three classes, combining metrics in pairs resulted in nine frontier types for each of our three themed typologies. Our first typology was geared towards assessing deforestation severity, combining the metrics of baseline woodland and the percentage of total woodland loss (Fig. 2 and Supplementary Fig. 4). Frontiers with high woodland cover and low woodland loss were most extensive (260.00 Mha, 45.0% of total frontier area), followed by medium woodland cover and low woodland loss (125.75 Mha, 21.8%). These frontiers were most common in central and southern Africa (for example, Northern Congolian forest-savanna and Central Zambezian wet miombo woodlands) and North America (for example, Puerto Rican dry forests). Over 40.02 Mha were classified as high severity frontiers, having both a high percentage of total woodland loss and high and medium baseline woodland (4.6 and 2.4%, respectively). High severity frontiers occurred mostly in South America (for example, Dry Chaco), and were more prevalent within South America and Asia (for example, Southeast Indochina dry forests and Southern Vietnam lowland dry forests in Asia).

In our second typology, we explored spatio-temporal patterns of woodland loss, combining metrics of speed of woodland loss and fragmentation (Fig. 3 and Supplementary Fig. 4). The most common type of frontier had medium speed of woodland loss with high levels of fragmentation (141.20 Mha, 24.5% of total frontier area). This type of frontier was more prevalent within Africa (for example, Guinean forest-savanna and Western Congolian dry forests) and parts of South American (for example, Ecuadorian and Lara-Falcón dry forests). A further 85.00 Mha were classified as slow frontiers with high fragmentation (14.7%), and were more prevalent within North America (for example, the Chiapas Depression and Central American dry forests) and parts of South America (for example, Cauca Valley and Patía Valley dry forests). In addition, 51.54 Mha were classified as fast frontiers with medium fragmentation (8.9%), mainly within Australia (for example, Cape York Peninsula), South America (for example, Dry Chaco) and Asia (for example, Southeast Indochina dry forests).

In our third typology, we explored the development stage of frontiers, combining metrics of activeness and remaining woodland (Fig. 4 and Supplementary Fig. 4). The most prevalent types here were old frontiers with little woodland left (101.43 Mha, 17.6%) and active frontiers with high levels of woodland left (105.24 Mha, 18.0%).
18.2% of total frontier area). Old frontiers with little woodland left were more prevalent within Australia (for example, Kimberly tropical savanna), South America (for example, Caatinga) and North America (for example, Sierra de la Laguna dry forests). Active frontiers with high levels of remaining woodland were more prevalent within African frontiers (for example, Western and Southern Congolian forest-savanna and Angolan miombo woodlands). In addition, 105.02 Mha were classified as emerging frontiers (18.42%), mostly in Africa (for example, Guinean forest-savanna and Northern Congolian forest-savanna). In total, 339.89 Mha were

Fig. 2 | Severity types of deforestation frontiers in tropical dry woodlands. a–f. Typology according to the severity of deforestation frontiers in tropical dry woodlands, based on baseline and percentage of total woodland loss (a). The insets show enlargements of the Gran Chaco (b), Cerrado and Caatinga (c), the miombo and mopane woodlands (d), West African dry forest (e) and Indochina tropical dry forests (f).

Fig. 3 | Spatio-temporal pattern types of deforestation frontiers in tropical dry woodlands. a–f. Typology according to the spatio-temporal pattern of deforestation frontiers in tropical dry woodlands, based on speed and fragmentation of woodland loss (a). The insets show enlargements of the Gran Chaco (b), Cerrado and Caatinga (c), the miombo and mopane woodlands (d), West African dry forest (e) and Indochina tropical dry forests (f).
classified as active or emerging frontiers (58.9%), most commonly in Africa and Asia.

Archetypal deforestation frontiers. Our final step combined the frontier types identified by our three themed typologies (severity, spatio-temporal patterns and development stage) to identify frontier archetypes, defined here as high-level frontier patterns across geographical contexts (step 4, Fig. 1). By qualitatively grouping combinations of types from our typologies, we derived five such frontier archetypes: inactive frontiers, consolidated frontiers, fragmented frontiers, looming frontiers and rampant frontiers (Fig. 5 and Supplementary Fig. 5). Importantly, the goal here was not to characterize and classify all frontier cells, but to group those frontier cells that clearly undergo recurrent and comparable patterns. In other words, our typologies (characterizing frontier processes in all cells) and archetype analyses (identifying high-level and recurring frontier patterns) should be seen as complementary.

Inactive frontiers correspond to old frontiers with high baseline woodland, yet still have high levels of remaining woodland. This archetype covered about 75.33 Mha (13.0% of all areas identified as frontiers), mostly in Africa (for example, Northern Congolian forest-savanna and Zambezian-Limpopo woodlands).

Consolidated frontiers have little remaining woodland, are old and deforestation is relatively slow (Fig. 5 and Supplementary Fig. 4). This archetype corresponded to 68.56 Mha (11.9% of all areas identified as frontiers), and was most prevalent within North America (for example, Sierra de la Laguna dry forests), South America (for example, Tumbes–Piura dry forests) and Australia (for example, New Caledonia forest-savanna).

Fragmented frontiers are active frontiers producing highly fragmented woodland loss patterns, mainly in Africa (for example, Southern and Western Congolian forest-savanna) and South America (for example, Maranhão Babaçu forests and Lara-Falcón dry forests). This archetype covered about 114.43 Mha (19.8% of all areas identified as frontiers).

Looming frontiers are frontiers emerging at slow-to-medium speed (Fig. 5 and Supplementary Fig. 4). This archetype covered about 91.82 Mha (15.9% of all areas identified as frontiers), and was most prevalent within Africa (for example, Guinean and Victoria Basin forest-savanna) and Australia (for example, New Caledonia dry forests).

Finally, rampant frontiers refer to rapidly advancing frontiers in situations with high baseline woodland and high woodland loss. This archetype expanded over about 24.3 Mha (4.2% of all areas identified as frontiers), and such frontiers were most prevalent within South America (for example, Dry Chaco and Chiquitano dry forests), followed by Asia (for example, Southeast Indochina and Southern Vietnam lowland dry forests). The remaining areas classified as frontiers in tropical dry woodlands regions, but not falling into one of our five archetypes, corresponded to about 202.92 Mha (35.1% of all areas identified as frontiers).

Social-ecological characteristics of frontiers. To characterize the social-ecological context of our identified frontiers, we described them according to a set of spatial determinants, selected based on prevalent frontier theories (see Methods). Specifically, we determined the key characteristics of our frontiers based on proximate drivers of woodland loss, capital inputs to farming (captured by field size), market integration (captured by accessibility) and agroecological suitability (Figs. 2–4 and Supplementary Fig. 6). Inactive frontiers mostly showed patterns of smallholder agriculture, very small field size, very low accessibility and marginal suitability (Fig. 6). Consolidated frontiers mostly showed patterns of smallholder agriculture, large field size, very high accessibility and marginal suitability. Fragmented frontiers mostly showed patterns of smallholder agriculture, very small field size, very high accessibility and marginal suitability. Looming frontiers mostly showed patterns of smallholder agriculture, diverse field size, varied accessibility and marginal suitability. Rampant frontiers mostly showed patterns of commodity-driven woodland loss, large field size, very low accessibility and moderate-to-marginal suitability. Other frontiers that did...
not fall into the five archetypes shown in Fig. 6 showed patterns of smallholder agriculture, large field size, very high accessibility and marginal suitability.

**Research effort across frontier archetypes.** To assess research effort across our frontier archetypes in tropical dry woodlands, we carried out a systematic literature search and identified 155 relevant studies (see Methods). Of these, 35 and 49 studies only analysed deforestation before and after 2000, respectively. Moreover, 126 focused on national to subnational scales, and 29 studied woodland deforestation across several countries or continents. The greatest number of studies was recoded in South America (66 records), followed by Africa (52), North America (19), Asia (7) and Australia (1). The most researched ecoregions were Cerrado (36), Dry Chaco (35) and the West Sudanian savanna (23), while the least researched ecoregions were in Australia and Asia, notably Southeast Indochina dry forests (4) and Central Indochina dry forests (5; Supplementary Fig. 8). Assessing the relative research effort across our types and archetypes showed that rampant frontiers received the most research attention, while the least researched archetypes were inactive frontiers (Supplementary Table 3). Research in South America showed a positive bias towards rampant frontiers, while in the other continents this bias was negative (Supplementary Table 3).

**Discussion**
Tropical dry woodlands are under high and rising pressure globally, yet have been neglected by sustainability research, policymaking and planning. In this study we have developed a generalizable approach to detect, map and describe deforestation frontiers in high spatial and temporal detail. Applying this approach to all tropical...
Dry woodlands globally yielded four major insights. First, the loss of woodlands is widespread, with more than 71 Mha of tropical dry woodlands lost since 2000 and one-third of all woodland areas within deforestation frontiers. However, existing research efforts have focused mostly on deforestation in the humid tropics with only a few studies in tropical dry woodlands, highlighting the urgent need to ramp up research there. Second, rampant frontiers are widespread and chiefly associated with expanding commodity agriculture, which, given the rising demand for agricultural commodities, suggests that pressure on these woodlands will continue to stay high. Third, much of the world’s tropical dry woodlands fall into early frontier stages, with many emerging frontiers in Africa, most of which remain overlooked and understudied. Together, this emphasizes the need for monitoring and forward-looking sustainability planning in those regions as frontier dynamics unfold. Finally, despite the high diversity in deforestation speed, patterns and drivers in frontiers, we identified five common, high-level archetypes of frontier dynamics that occur globally. These archetypes provide a basis for comparative research and cross-regional learning in sustainability science. More generally, our frontier metrics and typologies provide a flexible, repeatable and scalable approach to foster more context specificity in research, policymaking and land-use planning in frontier regions.

Deforestation frontiers occurred in a third of our study area, leading to the loss of over 71 Mha of tropical dry woodlands over the period 2000 to 2020. Over the same period, about 147 Mha of tropical moist forests were lost. Yet, despite major woodland losses and the huge social-ecological impacts these losses entail, research efforts have been lagging behind those in other threatened regions, such as tropical moist forests. Moreover, among understudied active frontiers in tropical dry woodlands, those in Africa and Asia are particularly under-researched compared with old frontiers in South America. This geographic bias can be explained by structural inequalities in research institutions, access and agendas across continents, the preferences of funding organizations and the fact that general deforestation studies often do not separate dry and moist ecosystems. Fostering tropical dry woodland research, particularly on Asian and African frontiers, would allow for timely policy and management responses in these threatened ecosystems.

Our second main finding was that rampant frontiers were mostly associated with conditions typical for capitalized commodity agriculture (commodity-driven woodland loss representing most of the deforestation, large field sizes, higher agroecological suitability and low accessibility areas). Commodity production drives rampant frontiers in several of those regions, such as the Dry Chaco, where export-oriented soybean production and cattle ranching have created one of the world’s most severe deforestation hotspots. Commodity production is likely a key frontier driver in less well researched regions, such as the Chiquitano forests, Venezuelan Llanos or Indochina dry forests. It is well recognized that commodity production, particularly for international markets, is increasingly driving tropical deforestation. Actors operating in commodity frontiers typically have the capital to overcome accessibility constraints, operate over large areas to leverage internal economies of scale, are active across international borders and target remote regions where land prices are still low. Policy responses, such as land-use planning, often lag behind in rampant frontier regions, and when frontiers slow down due to local resistance, regulation or spatial constraints, land-use pressure might be displaced to other regions. Rapid regulatory action should therefore be deployed in rampant frontiers, combining area-based interventions (for example, zoning and native habitat protection) as well as actor-focused ones (for example, supply chain agreements).

Many African frontiers were classified as fragmented or inactive frontiers, associated with conditions typical for smallholder regions (high prevalence of smallholder agriculture and small field sizes). Smallholders use land for subsistence, employment and income through the exploitation of forest resources or the expansion of small-scale agriculture that feeds both local and global markets. Fragmented frontiers thus likely represent active frontiers driven by smallholders and occur mostly in more accessible areas. In contrast, inactive frontiers are no longer active and might reflect pioneer efforts to advance to poorly accessible areas. Such inactive frontiers could also indicate areas where initial waves of resource exploration have built a technical, social or institutional basis for future, rapid reactivation. The final archetype identified was consolidated frontiers, where frontier dynamics slow down due to the scarcity of remaining forest. This archetype was common in South America, where some regions (for example, Caatinga) have a long history of deforestation.

A key advantage of our methodology is that it can uncover emerging frontiers, of which we found many, particularly in African woodlands. These frontiers emerge because of the availability of unexploited land suitable for agriculture, growing population densities, high dependency on woodland resources for energy and possible investments from actors leaving consolidated frontier regions. Frontiers in Africa currently develop under varying trends, with large-scale operations increasing in some areas such as the miombo woodlands. Within emerging frontiers, we identified an archetype of looming frontiers that develop slowly, yet are ubiquitous across Africa. Improved monitoring of woodland loss in these looming frontiers would provide early warning signs of frontiers that have the potential to become rampant. Given what is at stake, including some of the last wild places with intact communities of unique megafauna as well as vast areas where local communities depend on forests and woodlands for their livelihoods, forward-looking sustainability planning of African emerging frontiers is of the utmost importance.

Typologies and archetype approaches are a powerful tool for identifying and mapping high-level human–nature interactions. The archetype approach that we have developed can be useful for at least three purposes. First, our approach allows us to develop policy responses appropriate for specific, yet recurring contexts. For example, while in emerging frontiers there is an urgent need to focus on increasing protection and ensuring the rights of indigenous peoples and local communities, in consolidated frontiers it may be more important to plan restoration. Similarly, while supply chain measures are likely key in rampant frontiers driven by agribusiness actors, in fragmented frontiers dominated by smallholders, policies fostering local participation by recognizing local needs, knowledge and constraints could help protect remaining forests. Second, archetypes can enable learning and comparative research across geographies. For example, we can apply lessons from successful and failed interventions in South American frontiers to socially and ecologically similar conditions in Africa, or more generally to prevent leakage outcomes of policies against rampant frontiers.

Third, archetypes can be useful to build theory in sustainability science as our types and archetypes are boundary objects that can intersect with additional information, can be used to compile and synthesize case studies across frontier types or can be used to foster understanding of causal effects and mechanisms underlying deforestation frontiers. This could reveal, for instance, when and why frontiers emerge, under which conditions they become rampant or when inactive frontiers are reactivated.

We have developed a typology of deforestation frontiers for tropical dry woodlands using the best available data. Our approach is open and flexible, and while we derived our typologies for the purpose of our study, our methodology can easily be adjusted or refined to generate other typologies and archetypes for different applications. Likewise, our approach can easily absorb updated datasets to consistently trace frontier dynamics and archetypes over time. Our work adds to recent advances in global studies of deforestation frontiers.
by considering frontier dynamics, and by extending beyond only mapping deforestation hotspots (~92% of forest loss in tropical dry woodlands falls under our definition of frontiers). Nevertheless, a few limitations need to be mentioned. First, recent work has shown that tree cover in dryland areas can be under-represented\textsuperscript{18,49}. The Global Forest Change (GFC) dataset we used here is no exception and potentially underestimates tree cover at low tree densities\textsuperscript{30}. The result would be a subsequent underestimation of frontier dynamics in very sparsely wooded ecosystems. Second, the GFC dataset does not distinguish between native woodland and tree plantations. Retaining these areas is important as frontier processes in some tropical dry woodlands include the expansion of tree plantations\textsuperscript{11,51}. As a result, we cannot rule out the overestimation of frontier activeness in the few regions where tree plantations are widespread (for example, Uruguay, savanna, Vietnam lowland dry forests and southern Cerrado\textsuperscript{53}). Third, some forest loss might be due to fires, which are often an indication of the frontier-making process\textsuperscript{53,54}, but might also occur naturally. Fourth, as with any global analyses, uncertainty remains, and our results are therefore likely most insightful when interpreting the broad-scale dynamics we have uncovered across the world’s tropical dry woodlands. We explicitly caution against interpreting and analysing our results at the level of individual cells or localities. Lastly, to generate our archetypes, we qualitatively grouped frontier types, combining both deductive and inductive reasoning. This allowed us to highlight common patterns across geographies while building on prior knowledge and theories. Our analysis is open for expansion and updating as tree-loss time series grow. Currently, about 35% of frontier cells are not grouped into any frontier archetype,illustrating the diversity of frontier processes in tropical dry woodlands. This diversity is better represented in our three detailed thematic typologies.

Deforestation frontiers are rapidly advancing in tropical dry woodlands, driving biodiversity loss, degrading ecosystem services and impacting local livelihoods. To better understand these dynamics, we have developed an analytical and operational framework to identify recurrent frontier patterns, which we applied here to provide the first typology and map of global frontier dynamics in tropical dry woodlands. This confirmed that those woodlands are being lost rapidly, that these losses are weakly understood and poorly studied, and that particularly rampant woodland losses are associated with commodity agriculture, particularly in South America and Asia. However, our approach also uncovered the importance of emerging African frontiers, many of which remain virtually unstudied, highlighting the urgent need for more targeted research and sustainability planning. More generally, the frontier types and archetypes we identified can facilitate comparative studies of frontier development, contextualized policymaking and planning, and cross-regional learning. Our approach is generalizable and repeatable across scales, time and geographies, and its value will increase over time as forest-loss time series grow, providing an innovative tool for monitoring deforestation frontier dynamics. Together, this constitutes a major step towards governing deforestation frontiers and promoting more sustainable land use in the world’s tropical dry forests.

**Methods**

**Definition of tropical dry woodlands.** Many definitions of tropical dry forests or woodlands have been proposed\textsuperscript{54,55}. Here, we followed previous work on these systems globally\textsuperscript{56,57} and used an inclusive definition. Specifically, we focused on all forests, shrublands and savannas falling into two biomes according to the updated biome classification of Dinerstein et al.\textsuperscript{58}: (1) tropical and subtropical dry broad-leaved forests and (2) tropical and subtropical grasslands, savannas and shrublands. Within these biomes we defined woodlands as all areas with a minimum tree cover threshold of 10% in the year 2000, based on the GFC dataset. Tree cover in this dataset refers to vegetation taller than 5 m (ref. \textsuperscript{17}). Thus, all forests, shrublands and savannas exceeding this threshold are collectively referred to as tropical dry woodlands for the purpose of our manuscript.

Tropical dry woodlands are generally characterized by a marked dry season of 3 months or more, with average annual rainfall from 250 to 2,000 mm, as well as often mesotrophic soils\textsuperscript{59,60}. This results in typical, diverse vegetation structure within these woodlands, with semideciduous and deciduous trees, drought-resistant shrubs or succulents, as well as grasses. There are strong biogeographic and ecological differences between these woodlands, as tropical dry woodlands have long been a preferred zone for human settlement due to favourable agroclimatic conditions, resulting in various degrees of transformation. Tropical dry woodland regions therefore differ in terms of land-use history, dominant land-use practices or different use of fire as a management tool\textsuperscript{61}. Here, we defined a tropical dry woodlands as an area where woodland regions have retained much fauna, such as elephants or giraffes, which can substantially impact on vegetation patterns, while megafauna has been lost from other regions historically or recently\textsuperscript{62}.

A major activity in tropical dry woodlands is agriculture, including cropping and rearing livestock. Agriculture has caused major transformations of these regions, both historically and recently\textsuperscript{63}. Historically, these transformations were often driven by subsistence agriculture and the cultivation of staple crops (e.g. maize), using fire as a management tool\textsuperscript{64}. While subsistence agriculture still dominates over large swathes of tropical dry woodlands\textsuperscript{65,66}, land-use change in many of these regions today is driven by market-oriented actors expanding industrial agriculture to produce commodities for domestic and international markets\textsuperscript{67}. This has caused major tropical dry woodland loss in many regions, including the South American Chaco and Cerrado (for example, soy, maize and beef), Indochina dry forests (for example, rubber and coffee) or Zambia (for example, tobacco and cotton), which have recently experienced some of the highest deforestation rates worldwide\textsuperscript{68,69}.

Tropical dry woodlands are additionally exploited for their forest resources, including firewood and timber extraction, as well as charcoal production\textsuperscript{70}. Firewood remains an important energy source in many countries of Africa, translating into a major driver of woodland loss there\textsuperscript{71}.

**Developing a typology of deforestation frontiers.** To typify deforestation frontiers in tropical dry woodlands, we developed a four-step analytical framework (Fig. 1).

In step 1, to map deforestation frontiers in tropical dry woodlands, we relied on baseline tree cover and annual tree-loss time-series data from 2000 to 2020 from the GFC dataset\textsuperscript{17}. We aggregated the data from 30×30 m\textsuperscript{2} resolution to a resolution of 3×3 km\textsuperscript{2}. The GFC dataset has an overall accuracy of >99% (ref. \textsuperscript{17}), and aggregating these data to a lower resolution increases accuracy further\textsuperscript{66}.

The aggregation resulted in an annual time series of woodland loss for the period 2000 to 2020 at an unprecedented spatial and temporal resolution of analysis of deforestation frontiers. Our subsequent analyses were based on this annual tree-loss time-series. Our tree-loss analysis included both woodland conversion and degradation processes, which we jointly refer to as deforestation. We did not include tree-gain data from GFC because (1) these are not available annually, (2) are not available for our full analysis period, (3) are less accurate than tree loss and (4) lump together gains in tree plantations, tree crops and natural woodland regrowth\textsuperscript{72}. Although assessing tree cover gain in frontiers would be interesting, there is currently no robust dataset allowing us to do this at the spatial and temporal resolution of our analysis. To identify areas potentially qualifying as frontiers, we first selected all cells that had more than 5% of forest cover in 2000, to exclude areas with very low initial forest cover and with little potential to display frontier processes. Next, we selected cells that had an average annual percentage of forest loss of at least 0.5% within a consecutive 5-year period\textsuperscript{17}. This ensures potential frontier areas are in line with the common conceptualization of frontiers as progressively expanding\textsuperscript{73} and through this causing considerable forest loss.

In step 2, to characterize deforestation frontiers, we created a set of frontier metrics based on our aggregated time series of woodland loss and cover. These frontier metrics go substantially beyond conventional change analyses as they represent multiple facets of frontier expansion, allowing for a deeper characterization of frontiers in space and time. Specifically, we derived metrics capturing (1) the severity of the frontier (that is, the percentage of total woodland loss and baseline woodland), (2) the spatio-temporal pattern of frontier development (that is, the speed and fragmentation of woodland loss) and (3) the development stage of frontiers (that is, frontier activeness and woodland left). We calculated the percentage of total woodland loss by dividing total woodland loss by baseline woodland, where the latter is woodland cover in the year 2000. We calculated speed as the maximum rate of change of woodland loss through the time period, and fragmentation as the maximum value of edge density of the spatial pattern of woodland loss through the time period. We categorized the activeness of the frontier based on when in the time period the frontier was detected. Finally, we considered the extent of woodland left after the period of woodland loss analysed (Supplementary Text 1 and Supplementary Fig. 2).

In step 3, we combined the frontier metrics into three thematic typologies. To do so we first classified each metric into three classes based on the available literature when available (Supplementary Text 1). Our first thematic typology focuses on severity, and we combined baseline woodland with the total percentage of total woodland loss to show the accumulated impact of the frontier over the period analysed. The rationale for this typology is that the accumulated impact of deforestation frontiers can result from the varied ability of frontier actors to cause deforestation\textsuperscript{74,75}. The second thematic typology focuses on the development pattern, where we pared speed and fragmentation to show how frontiers progress. The rationale is that the spatio-temporal patterns in frontiers result from
Different contexts underlying forest expansion. For instance, commodity-driven frontiers might result in faster and less fragmented forest progression, given their higher access to technologies and capital. Our third thematic typology represents the frontier development stage, where we portray the activation of the frontier with the amount of forest left to understand when a frontier is active and the potential of further frontier activity. This typology further allows us to indicate the status of a frontier in a pre-to-post frontier gradient. To identify frontier types for each of our three thematic typologies, we classified each frontier metric into three subcategories. This classification follows former frontier studies and a set of heuristic rules that best represent the variability in our metrics. The combination of metrics and their subclasses in pairs yielded nine frontier types per thematic typology (further information on each metric is provided in Supplementary Text 1).

In step 4, we qualitatively grouped frontier types into a second level of high-level frontier archetypes by combining specific types, based on the most prevalent types and insightful combinations thereof, potentially reflecting distinct mechanisms of frontier development, and configurations of commodity frontiers, post frontiers, smallholder frontiers and pioneer frontiers. These archetypes were built to provide a coherent understanding of the most common frontier patterns, complementing the full description of frontiers captured by the typologies. Thus, not all frontiers are included in our archetypes, and future studies could adjust our archetypes to highlight different, or more, archetypes based on the specific goals of the analyses. In other words, our archetype exercise is an approach that can be purposefully adapted, and our implementation serves as an example. Finally, we quantified the occurrence of frontier types and archetypes, as well as of the total area occupied by frontiers. We further quantified the proportions of frontier types and archetypes within continents and ecoregions. For visualization purposes, in the frontier types and archetypes maps (Figs. 2–5), we applied a moving window calculation based on the modal value of neighbouring 3 × 3 grid cells. The combination of our thematic typologies (step 3) and our archetypes (step 4) allows us to study complexity in frontier processes and explore emerging patterns at high thematic resolution while identifying high-level, recurring frontier archetypes with high generalization potential.

Characteristics of deforestation frontiers. To further characterize our frontiers, we identified a set of spatial determinants (Supplementary Text 2), building on theories of frontiers, land rent theory and location theory. We used four global datasets. First, we used a classification of the dominant drivers of tree loss (for example, commodity-driven forest loss). Second, we used a dataset on field size, as large field sizes proxy capital inputs to farming. Third, to characterize market accessibility, we used a dataset on travel time to cities. Finally, we used a dataset that proxies agricultural suitability via the summed agroclimatic potential for low-input, rain-fed agriculture of main crops and commodities. For the forest-loss driver’s dataset, particularly in Africa, the class ‘shifting agriculture’ encompasses various forms of subsistence and market-oriented forms of agriculture practised by smallholders. In Africa specifically, the importance of shifting agriculture in a strict sense has been decreasing recently. We thus refer to the shifting agriculture class as ‘smallholder agriculture’ in our manuscript, encompassing shifting agriculture as well as other forms of smallholder agriculture. Each characterizing variable had five categories (Supplementary Text 2). We overlaid the deforestation frontier types with all spatial determinants. We extracted the median value of each spatial determinant per pixel of analysed frontiers and then calculated the share of each spatial determinant category for each type and archetype. The dataset of dominant drivers of forest loss did not overlap with 5.4% of our frontiers, and the field size dataset with 54.70% of our frontiers. For each combination, frontiers with no overlap are not displayed in the results.

Research effort across frontier types. To evaluate past research effort on deforestation in tropical dry woodlands, and how this research effort relates to our frontier types, we carried out a systematic literature review following the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) approach. We selected a set of keywords characterizing the object of study (tropical dry woodlands) and process studied (woodland loss). We tested keywords interactively in the Institute for Scientific Information (ISI) Web of Knowledge. We finally used the following search string: "("Frontier" OR "Defore") AND ("Dry Forest" OR "Savanna" OR "Dry tropical forest" OR "Woodland")", We searched the ISI Web of Knowledge (https://www.webofknowledge.com) and Scopus (https://www.scopus.com) databases using these keywords in July 2019, the search yielding 2,146 records. We removed duplicates, leaving 1,439 records (Supplementary Fig. 7).

We then reviewed the remaining records using an inclusion criterion by reading, depending on necessity, the title, abstract and then the full text. The inclusion criteria retained papers that quantitatively or qualitatively analysed forest loss in our study area. We included papers that directly or indirectly calculated or inferred forest loss to analyse other social-ecological components (for example, carbon storage) if the forest-loss data were disclosed. We finally selected 155 records for further analysis. Next, we reviewed the full text of each of these records to classify each record on geographical location, ecoregion studied, and spatial and temporal scale of the analysis. We cross-referenced these records to ecoregion resolution. To relate frontier archetypes with research effort, we compared the occurrence of each ecoregion’s frontier archetypes with the number of studies per ecoregion. For that, we calculated the weighted occurrence of archetypes by the number of studies by multiplying the share of archetypes by the share of records found in each ecoregion. We then summed the ecoregion-level weighted occurrences by archetype and divided it by the total share of archetype and by continent, resulting in the research effort bias by archetype and by continent, respectively.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
All datasets used here are publicly available and are referenced. Data outputs from this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.6141799. The methodological steps are described in the Methods and Supplementary Information.

Code availability
The code used for the development of frontier metrics, typologies and archetypes in this study is permanently and publicly available on Zenodo at https://doi.org/10.5281/zenodo.6141799.

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The authors declare no competing interests.

### Additional information

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- For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection  No software was used to collect data.

Data analysis  Forest loss was summarized in Python 3.8, deforestation frontiers metrics were calculated and typologies developed in RStudio 1.3.1056. Types and archetypes analyses were plotted with ggplot2 and alluvial. Maps were made using ArcMap 10.5. Literature review was conducted in MAXQDA 2020 and results summarized in MS Excel. The code used for the development of frontier metrics, typologies and archetypes in this study is permanently and publicly available on Zenodo at https://doi.org/10.5281/zenodo.6141799.

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Datasets used in this analysis are publicly available from the references provided within the paper. Forest cover and loss data are available at: https://data.globalforestwatch.org/. Accessibility data are available at: https://www.edenextdata.com/?q=content/jrc-accessibility-map-estimated-travel-time-nearest-city-population-50000; Agricultural suitability data are available at: https://www.gaez.iiasa.ac.at/; Drivers of forest loss data are available at: https://data.globalforestwatch.org/; Field size data is available here: https://pure.iiasa.ac.at/id/eprint/15526/. Ecoregion data is available at: https://ecoregions.appspot.com/. Data outputs from this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.6141799.
Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

| Study description | We developed and mapped deforestation frontier metrics at 3 km spatial resolution in tropical dry forest and woodlands for the period between 2000 and 2020. Deforestation frontiers metrics were combined to yield typologies and archetypes of deforestation frontiers. Types and archetypes were overlayed with spatial determinants of deforestation frontiers and results summarized. A literature review was conducted to evaluate the spatial distribution of past research effort on TDF deforestation. |
| Research sample | There was no sampling, as we have continuous coverage data (i.e., maps). |
| Sampling strategy | Sampling strategy is not relevant for this study. |
| Data collection | We collected and integrated data from a variety of sources, which are needed to reproduce results presented in this work. |
| Timing and spatial scale | The forest cover and loss product cover the period between 2000 to 2020 and at 30m resolution. Dominant drivers of forest loss cover the period 2001 to 2015 at 10 km resolution. Global field size map was for the year of 2015 at 1km resolution. Agricultural suitability data was available for the period baseline 1961-1990 and at a five arc-minute grid-cell resolution. Global map of travel time to cities to assess inequalities in accessibility was available for the year of 2015 at 1 km resolution. Analyses were conducted at a 3km resolution, and cover tropical dry forests and woodlands worldwide. |
| Data exclusions | No data were excluded from the analysis. |
| Reproducibility | The study is fully reproducible by acquiring necessary datasets and applying the same methodology, or by re-running developed custom code. |
| Randomization | Randomization is not relevant for this study. |
| Blinding | Blinding is not relevant as no experiments were involved. |

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| Materials & experimental systems | Involved in the study |
|---------------------------------|-----------------------|
| n/a                             | ☑ Antibodies  ☐ Eukaryotic cell lines  ☑ Palaeontology and archaeology  ☑ Animals and other organisms  ☑ Human research participants  ☑ Clinical data  ☑ Dual use research of concern |

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|---------|-----------------------|
| n/a     | ☑ ChIP-seq  ☑ Flow cytometry  ☑ MRI-based neuroimaging |