The Landscape Ecology of Swidden: A Global Comparison Indicates Swidden Landscape Mosaics Contribute to Vegetation Diversity at Intermediate Levels of Disturbance

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Abstract

Purpose: Swidden agriculture is one of the most significant agricultural developments in human history and it has major ecological implications for the structure of the landscapes where it is practiced, yet it has long been theorized to be a primary cause of deforestation. Few studies have explored the structure of swidden mosaics and its relationship to vegetation diversity over large spatial scales.

Methods: We classify satellite imagery from 18 swidden societies in the African, SE Asian, and American tropics using a random forest model and a segment anything model. We use landscape metrics to describe variation in the composition and configuration of swidden mosaics and develop a nonlinear Bayesian model, accompanied by general mathematical solution, to model the relationship between the local structure of swidden disturbances and vegetation diversity measured from spectral variation.
Results: Our analysis shows that swidden landscapes can be distinguished by their spatial entropy, connectivity, and patch synchronization. Our modeling results show that amid this variation, several swidden landscapes exhibit a nonlinear relationship in which vegetation diversity peaks at intermediate levels of swidden disturbance.
Conclusion: By using approaches from landscape ecology to study the heterogeneity of swidden mosaics, we provide evidence that swidden practices can change landscape structure in ways that increase vegetation diversity when the scale of swidden disturbances occurs at an intermediate level. We suggest that this conclusion provides new insights into the potential environmental outcomes of swidden cultivation which may have significant theoretical implications for interpretations of human paleoecology during the Holocene, and contemporary issues of sustainability.

Keywords: swidden agriculture, landscape structure, human disturbance, Bayesian modeling

1 Introduction

Swidden agriculture is one the oldest and most widespread agricultural techniques still in use today. Supporting between 200 million [1] and 1 billion [2] people throughout tropical and temperate forest ecosystems, swidden has major ecological implications for the structure of the landscapes where it is practiced. Our current understanding of the landscape structure of swidden mosaics is based primarily upon small-scale case studies, which provide context to these practices [3, 4], or large-scale analyses that provide estimates of aggregate swidden activity across a nation [5] or the planet [6, 7]. Relatively few studies have focused explicitly between these scales by comparing the landscape structure across swidden societies using tools from landscape ecology like landscape metrics [8].

Understanding how swidden agriculture shapes the configuration and composition of landscape structure is critical for supporting both conservation and Indigenous and rural livelihoods [9]. Agricultural practices which create complex landscapes are more likely to support plant and animal diversity [10]. Indigenous communities, many of whom practice swidden, steward an estimated 36% of intact forests [11]. Several ethnographic studies have documented substantial plant diversity within swidden landscapes [12–14], suggesting a link between histories of swidden disturbance and the emergence of diverse vegetation mosaics [15, 16]. The diversity of crops swidden farmers cultivate may offer some immediate ecological benefits [17], however swidden alters landscape

structure in significant ways that may offer unique dispersal and foraging opportunities that support flora and attract fauna [18, 19] due to the increased prevalence of unique ecotones [20].

Previously published work from southern Belize provided a comprehensive description of mosaic spatial structure and showed that the greatest levels of vegetation diversity can occur when swidden activities disturb forests at an intermediate scale [21], creating a landscape mosaic that contains a mixture of mature forest and anthropogenic vegetation classes. The purpose of this study is to test whether this relationship between disturbance and vegetation diversity is found in other swidden mosaics across the world's tropics. To do this, we address two research questions:

1. What are the structural characteristics of swidden landscapes and how do they vary?
2. What is the relationship between localized disturbances and vegetation diversity in tropical swidden mosaics?

1.1 Swidden as a Disturbance Regime

Swidden, also known pejoratively as "shifting cultivation" or "slash-and-burn", is a farming method that involves clearing forested land by cutting and burning vegetation. This technique is commonly used in tropical landscapes with poor soils, where the ash and mulch from cleared vegetation are used as soil amendments. New clearings are usually cultivated for 1-3 years before farmers move to a new location. When a field is abandoned, forest succession takes over. Successional forests are used by humans for foraging and hunting, and are sometimes managed to encourage the recruitment and productivity of a diverse range of useful and economically valuable plants [22, 23]. How long succession proceeds before an area is cleared and cultivated again is sometimes called the "fallow period", and is a subject of debate in the literature on swidden [24–26]. In general, fallow periods are longer than the period of cultivation, and typically range from 5 to 20 years. Thus, swidden is an anthropogenic disturbance regime characterized by periodic disturbance events that align with seasonal agricultural cycles. While swidden disturbances occur more frequently than many natural disturbances [27], each event is brief compared to the time the forest requires to regenerate.

Studies of the effects of swidden on local ecology are plagued by the *a priori* assumption that swidden is an external, destructive force on the local ecology [17], and this bias can lead to ill-conceived arguments about the effects of swidden. For example, a recent study found a correlation between the proportion of threatened and endangered species habitats and home ranges, and areas of human activity, including swidden, and concluded that "...shifting agriculture causes forest degradation" and that expansion of protected areas is necessary to stop it [28]. Arguments of this kind are examples of the *unraveled rope problem* [29]: a class of arguments about conservation that are ultimately defective due to the fallacious relationship they draw between empirical results and the normative premise(s) and values that underlie their conclusions. One such fallacy is the *derelict normative premise* [29] in which an argument fails to elaborate key premises or alternative premises that are plausible given the empirical

results. Although [28] provide considerable empirical detail regarding the spatial overlap of species habitats and human activities, their argument fails to consider an equally valid normative premise: the extensive overlap of endangered species habitats and swidden activities can arise if these regrowing forests offer access to ecotones that cannot be found in mature forests alone. In fact, there are numerous empirical examples and reviews of how swidden can positively influence flora and fauna [16, 17, 30–33].

A second fallacy is *ironic community bias* [29], which occurs when a research community holds biases that ultimately lead to study designs that reinforce the bias while at the same time generating results that oppose it, thus making it ironic. According to [29], this arises most often when researchers arrive at conclusions on a small-scale and use them to make inferences at a much larger scale. This a common design in studies of swidden that compare levels of diversity within primary and secondary forests, often finding that one has more or less diversity than the other [e.g. 34]. Based on this comparison, a conclusion is reached regarding the value of primary or secondary forests for supporting biodiversity, generally. What makes this argument ironic is that such studies frequently report species that do not overlap between the two land classes [35], effectively demonstrating that the overall landscape that contains *both* classes is the most diverse condition. In fact, long-term studies of forest recovery have confirmed that while the species composition differs in secondary and primary forest, they often have comparable levels of species richness [36, 37]. We can overcome this bias by embracing that idea that (anthropogenic) landscapes can be highly complex mixtures of vegetation with important ecological dynamics that are obscured by categories like disturbed versus undisturbed, or primary versus secondary [38].

We appreciate that a potential reason the *unraveled rope problem* dominates our understanding of swidden is the difficulty of linking landscape level patterns to local ecological outcomes. Studies which have found that swidden benefits local flora and fauna rely on field inventories which are context specific and challenging to generalize. Studies of aggregate swidden activity can also have a limited capacity to comment on local plant and animal diversity. Recent efforts to overcome this have led to the development of improved proxy measures, including tools which quantify plant diversity using satellite imagery [e.g., 39]. The spectral variation hypothesis proposes that variation in plant morphology produces distinct spectral signatures that can be used to a calculate a proxy measure of plant diversity called spectral diversity [40, 41]. Studies testing the validity of spectral diversity find that it typically correlates with functional diversity and is especially useful in the study of forest mosaics [42]. Although this approach is not without limitations (such as the underappreciated influence of intraspecific trait variation [42]), it is a promising approach for linking structural patterns and plant diversity at a landscape scale. This is precisely the kind of methodological advancement that is needed to better understand how swidden influences local ecologies.

However, it is also evident that our current theories of swidden struggle to contend with it's dynamism [17, 25]. In our own work, we have conceptualized swidden as a complex adaptive cultivation system with integrated sociocultural, economic, and ecological dynamics. We have shown elsewhere how cultural norms [43] and social networks [44] influence swidden disturbance patterns [21], leading to a recently developed

complex adaptive systems model that formalizes these dynamics [45]. This study contributes to the burgeoning literature on swidden agriculture by describing how the landscape ecology of swidden agriculture relates to complexity theory.

1.2 The Landscape Ecology of Swidden: Disturbance, Scale, and Complexity

Landscape structure refers to the observable patterning of spatial patches within a landscape and is a critical dimension of landscape heterogeneity. As stated by Turner [46, 174], the "spatial patterns observed in landscapes result from complex interactions between physical, biological, and social forces.... This spatial patterning is a unique phenomenon that emerges at the landscape level." Structural patterns are described by analyzing the composition (types of elements present) and configuration (spatial arrangement) of distinct landscape elements at a particular scale [47]. In swidden systems, the spatial scale of the landscape is defined by the spatial extent of the biologically and technologically constrained human activities that drive these patterns, and by the spatial extent of the ecological dynamics that regulate forest succession. A swidden landscape includes the entire set of distinct successional vegetation classes, sometimes called "fallow stages", that emerge within a matrix of mature forest as swidden is practiced over time [48].

Swidden landscapes exemplify how disturbance fuels landscape heterogeneity. Swidden activities produce mosaics of active farms, successional vegetation, and mature forests that arise from cycles of disturbance, cultivation, and forest succession. A swidden disturbance is a discrete clearing event that resets succession locally and reshapes the geometry of a forested landscape by temporarily reducing plant biomass [49]. Over time, newly created patches contribute to the evolving mosaic. This growing heterogeneity could contribute to biodiversity at the landscape level [50]. For example, Balée [13] documented the farming practices of Indigenous Ka'apor people of the Brazilian Amazon, showing that the combination of fallows and mature forest is more diverse than mature forest alone. This is possible because each patch exists within a matrix of other vegetation classes that serve as reservoirs of plant species that may disperse into a new clearing [51]. The local configuration of adjacent vegetation classes creates ecotones that offer additional niche fulfillment opportunities, further enhancing biodiversity potential [20].

Studies examining anthropogenic disturbance and landscape structure at a comparable scale to swidden are typically embedded within analyses of land cover change, fragmentation, and deforestation [cf. 52]. For example, de Oliveira and Metzger [53] used aerial imagery from the Amazon to track the development of three anthropogenic landscape patterns over time (some of which arise from swidden): fishbone, independent settlement, and large property. Although they focused primarily on the rate of deforestation, they also emphasized the importance of structural characteristics like patch aggregation, core area size, and connectivity in maintaining ecological integrity and facilitating species dispersal [see also 4, 54]. They explain that fishbone patterns – fields and residences placed along roads and river systems – as well as independent settlements – pseudo randomly distributed fields and residences – are much more likely to maintain these structural features when the proportion of forest (p_c) remains greater

than 0.6 (although beneficial outcomes are still possible at $0.4 \leq p_c \leq 0.6$). Below these thresholds, percolation theory – a mathematical theory that describes how landscape structure changes as patches are added or removed – predicts the emergence of large connected clusters of bare land and a critical transition of the landscape to an degraded state.

Contemporary theories of forest landscapes are now rooted in complexity science, which identifies tropical forests as prototypical examples of complex adaptive systems [55, 56]. This perspective has existed for many decades [57, 58], and has recently been accepted as a fundamental lens through which the study and management of forested landscapes can be viewed [59]. Complex adaptive systems are characterized by feedback relationships and nonlinear dynamics, which are relevant to swidden agriculture and landscape ecology. For instance, decisions about where and when to clear new fields are made by individuals or households during each agricultural season and these localized, adaptive decisions exert tremendous influence over the disturbance patterns across the landscape [60]. The resulting mosaic serves as the context for subsequent agricultural decisions [see 45], creating feedback loops that drive a recursive process with the potential for emergent patterns. Emergence refers to the idea that local processes can lead to global patterns with characteristics that are qualitatively different from those at the local level, and therefore cannot be fully explained in terms of just these local patterns [61]. The shifting steady state mosaic concept, for example, recognizes that disturbance processes can alter the state of a patch locally, while leading to an emergent steady state mosaic at the level of the landscape [62–64]. The presence of emergent properties in swidden mosaics makes it possible to analyze them at the scale at which they occur, much like we can describe a moving object in terms of its velocity without specifying the particular arrangement of the molecules that make up the object [65].

Tropical forests fluctuate dynamically [66]. Disturbance and self-organization are critical to this dynamism and – together with geomorphology [51] – they drive the configuration of landscape patterns. Self-organization refers to local interactions that produce emergent complexity in the absence of top-down forces [55]. It also means that the specific state or configuration of a forest is impossible to predict due Lorenz' famous "butterfly effect", more formally known as a sensitivity to initial conditions [67]. In tropical ecosystems, competition and dispersal drive local biotic interactions and the self-organization of ecological communities. These processes underlie the functioning of forest ecosystems, and disturbances can catalyze or stifle them [68, 69], an outcome which depends on the scale of disturbance. The Intermediate Disturbance Hypothesis (IDH), posited by Connell [70], argues that an intermediate size and frequency of disturbance can encourage forest productivity and biodiversity.

The IDH is the subject of extensive debate, with disagreements surrounding both its theoretical conception and empirical validation [71, 72]. The IDH posits that an intermediate spatial and temporal scale of disturbance could encourage more diverse and productive landscapes if disturbances disrupt competitively dominant species without disrupting species dispersal. Disturbances that raise the average mortality of dominant species create opportunities for the recruitment of less dominant species [71, p. 88], thereby promoting diversity at the landscape level. This is possible in swidden

agriculture, specifically because of the spatial extent, temporal frequency, and intensity of swidden disturbances. Defining the scale of disturbance (and thus, what "intermediate" means) is critical to understanding swidden and its effects on landscapes [73]. Large-scale disturbances on the order of thousands or even millions of hectares can obliterate competition and dispersal networks, creating novel, homogenized ecosystems governed by qualitatively different forces [63, 74]. Small-scale disturbances like herbivory or tree falls often fail to sufficiently disrupt competitively dominant species. New swidden fields are typically no larger than 2 hectares, however the total hectares disturbed by all fields can vary considerably based on population size. At its most frequent, these disturbances are annual. Most importantly, while swidden removes biomass from a forest, this is done intentionally using cool, prescribed fires because hot, severe burns would undermine one of the primary objectives of burning – to amend tropical soils [75, 76].

We hypothesize that swidden mosaics which exhibit emergent complexity will have a quantitative signature that can be identified by the shape of the curve that relates local disturbance to vegetation diversity, with a unimodel curve opening downward providing support for the IDH. In our previous work, we found that an intermediate level of disturbance from swidden was associated with greater vegetation diversity in southern Belize [21]. This result prompts us to investigate the landscape structure of swidden mosaics more generally and determine whether the disturbance curve we observed in Belize is a general feature of swidden landscapes across the planet.

2 Methods

2.1 Sampling and Data Acquisition

We reviewed the ethnographic literature and identified 18 sites in several key areas of Central and South American neotropics, equatorial Africa, and southeast Asia where swidden is known to be practiced. We collected variables from published literature and publicly available datasets to contextualize each site (Table 1). Using geographic information provided in this literature search, we obtained 4-band remotely sensed Planetscope imagery from Planet Labs [77], which provides weekly (and in some cases daily) images around the world at resolutions as fine as 3.125 m^2 pixels. Crucially, Planet Labs standardizes all images upon download, making it possible to compare imagery taken in different regions at different times. We centered spatial coordinates on a focal settlement and drew a 50 km^2 circular area of interest to encapsulate the surrounding swidden mosaic.

Table 1: Description of sites.

Site (Code)	Ethnicity, Indigenous heritage	People per km^2	Time to nearest major city	Mean field size (SD)	Crops	Market production	Land tenure

Crique Sarco, Belize (BLZ_CRS)	Q'eqchi' Maya, Mopan Maya	1.83	4-6 hours	0.60 (1.82)	Maize, yucca, sweet potato, yam, chile pepper, cacao, pineapple	Limited	Legally recognized communal land
Bao Vista do Calafate, Brazil (BRA_BVC)	Ribierinhos	0.74	1-2 days	0.27 (0.42)		Limited	State-owned, locally managed as common property
Banzoum, Central Africa Republic (CAF_BZM)	Baka	19.88	61-90 minutes	0.18 (0.39)	Limited	Customary land tenure	
Nganda, Democratic Republic of Congo (COD_NGD)	Yaka	354.16	<30 minutes	0.29 (0.89)	Cassava, maize, plantains, yams, sweet potatoes, taro	Limited	State-owned, locally managed
Souanke, Democratic Republic of Congo (COD_SOU)	Baka	2.68	8-12 hours	0.13 (0.28)	Plantain, cassave, cocoyam, maize, tobacco, cacao	Increasing cash-crop production (e.g., cacao)	State-owned, locally managed

Mondayacu, Ecuador (ECU_MON)	Kichwa	7.32	61-90 minutes	0.26 (0.71)	Yuca, plantain, palm fruit, pineapple, citrus, chirimoya, papaya, avocado, greens	Limited	Informal communal land
French Guiana, Camopi (GUF_CAM)	Wayapi and Teko	0.8	2-3 days	0.22 (0.45)	Cassava	None	State-administered Communal User Right Zones
Kantu, Indonesia (IDN_KAN)	Dayak	3.55	12-18 hours	0.43 (1.26)	Rice, maize, various tubers and greens, fruit trees, nuts, non-timber forest products	Palm oil production, specialty items	Intergenerational cultivation rights overseen by village authority
Sulawesi, Indonesia (IDN_SUL)	Bugis, Makassarese, Torajan	25.1	2-4 hours	0.25 (0.39)	Rice and maize	Coconut oil, cacao, coffee, golf dust, and forest products	Communal ownership managed by village authority
Assanangre, India (IND_ASA)	Tibetan-Burman, Garo	52.2	4-6 hours	0.19 (0.30)	Millets, pulses, pumpkins, brinjal, cabbage, cauliflower, tomatoes	None	Informal communal land

Pak Keng, Laos (LAO_PAK)	Khmu, Hmong	7.11	4-6 hours	0.92 (1.95)	Increasing	State-owned, locally managed	
Dambana, Sri Lanka (LKA_DAM)	Wanniyala-Aetto	11.27	2-4 hours	0.35 (2.00)	Rice, maize, finger millet, manioc, beans, chiles	None	Communal ownership
Antalaha, Madagascar (MDG_ANT)	Betsimisaraka, Merina	35.4	18-24 hours	0.39 (0.86)	Rice, manioc, maize, sweet potatoes	Vanilla, coffee, cloves	Customary land tenure
Arang Dak, Nicaragua (NIC_ADK)	Mayangna and Miskito	4.6	1-2 days		Bananas, rice, plantains, manioc	Livestock	Informal communal land
Akampka, Nigeria (NGA_AKM)	Predominantly Igbo, Yoruba, and Hausa	143.26	2-4 hours	0.22 (0.51)	Cassava, yam, maize, millet	Cocao, palm oil, rubber	Communal trust with individual access rights
Nuevo Eden, Peru (PER_NUD)	Matsigenka	4.6	1-2 days	0.30 (0.48)	67 varietes of cassava, bananas, plantains, maize, peanuts, squash	Limited	National reserve

Benli, Philippines (PHL_BEN)	Hanunoo	0.15	91-120 minutes	0.33 (1.81)	Maize, rice, beans, sugarcane, sweet potatoes, bananas, papayas	None	Customary land tenure
Ibingu, Tanzania (TZA_IBG)	7.61	8-12 hours	0.56 (4.22)				

2.2 Classification

Landscape Classification. To construct maps of the swidden mosaics, we used supervised machine learning to classify each pixel as 1 of 13 classes: bare ground, recent clearing, early fallow, late fallow, mature forest, village/road, water, clouds, miscellaneous mask, palm oil fields, cattle pasture, urban, and wetland (Figure 1). We manually curated training data for each site by creating spatial polygons labeled with the respective class in QGIS [78]. With this training data, we classified all spatial images using a random forest model [79]. Classification of secondary forests in swidden mosaics is known to be a technical challenge [80], so in several sites we further refined our classifications using the segment anything model [81]. To determine the quality of the classification we used confusion matrices and accuracy statistics (Online Resource 1), and met iteratively as a group to qualitatively inspect classifications for obvious errors or artifacts. Based on these diagnostics, we added or removed training data and made adjustments that would reduce confusion and improve accuracy, while maintaining the vegetation class distinctions. With the classification complete, we focus our analysis on the structure on swidden vegetation classes 1-5 (Figure 1).

Spectral Species Classification. We use spectral diversity as a proxy for vegetation diversity. These signatures are detected through a process of radiometric filtering, dimensionality reduction (e.g., Principal Component Analysis), and spectral clustering (e.g., K-means) applied to multi-spectral imagery. We used the *biodivmapr* package [39] to classify each pixel in our raster as a one of 20 spectral species. We previously used this method to analyze a swidden mosaic in southern Belize and additional details can be found be found in the Supplementary Information of that study [21].

2.3 Landscape Metrics and Variable Calculation

To address question 1, we used the *landscapemetrics* R package [82] to calculate a parsimonious set of landscape metrics to describe landscape structure. We selected these metrics based on recommendations in Cushman et al. [83]. We focus on edge contrast, patch shape variability, contagion, juxtaposition, large patch dominance, and nearest neighbor distance/proximity. A full description of each metric and an ecological interpretation in the context of swidden is provided in the supplementary

materials (Supplementary Information, Landscape Metrics and Their Interpretations in Swidden). To describe how landscape structure varies across swidden societies, we apply a Principal Components Analysis (PCA) to the landscape metrics. Focusing on two primary axes of variation, we apply a K-means cluster analysis to partition the mosaics and identify qualitatively different mosaic categories, building on the notion of fundamental types of anthropogenic patterns described by [3].

To answer question 2, we analyzed the local patterns of landscape structure by sampling the landscape classification and spectral diversity maps. To do this, we overlaid a hexagonal grid using the *sf* package [84] onto the landscape. The size of grid cells was chosen by selecting the number of pixels spanning the distance between edges of a hexagon. Several cell sizes and placements were tested, revealing little difference in the overall patterns. Our final hexagonal grid contains cells with a 2.5km width, making them large enough to encompass an active swidden field and the surrounding vegetation classes. Within each cell, we calculated patch density P_i and the proportion of mature forest F_i. As a measure of vegetation diversity V_i, we calculate Shannon's Index in each cell and convert this value to effective species diversity (e^{V_i}) which yields values that can be interpreted similarly to species richness [85]. We create a composite measure of disturbance using P_i and F_i calculated as $D_i = \frac{P_i+(1-F_i)}{2}$. D_i ranges from 0 (low disturbance) to 1 (high disturbance). A value of 0 indicates that a hexagonal cell that contains a single patch (i.e., patch density= 0) that is 100% mature forest. A value of 1 indicates extreme patch density and zero mature forest present. Additional details about variable calculations can be found in the Supplementary Information.

2.4 Disturbance-Diversity Model

The full model specification and a discussion of priors can be found in the Supplementary Information. We model the relationship between disturbance and vegetation diversity in each hexagonal grid cell i and site u using a hierarchical Bayesian model. We model the distribution of vegetation diversity V_{iu} using the Gaussian family with parameters μ_{iu} and σ_{iu} to estimate the average and standard deviation of vegetation diversity at the site and grid cell level:

$$V_{iu} \sim \text{Gaussian}(\mu_{iu}, \sigma_{iu}) \tag{1}$$

Due to the spectral species classification procedure, the values of vegetation diversity are strictly positive real numbers that cannot exceed 20. We obtain μ_{iu} by passing predicted values of vegetation diversity γ_{iu} through a logistic link function:

$$\mu_{iu} = \frac{K}{1 + e^{-\gamma_{iu}}} \tag{2}$$

where the maximum value of spectral species is $K = 20$. In general, this function can be applied to any value of K, and when K is unknown, it can be estimated using a weakly informative prior. We model the effect of disturbance on vegetation diversity using a quadratic function:

$$\gamma_{iu} = \alpha_u + \beta_{D[u]} D_{iu} + \beta_{D^2[u]} D_{iu}^2 \tag{3}$$

where the parameters $\beta_{D[u]}$ and $\beta_{D^2[u]}$ estimate the shape of disturbance for each site u. Using this varying slopes approach allows us partially pool information across sites to estimate a global disturbance curve in addition to distinct site level curves. This model can produce a variety of functional forms that are constrained within the range of vegetation diversity that is possible given our classification procedures. Examples of possible curves are shown in Figure 2. In the Analytic Results section of the Supplementary Information, we formalize a subset of the parameter space which would indicate empirical support for the IDH. Our analytic results define the range of disturbance values ($d_1 = 0.2, d_2 = 0.8$) at which a unimodal disturbance curve must peak to support the IDH. We note that these analytic results are generic, and can be used by researchers in future analyses of disturbance in landscape mosaics.

All models were fit using the *brms* R package [86] and sampled using Markov Chain Monte Carlo (MCMC) with a no U-turn sampler implemented in Stan [87]. Using a step size of 0.999 and a tree depth of 12, all models converged with no divergent transitions on 4000 iterations and 1000 iteration warm-up period. $\hat{R}$ values for all MCMC chains were < 1.01, indicating that chains were properly mixed and bulk effective sample sizes show that the parameter space was adequately sampled.

3 Results

We observe that the average size recently cleared swidden field is less than a hectare across all sites (0.13 - 0.92 ha). Some sites, however, exhibit considerable variation (e.g., TZA_IBG [SD = 4.22 ha]). Figure 3 shows the proportion of the landscape covered by anthropogenic vegetation classes. Across all classes, an average of 45.6% of the landscape is covered in mature forest, ranging from 13.97% in COD_NGD to 82.8% in GUF_CAM. Mature forest covers more than 40% of the landscape in nine of eighteen sites.

3.1 Structural Variation across Swidden Mosaics

We focus on six essential components of landscape structure outlined by [83]: edge contrast, shape variability, contagion, juxtaposition, large patch dominance, and nearest neighbor distance. For *edge contrast*, which we measure the proportion of like adjacency (pladj), a measure of how frequently pixels of the same class are adjacent to each other. Across all sites, pladj ranges from 80% to 93%, suggesting that swidden mosaics are highly aggregated landscapes. This metric is especially high in sites which have large contiguous patches of mature forest and late stage fallow forests (e.g., NIC_ADK, PER_NUD, BRA_BVC), a scenario that is more common in our neotropical sites.

Patch shape variability characterizes the irregularity of landscape patches in space. This characteristic is measured using the mean shape index (*shape_mn*) which ranges from 1.27 to 1.39. This modest range indicates that most patches are relatively square, owing the anthropogenic nature of the swidden disturbance regime. The shape index increases without limit and greater values would indicate highly irregular shapes, such as the labyrinthine, Turing-like vegetation structures observed in arid grasslands [see 88], which do not appear to be a common feature of swidden mosaics. Variation in the shape index (*shape_sd*) is greatest in our Madgascar (MDG_ANT), Philippines

(PHL_BEN), and Democratic Republic of Congo, Nganda (COD_NGD) sites, which all contain highly connected regions of late fallows and mature forest (see Figure 1).

The *contagion* component of a landscape describes the degree of clustering of various vegetation classes. Landscapes which have high values of contagion can be described as low entropy landscapes. Here the neotropics stand out as having high levels of the contagion index (*contag*), a pattern driven by the presence of large regions of intact mature forest. Similar patterns are observed in Indonesia, Sulawesi (IDN_SUL) and Democratic Republic of Congo, Souanke (COD_SOU) sites.

The *juxtaposition* component contrasts the contagion component. Landscapes in which vegetation classes are juxtaposed may contain regions of spatial periodicity and/or the presence of vegetation "islands". Landscapes with high juxtaposition can be described as having configurations with greater spatial entropy. For example, our Nigeria (NGA_AKM) site contains small fragments of mature forest islands within a matrix of fallows. This is evident from the interspersion and juxtaposition index (*iji*), a metric which is lowest in the neotropics.

The *large patch dominance* component is quantified by the largest patch index (*lpi*) – the percentage of a landscape covered in a single patch of any vegetation class. Nicaragua (NIC_ADK) stands out as have 80% covered in a single mature forest patch. Other sites vary between 16% and 60%.

The final component looks at the proximity of patches in a vegetation class using mean Euclidean nearest neighbor distance (*enn_mn*). While many sites may have large expanses of forest vegetation and clusters, most patches tend co-occur within 100 meters of a similar patch, a pattern which likely reflects farmer decisions to plant near to one another.

3.1.1 Axes of Variation

Our first two principal component axes cover 77.4% of the variation in landscape structure. Example biplots can be found in the Supplementary Information (Landscape Metrics and Their Interpretations in Swidden). The first component is characterized by measures of aggregation and patch size (lpi, contagion, pf_prop) and measures which describe the complexity of shapes and configuration of patches in space (iji, shape_mn, shape_sd). This axis describes the spatial entropy in the landscape, with one end of the axis representing landscapes with large contiguous regions of forest surrounding fields with regular square-like patch shapes that line rivers and roadways. Our French Guiana and Nicaragua sites are characteristic examples (Figure 1, GUF_CAM and NIC_ADK). At the other extreme, Madagascar and Sri Lanka exemplify the high entropy configuration (Figure 1, MDG_ANT and LKA_DAM), although these two sites differ from one another on the second axis.

The second axis describes the density of patches and their spatial synchronization. One end of this spectrum is characterized by low patch density (pd) and greater nearest neighbor distances (enn_mn). Madagascar and Laos lie at this end of the spectrum, with new clearings that are spread out across the landscape (Figure 1, MDG_ANT and LAO_PAK). The other end of this axis is defined by high patch density with short distances between neighboring patches, a pattern that arises when new clearings are tightly synchronized in space with very small buffers between them. For example,

Sri Lanka is a high entropy landscape (axis 1) with new clearings occurring clustered together in the same region (Figure 1, LKA_DAM).

A cluster analysis of these two axes reveals some distinctive landscape configurations. Focusing on three clusters, there are 6 swidden landscapes (4 in the neotropics) that are distinguished by low spatial entropy, with patterns driven by aggregated mature forest classes and highly ordered patch configurations. The remaining 12 landscapes all exhibit moderate to high spatial entropy, but are distinguished by the level of connectivity and the degree to which disturbances are spatially synchronized. Four of these landscapes contain low patch density with highly connected patches between new clearings. The remaining 8 landscapes have moderate to high patch density combined moderate or low connectivity. These landscapes contain shorter average nearest neighbor distances, indicating that vegetation classes tend to occur closer together in space. Biplots and cluster analyses can be found in the Supplementary Materials.

3.2 Disturbance Curves

Figure 5 shows the average disturbance curve after marginalizing over the estimates from all 18 sites. At this aggregate level, the β parameters that dictate the shape of the disturbance curve indicate that, on average, the curve is unimodal and opens downward ($\beta_D = 3.13$ [$SE = 0.56$] and $\beta_{D^2} = -2.24$ [$SE = 1.03$]). However, there is considerable variation in β_{D^2} relative to β_D indicated by their respective σ parameters ($\sigma_{\beta_D} = 0.79[SE = 0.76]$ vs. $\sigma_{\beta_{D^2}} = 7.43[SE = 1.74]$). The variation β_{D^2} arises from sites with different curvature or which have fewer observations of extremely disturbed areas. These are identified in the next section.

3.2.1 Site Level Disturbance Curves

Figure 6 shows the disturbance curves for each of the 18 sites. We provide 50 draws from the posterior predictive distribution to show a range of plausible relationships predicted by fitting data to equations 2-3. Our analytic results define a region within which a unimodal peak of the disturbance curve that would provide plausible evidence of the IDH. We observe such a peak in 12 of 18 sites. Indonesia, Sulawesi (IDN_SUL) provides is a characteristic example of IDH curve. Here, the lowest levels of disturbance are associated with moderate levels of vegetation diversity that increases at intermediate levels of disturbance, and declines to 0 as disturbance reaches the maximum.

Of the six sites that do not support the IDH, two (GUF_CAM and LAO_PAK) exhibit peak diversity at low disturbance which then declines as disturbance increases. A third site (TZA_IBG) shows a relatively flat relationship at low and intermediate disturbance that becomes inconclusive at high disturbance. The final three sites are all inconclusive due to high uncertainty surrounding the β_{D^2} estimate (NGA_AKM, NIC_ADK, and PER_NUD). Both the Nicaragua and Peru sites show very low levels of disturbance in general, leading to uncertainty around the shape of the full disturbance curve, even after partially pooling information from the other sites.

4 Discussion

4.1 Common Patterns in the Structure of Swidden Mosaics

This study offers a quantitative analysis of structural patterns in 18 swidden mosaic landscapes, addressing a significant gap in the literature on the ecology of swidden. Our findings reveal that while swidden mosaics exhibit substantial variation, distinct types of mosaic patterns are discernible within this variation. Specifically, we differentiate swidden mosaics based their spatial entropy and the degree to which disturbances are spatial synchronized. Notably, sites situated within large contiguous regions of mature forest exhibited more aggregated patch structures and lower spatial entropy. This pattern is closely tied to human settlement in which fields and residences are systematically arranged along rivers or roadways within extensive undisturbed forests. This configuration resembles the "fishbone" pattern studied by De Oliveira and Metzger [53], wherein disturbances align with infrastructural or natural boundaries.

A subset of landscapes in our analysis contained moderate to high connectivity among patches of fallows and/or mature forest with swidden fields dispersed throughout the landscape. This pattern is characterized by greater nearest neighbor distances and contiguous patches interspersed among recent clearings and early stages of forest regrowth. This configuration is similar to the "independent settlement" pattern described in [53], and our findings reinforce their claim that this settlement pattern could maintain connectivity. Numerous local processes might drive this configuration. Farmers likely draw on local ecological knowledge to determine field placement, considering factors such as soil quality, geomorphology, travel time, and vegetation characteristics. Cultural practices and cosmology may also influence these decisions. For instance, Dove [1] demonstrated how Bornean swidden farmers use bird omen rituals to guide field clearance, a practice that effectively randomizes field placements. While no single set of decision rules could account for the full range of possible landscape structures, studies like Dove's [1] as well as Rappaport's [89] demonstrate that human culture can have a profound influence on local ecology and landscape structure.

The final eight sites in our analysis exhibited moderate to high patch density, shorter nearest neighbor distances, and more spatially synchronized disturbance patterns. We speculate that this pattern could be influenced by a variety of constraints, such as government regulations on forest clearing, competing land uses, and labor coordination. For example, in Sri Lanka (LKA_DAM), restrictions on forest clearing lead to compact field arrangements, while in Indonesia (IND_KAN) and Belize (BLZ_CRS), the expansion of palm oil plantations and cattle ranching, respectively, compete with swidden for available land. Labor coordination and scarcity can also shape field placements. For example, farmers may synchronize their fields to make labor sharing more convenient. When labor is scarce, farmers may reduce fallow lengths, leading to landscapes in which vegetation regenerates more slowly. This process can lead to vegetation patterns that are more synchronized in space.

4.2 Vegetation Diversity at Different Levels of Disturbance

While our measure of vegetation diversity does not directly estimate number of species or serve as a comprehensive measure of biodiversity, it provides valuable insights for large-scale analyses of plant diversity. Measures of vegetation diversity derived from satellite imagery facilitate the study of relationships between landscape structure and diversity at a spatial scale that would be impractical to survey using detailed field inventories. Spectral diversity, as measured in this study, has been interpeted as an integrated signature of functional and phylogenetic plant diversity [90], as the spectral signatures reflect variations in the functional morphology of plant species. This classification method [39] is based on research demonstrating that functionally distinct plants reflect light spectra in unique ways [40]. From this perspective, the observed pattern of peak diversity at intermediate disturbance levels can be interpreted as follows: vegetation classes that regrow after anthropogenic disturbance contain distinct types of vegetation that make significant contributions to the overall diversity of plant species in tropical landscape mosaics.

In most of the landscapes we studied, we observed a unimodal disturbance curve consistent with the IDH. If swidden tends to degrade forest landscapes, then the conventional expectation is that vegetation diversity should peak at low levels of anthropogenic disturbance and decline as disturbance intensifies. While this outcome is possible from our model, it is rarely observed. The closest example is Laos where high connectivity of fallows coincides with low levels of mature forest and low patch density, resulting in large, aggregated disturbances. These aggregated disturbance patterns can negatively impact species diversity by increasing the dispersal distances that must be traveled in order to recruit [91]. This effect could be exacerbated if new disturbances tend to be surrounded by successional vegetation with a diminished seed bank potential. We also do not observe an IDH curve in French Guiana, where disturbances are concentrated along the river's edge. Despite high diversity of mature forest in this site, the benefits of this diversity are not fully realized in the disturbed patches, as they are clustered together with minimal adjacency to mature forests. If farmers occasionally established pioneering fields farther away, these disturbed areas could be integrated with the surround diverse forest matrix, potentially enhancing vegetation diversity over time – though this could require significant labor and energy investments.

The high diversity at intermediate levels of disturbance suggests that potential benefits from anthropogenic disturbance may be more widespread in swidden landscapes that previously recognized. Notably, IDH curves were observed across a range of landscape structures identified by our multivariate analyses, including those with competing land uses. These findings suggest the importance of understanding if and how anthropogenic swidden mosaics contribute to overall diversity of tropical landscapes. Doing this requires a detailed investigation of structural patterns and a recognition of the structural variability of swidden mosaics, as well as additional research linking local patterns of biodiversity to structural patterns like those found in this study. We hope the results from this study are provocative enough to inspire further field

research in tropical regions focusing on the considerable heterogeneity of swidden landscapes that could test and validate our macro-scale model predictions and deepen our understanding of these complex landscapes.

4.3 Swidden as a Disturbance Regime: Redux

While comparing swidden to rice terraces in Java, the eminent ecological anthropologist Clifford Geertz observed:

> Any form of agriculture represents an effort to alter a given ecosystem in such a way as to increase the flow of energy to man: but a wet-rice terrace accomplishes this through a bold reworking of the natural landscape; a swidden through an uncanny imitation of it. [92, p. 16]

The tropical forests Geertz observed that led him to make this remark were not the highly fragmented, degraded, over-exploited landscapes that many associate with agricultural activities in the tropics. They were swidden mosaics, much like those that we have studied in this paper, created through agricultural practices that have persisted in tropical forests for more than 10,000 years [93, 94]. In some tropical regions, human modification of forests began 50,000 years ago [95] and this deep history is essential for understanding not just contemporary swidden practices, but biodiversity conservation in general throughout tropical environments [96]. The widespread presence of peak diversity at intermediate levels of disturbance across our study sites suggests that disturbances from swidden are an integral part of these forest ecosystems. This underscores both the potential role of the human disturbances in landscapes [97] and the approach needed to detect them; one which focuses on distributed disturbances, scale, and structure rather than aggregate disturbance and population dynamics [98].

While there have been many researchers who have noted that swidden agricultural patterns can mimic those in tropical forests [13, 92, 99, 100], the majority focus on practices like inter-planting and crop rotation that appear to resemble the understory-canopy structure of forests. While our results cannot comment on this aspect of cultivation techniques, we instead argue that these results indicate that swidden may mimic the effects that natural disturbances have on competition and dispersal. The presence of greater diversity at intermediate levels suggests that these human activities may not universally compromise the dispersal dynamics of tropical forests, while at the same time they reduce the dominance of superior competitive species. This is the precise recipe needed for intermediate disturbance to have the benefits theorized in the IDH [70].

Roxburgh et al [73] and Fox [71] discuss how species responses to competition and seed banks may determine whether the impacts of disturbance are positive or negative. For example, species whose responses exhibit relative nonlinearity can rapidly proliferate after a disturbance event. These are the species which have the potential to benefit when swidden disrupts the composition of an existing ecological community because they have a competitive advantage when vegetation is cleared. As this newly formed community succeeds over time, these pioneer competitors may give way to persistent species that respond more linearly to competition. The storage effect acts as a complimentary mechanism, enabling species not be present within the prior

plant community to recruit after a disturbance. This is possible if a viable seed bank from the surrounding vegetation matrix is stored and can disperse after a disturbance occurs. Disturbances which are too large or which tend to occur within a lower diversity matrix are unlikely to encourage these competitive responses and will tend to store a lower diversity of seeds. This may be one reason why we do not observe increased levels of diversity in sites where disturbances tend to be larger on average or which only occur close to rivers and infrastructure, as the surrounding matrix is limited. For swidden societies to be integrated with forest ecosystems, they must not be confined to roadside settlements or enclosures, as this can diminish community agency and constrain the ecological and cultural benefits that swidden can provide.

5 Conclusion

To conclude, we reiterate a point that we made in the Introduction of the paper: as of 2018, an estimated 36% of intact forests lie on Indigenous lands [11]. Statistics like this one have led many to focus on the role of Indigenous and rural peoples, many of whom practice swidden, as stewards of global biodiversity and total above-ground carbon [101]. Many ethnographic case studies of swidden agriculture have found evidence that swidden landscapes can harbor substantial diversity, both ecologically and culturally. At the same time, a parallel literature views swidden as fundamentally destructive and a primary driver of the degradation of forest landscapes. Such polarized perspectives exist because of biases that have prevented scientists from recognizing swidden as complex adaptive system, capable of many positive, negative and neutral effects on landscape structure. We urge researchers trying to understand the impacts of swidden to be cautious of the unraveled rope problem and the community biases that have dominated ecological theories of swidden and anthropogenic disturbance more generally. In this study, we have tried to overcome these overtly positive and negative biases by studying the overall landscape structure of swidden mosaics and the relationship between this structure and indicators of plant diversity. Our results show that swidden mosaics can exhibit some characteristic patterns. Notably, we found that when disturbances are intermediate in scale, the anthropogenic vegetation classes associated with swidden combined with mature forest lead to a landscape with greater levels of vegetation diversity than expected in the absence of swidden activity.

Supplementary Information. This study includes Supplementary Information which contains ancillary results, as well as complete descriptions of the landscape metrics, statistical modeling, and analytic results referenced in the paper. Further supporting material, including code for processing and classifying spatial imagery, as well as diagnostic reports can be found in Online Resource 1, a repository on GitHub: https://github.com/downey205/globalswidden.

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Author contributions. SAS and SSD wrote the main manuscript text. SAS prepared figures and tables. SAS and ZS curated spatial data and training data. XW created the GitHub repository, built machine learning pipelines, and conducted vegetation classification procedures with supervision from RQ. SAS calculated all landscape metrics and developed and fit statistical models. JA conducted site level contextual analyses and provided contextual information about study sites. SAS, SSD, and RQ made substantial contributions to the conception and design of the study. SAS and SSD drafted and revised the manuscript. All authors reviewed and approved the manuscript.

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References

[1] Dove, M. R. Theories of swidden agriculture, and the political economy of ignorance. *Agroforestry systems* **1**, 85–99 (1983).

[2] Ribeiro Filho, A. A., Adams, C. & Murrieta, R. S. S. The impacts of shifting cultivation on tropical forest soil: a review. *Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas* **8**, 693–727 (2013).

[3] Metzger, J. P. Effects of slash-and-burn fallow periods on landscape structure. *Environmental Conservation* **30**, 325–333 (2003).

[4] Metzger, J. P. Landscape dynamics and equilibrium in areas of slash-and-burn agriculture with short and long fallow period (bragantina region, ne brazilian amazon). *Landscape Ecology* **17**, 419–431 (2002).

[5] Messerli, P., Heinimann, A. & Epprecht, M. Finding homogeneity in heterogeneity—a new approach to quantifying landscape mosaics developed for the lao pdr. *Human Ecology* **37**, 291–304 (2009).

[6] Heinimann, A. *et al.* A global view of shifting cultivation: Recent, current, and future extent. *PloS one* **12**, e0184479 (2017).

[7] Van Vliet, N. *et al.* Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. *Global environmental change* **22**, 418–429 (2012).

[8] Hesselbarth, M. H., Sciaini, M., With, K. A., Wiegand, K. & Nowosad, J. landscapemetrics: an open-source r tool to calculate landscape metrics. *Ecography* **42**, 1648–1657 (2019).

[9] O'Bryan, C. J. *et al.* The importance of indigenous peoples' lands for the conservation of terrestrial mammals. *Conservation Biology* **35**, 1002–1008 (2021).

[10] Estrada-Carmona, N., Sánchez, A. C., Remans, R. & Jones, S. K. Complex agricultural landscapes host more biodiversity than simple ones: A global meta-analysis. *Proceedings of the National Academy of Sciences* **119**, e2203385119 (2022).

[11] Fa, J. E. *et al.* Importance of indigenous peoples' lands for the conservation of intact forest landscapes. *Frontiers in Ecology and the Environment* **18**, 135–140 (2020).

[12] Conklin, H. C. Hanunóo agriculture. a report on an integral system of shifting cultivation in the philippines. vol. 2. *FAO Forestry Development Papers (FAO). no. 12.* (1957).

[13] Balee, W. *Footprints of the forest: Ka'apor ethnobotany-the historical ecology of plant utilization by an Amazonian people.* (Columbia University Press, 1994).

[14] Hecht, S. B. Indigenous soil management and the creation of amazonian dark earths: implications of kayapó practices. *Amazonian dark earths: origin, properties, management* 355–371 (2003).

[15] Siebert, S. F. & Belsky, J. M. Historic livelihoods and land uses as ecological disturbances and their role in enhancing biodiversity: an example from bhutan. *Biological Conservation* **177**, 82–89 (2014).

[16] Balée, W. *Cultural forests of the Amazon: a historical ecology of people and their landscapes* (University of Alabama Press, 2013).

[17] Padoch, C. & Pinedo-Vasquez, M. Saving slash-and-burn to save biodiversity. *Biotropica* **42**, 550–552 (2010).

[18] Smith, D. A. Garden game: shifting cultivation, indigenous hunting and wildlife ecology in western panama. *Human Ecology* **33**, 505–537 (2005).

[19] Datta-Roy, A. Spatial and temporal patterns of large mammal hunting in a changing swidden system of arunachal pradesh, india. *Human Ecology* **50**, 697–710 (2022).

[20] Turner, N. J., Davidson-Hunt, I. J. & O'flaherty, M. Living on the edge: ecological and cultural edges as sources of diversity for social—ecological resilience. *Human Ecology* **31**, 439–461 (2003).

[21] Downey, S. S. *et al.* An intermediate level of disturbance with customary agricultural practices increases species diversity in maya community forests in belize.

Communications Earth & Environment **4**, 428 (2023).

[22] Ford, A. & Nigh, R. Origins of the maya forest garden: Maya resource management. *Journal of Ethnobiology* **29**, 213–236 (2009).

[23] Ford, A. & Nigh, R. *The Maya forest garden: Eight millennia of sustainable cultivation of the tropical woodlands* Vol. 6 (Routledge, 2016).

[24] Henley, D. Swidden farming as an agent of environmental change: Ecological myth and historical reality in indonesia. *Environment and History* **17**, 525–554 (2011).

[25] Ellen, R. Studies of swidden agriculture in southeast asia since 1960: an overview and commentary on recent research and syntheses. *Asia Pacific World* **3**, 18–39 (2012).

[26] Marquardt, K., Milestad, R. & Salomonsson, L. Improved fallows: a case study of an adaptive response in amazonian swidden farming systems. *Agriculture and Human Values* **30**, 417–428 (2013).

[27] Jiang, N., Li, P. & Feng, Z. Remote sensing of swidden agriculture in the tropics: A review. *International Journal of Applied Earth Observation and Geoinformation* **112**, 102876 (2022).

[28] Kadoya, T., Takeuchi, Y., Shinoda, Y. & Nansai, K. Shifting agriculture is the dominant driver of forest disturbance in threatened forest species' ranges. *Communications Earth & Environment* **3**, 108 (2022).

[29] Barker, M. J. & Fraser, D. J. Misrelating values and empirical matters in conservation: A problem and solutions. *Biological Conservation* **281**, 109966 (2023).

[30] Labriere, N., Laumonier, Y., Locatelli, B., Vieilledent, G. & Comptour, M. Ecosystem services and biodiversity in a rapidly transforming landscape in northern borneo. *PloS one* **10**, e0140423 (2015).

[31] Dunn, M., Estrada, N. & Smith, D. A. The coexistence of baird's tapir (tapirus bairdii) and indigenous hunters in northeastern honduras. *Integrative zoology* **7**, 429–438 (2012).

[32] Padoch, C. *et al.* The demise of swidden in southeast asia? local realities and regional ambiguities. *Geografisk Tidsskrift-Danish Journal of Geography* **107**, 29–41 (2007).

[33] Medellin, R. A. & Gaona, O. Seed dispersal by bats and birds in forest and disturbed habitats of chiapas, mexico 1. *Biotropica* **31**, 478–485 (1999).

[34] Murdjoko, A., Brearley, F. Q., Ungirwalu, A., Djitmau, D. A. & Benu, N. M. Secondary succession after slash-and-burn cultivation in papuan lowland forest, indonesia. *Forests* **13**, 434 (2022).

[35] Caroline, M. S. M., Romain, N. J., Bernard-Aloys, N. *et al.* Comparison of plant communities between primary and secondary tropical forests of mount oku, cameroon. *Journal of Ecology and The Natural Environment* **8**, 163–174 (2016).

[36] Liu, X., Liu, X., Skidmore, A. & Garcia, C. Recovery of woody plant species richness in secondary forests in china: a meta-analysis. *Scientific Reports* **7**, 10614 (2017).

[37] Marín-Spiotta, E., Silver, W. & Ostertag, R. Long-term patterns in tropical reforestation: Plant community composition and aboveground biomass accumulation. *Ecological Applications* **17**, 828–839 (2007).

[38] Pain, A., Marquardt, K., Lindh, A. & Hasselquist, N. J. What is secondary about secondary tropical forest? rethinking forest landscapes. *Human Ecology* **49**, 239–247 (2021).

[39] Feret, J.-B. & de Boissieu, F. *biodivMapR: biodivMapR: an R package for α- and ß-diversity mapping using remotely-sensed images* (2024). URL https://github.com/jbferet/biodivMapR. R package version 1.14.2.

[40] Rocchini, D., Chiarucci, A. & Loiselle, S. A. Testing the spectral variation hypothesis by using satellite multispectral images. *Acta Oecologica* **26**, 117–120 (2004).

[41] Torresani, M. *et al.* Reviewing the spectral variation hypothesis: Twenty years in the tumultuous sea of biodiversity estimation by remote sensing. *Ecological Informatics* 102702 (2024).

[42] Wallis, C. I. *et al.* Exploring the spectral variation hypothesis for α-and β-diversity: a comparison of open vegetation and forests. *Environmental Research Letters* **19**, 064005 (2024).

[43] Downey, S. S., Gerkey, D. & Scaggs, S. A. The milpa game: a field experiment investigating the social and ecological dynamics of q'eqchi' maya swidden agriculture. *Human Ecology* **48**, 423–438 (2020).

[44] Scaggs, S. A. & Downey, S. S. Graduated sanctions, common pool resource management, and the social organization of labor in swidden agriculture. *Current Anthropology* (2024). In review.

[45] Tverskoi, D., Scaggs, S. A. & Downey, S. S. A complex adaptive systems model of labor reciprocity and normative reasoning in swidden agriculture. *bioRxiv* 2024–12 (2024).

[46] Turner, M. G. Landscape ecology: the effect of pattern on process. *Annual review of ecology and systematics* **20**, 171–197 (1989).

[47] Wu, J. & Qi, Y. Dealing with scale in landscape analysis: an overview. *Geographic Information Sciences* **6**, 1–5 (2000).

[48] Vongvisouk, T., Mertz, O., Thongmanivong, S., Heinimann, A. & Phanvilay, K. Shifting cultivation stability and change: Contrasting pathways of land use and livelihood change in laos. *Applied geography* **46**, 1–10 (2014).

[49] Jentsch, A. *et al.* in *Disturbances and disturbance regimes* 11–40 (Springer, 2022).

[50] Walz, U. Landscape structure, landscape metrics and biodiversity. *Living reviews in landscape research* **5**, 1–35 (2011).

[51] Walz, U. & Syrbe, R.-U. Linking landscape structure and biodiversity. *Ecological indicators* **31**, 1–5 (2013).

[52] Alencar, L., Escada, M. I. S. & Camargo, J. L. C. Forest regeneration pathways in contrasting deforestation patterns of amazonia. *Frontiers in Environmental Science* **11**, 991695 (2023).

[53] de Filho, F. J. B. O. & Metzger, J. P. Thresholds in landscape structure for three common deforestation patterns in the brazilian amazon. *Landscape Ecology* **21**, 1061–1073 (2006).

[54] Alencar, L., Escada, M. I. S. & Camargo, J. L. C. Long-term landscape structure change in contrasting land occupation strategies of the brazilian amazon. *Land Use Policy* **150**, 107442 (2025).

[55] Levin, S. A. Self-organization and the emergence of complexity in ecological systems. *Bioscience* **55**, 1075–1079 (2005).

[56] Solé, R. & Bascompte, J. in *Self-organization in complex ecosystems.(mpb-42)* (Princeton University Press, 2012).

[57] May, R. M. Will a large complex system be stable? *Nature* **238**, 413–414 (1972).

[58] Levin, S. A. The problem of pattern and scale in ecology: the robert h. macarthur award lecture. *Ecology* **73**, 1943–1967 (1992).

[59] Puettmann, K. J., Messier, C. & Coates, K. D. in *Managing forests as complex adaptive systems: introductory concepts and applications* 3–16 (Routledge, 2013).

[60] Barton, C. M. Complexity, social complexity, and modeling. *Journal of Archaeological Method and Theory* **21**, 306–324 (2014).

[61] Lansing, J. S. Complex adaptive systems. *Annual review of anthropology* **32**, 183–204 (2003). URL http://www.annualreviews.org/doi/10.1146/annurev.anthro.32.061002.093440.

[62] Bormann, F. H. & Likens, G. E. *Pattern and process in a forested ecosystem: disturbance, development and the steady state based on the Hubbard Brook ecosystem study* (Springer Science & Business Media, 2012).

[63] Turner, M. G. Disturbance and landscape dynamics in a changing world. *Ecology* **91**, 2833–2849 (2010).

[64] Wiens, J. A. Habitat fragmentation: island v landscape perspectives on bird conservation. *Ibis* **137**, S97–S104 (1995).

[65] Carroll, S. M. & Parola, A. What emergence can possibly mean. *arXiv preprint arXiv:2410.15468* (2024).

[66] Chazdon, R. L. & Arroyo, J. P. in *Tropical forests as complex adaptive systems* 35–59 (Taylor & Francis Ltd., 2013).

[67] Lorenz, E. The butterfly effect. *World Scientific Series on Nonlinear Science Series A* **39**, 91–94 (2000).

[68] Liao, J. *et al.* Coexistence of species with different dispersal across landscapes: a critical role of spatial correlation in disturbance. *Proceedings of the Royal Society B: Biological Sciences* **283**, 20160537 (2016).

[69] Kallimanis, A., Kunin, W., Halley, J. & Sgardelis, S. Patchy disturbance favours longer dispersal distance. *Evolutionary ecology research* **8**, 529–541 (2006).

[70] Connell, J. Response: intermediate-disturbance hypothesis. *Science* **204**, 1345–1345 (1979).

[71] Fox, J. W. The intermediate disturbance hypothesis should be abandoned. *Trends in ecology & evolution* **28**, 86–92 (2013).

[72] Huston, M. A. Disturbance, productivity, and species diversity: empiricism vs. logic in ecological theory. *Ecology* **95**, 2382–2396 (2014).

[73] Roxburgh, S. H., Shea, K. & Wilson, J. B. The intermediate disturbance hypothesis: patch dynamics and mechanisms of species coexistence. *Ecology* **85**, 359–371 (2004).

[74] Turner, M. G. & Dale, V. H. Comparing large, infrequent disturbances: what have we learned? *Ecosystems* 493–496 (1998).

[75] Nigh, R. & Diemont, S. A. The maya milpa: fire and the legacy of living soil. *Frontiers in Ecology and the Environment* **11**, e45–e54 (2013).

[76] Kleinman, P. J., Pimentel, D. & Bryant, R. B. The ecological sustainability of slash-and-burn agriculture. *Agriculture, Ecosystems & Environment* **52**, 235–249 (1995).

[77] PBC, P. L. Planet application program interface: In space for life on earth (2022). URL https://api.planet.com.

[78] QGIS Development Team. *QGIS Geographic Information System.* QGIS Association (2022). URL https://www.qgis.org.

[79] Breiman, L. Random forests. *Machine learning* **45**, 5–32 (2001).

[80] Gao, Y., Skutsch, M., Paneque-Gálvez, J. & Ghilardi, A. Remote sensing of forest degradation: a review. *Environmental Research Letters* **15**, 103001 (2020).

[81] Kirillov, A. *et al.* *Segment anything*, 4015–4026 (2023).

[82] Hesselbarth, M. H., Sciaini, M., With, K. A., Wiegand, K. & Nowosad, J. landscapemetrics: an open-source r tool to calculate landscape metrics. *Ecography* **42**, 1648–1657 (2019).

[83] Cushman, S. A., McGarigal, K. & Neel, M. C. Parsimony in landscape metrics: strength, universality, and consistency. *Ecological indicators* **8**, 691–703 (2008).

[84] Pebesma, E. Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal* **10**, 439–446 (2018). URL https://doi.org/10.32614/RJ-2018-009.

[85] Jost, L. Entropy and diversity. *Oikos* **113**, 363–375 (2006).

[86] Bürkner, P.-C. brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software* **80**, 1–28 (2017).

[87] Stan Development Team. Stan modeling language users guide and reference manual, version 2.32 (2024). URL https://mc-stan.org.

[88] Kéfi, S. *et al.* Early warning signals of ecological transitions: methods for spatial patterns. *PloS one* **9**, e92097 (2014).

[89] Rappaport, R. A. Ritual regulation of environmental relations among a new guinea people. *Ethnology* **6**, 17–30 (1967).

[90] Schweiger, A. K. *et al.* Plant spectral diversity integrates functional and phylogenetic components of biodiversity and predicts ecosystem function. *Nature Ecology & Evolution* **2**, 976–982 (2018).

[91] Treep, J., de Jager, M., Bartumeus, F. & Soons, M. B. Seed dispersal as a search strategy: dynamic and fragmented landscapes select for multi-scale movement

strategies in plants. *Movement Ecology* **9**, 1–14 (2021).

[92] Geertz, C. *Agricultural involution: The processes of ecological change in Indonesia* 11 (Univ of California Press, 1963).

[93] Piperno, D. R. Quaternary environmental history and agricultural impact on vegetation in central america. *Annals of the Missouri Botanical Garden* 274–296 (2006).

[94] Piperno, D. R., Ranere, A. J., Dickau, R. & Aceituno, F. Niche construction and optimal foraging theory in neotropical agricultural origins: A re-evaluation in consideration of the empirical evidence. *Journal of Archaeological Science* **78**, 214–220 (2017).

[95] Hunt, C. O., Gilbertson, D. D. & Rushworth, G. A 50,000-year record of late pleistocene tropical vegetation and human impact in lowland borneo. *Quaternary Science Reviews* **37**, 61–80 (2012).

[96] Roberts, P., Hunt, C., Arroyo-Kalin, M., Evans, D. & Boivin, N. The deep human prehistory of global tropical forests and its relevance for modern conservation. *Nature plants* **3**, 1–9 (2017).

[97] Bird, R. B. & Nimmo, D. Restore the lost ecological functions of people. *Nature ecology & evolution* **2**, 1050–1052 (2018).

[98] Bird, R. B. Disturbance, complexity, scale: New approaches to the study of human–environment interactions. *Annual Review of Anthropology* **44**, 241–257 (2015).

[99] Altieri, M. A. & Anderson, M. K. An ecological basis for the development of alternative agricultural systems for small farmers in the third world. *American Journal of Alternative Agriculture* 30–38 (1986).

[100] Hames, R. Garden labor exchange among the ye'kwana. *Ethology and Sociobiology* **8**, 259–284 (1987).

[101] Brondízio, E. S. *et al.* Locally based, regionally manifested, and globally relevant: Indigenous and local knowledge, values, and practices for nature. *Annual Review of Environment and Resources* **46**, 481–509 (2021).

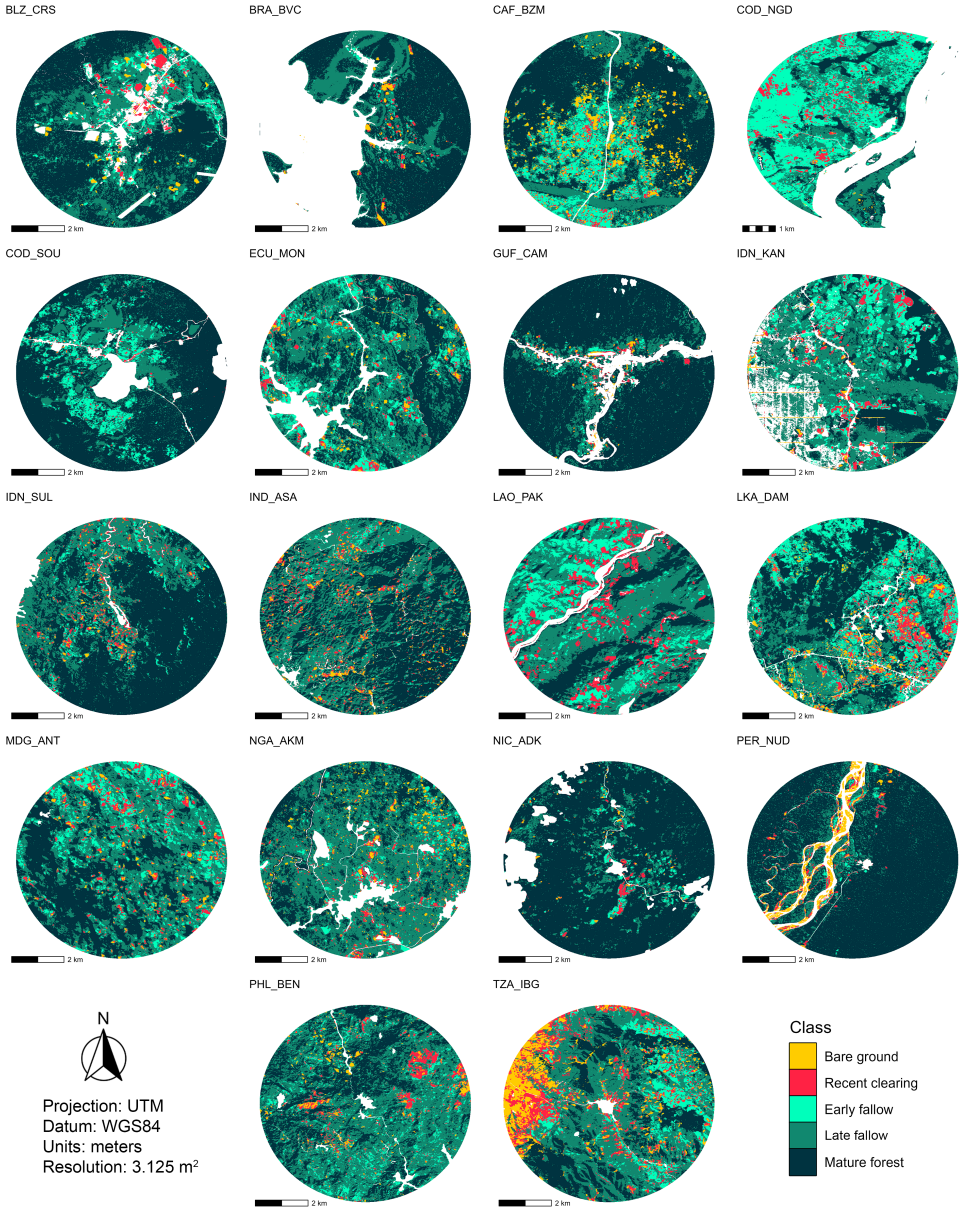

Fig. 1 Classified maps of all 18 study sites. Site codes are found in Table 1.

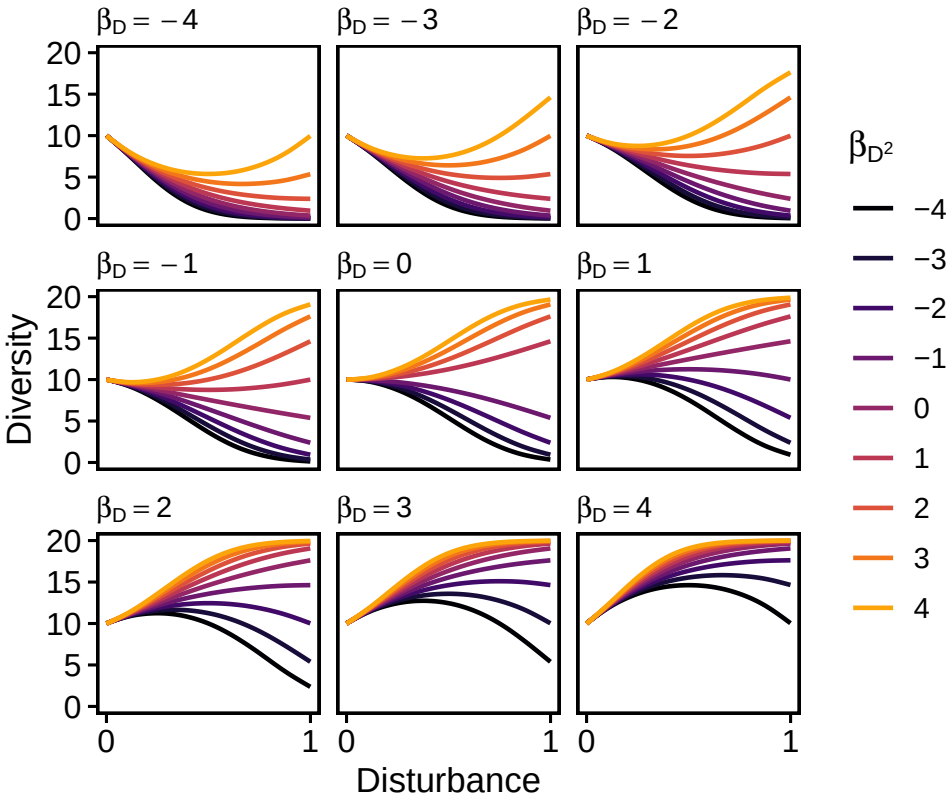

Fig. 2 Simulated disturbance curves based on equations 2 and 3 using a grid of β_D and β_{D^2} values where $\alpha = 0$. Values of disturbances are drawn randomly from a uniform distribution and curves represent average trends.

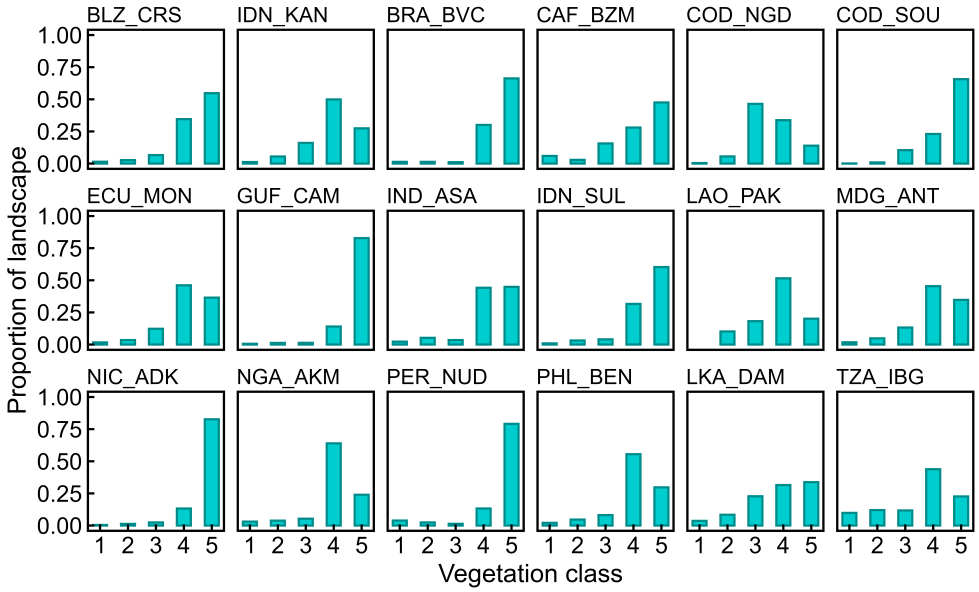

Fig. 3 The proportion of the landscape covered in swidden vegetation classes (1 = bare ground, 2 = recent clearing, 3 = early fallow, 4 = late fallow, and 5 = mature forest).

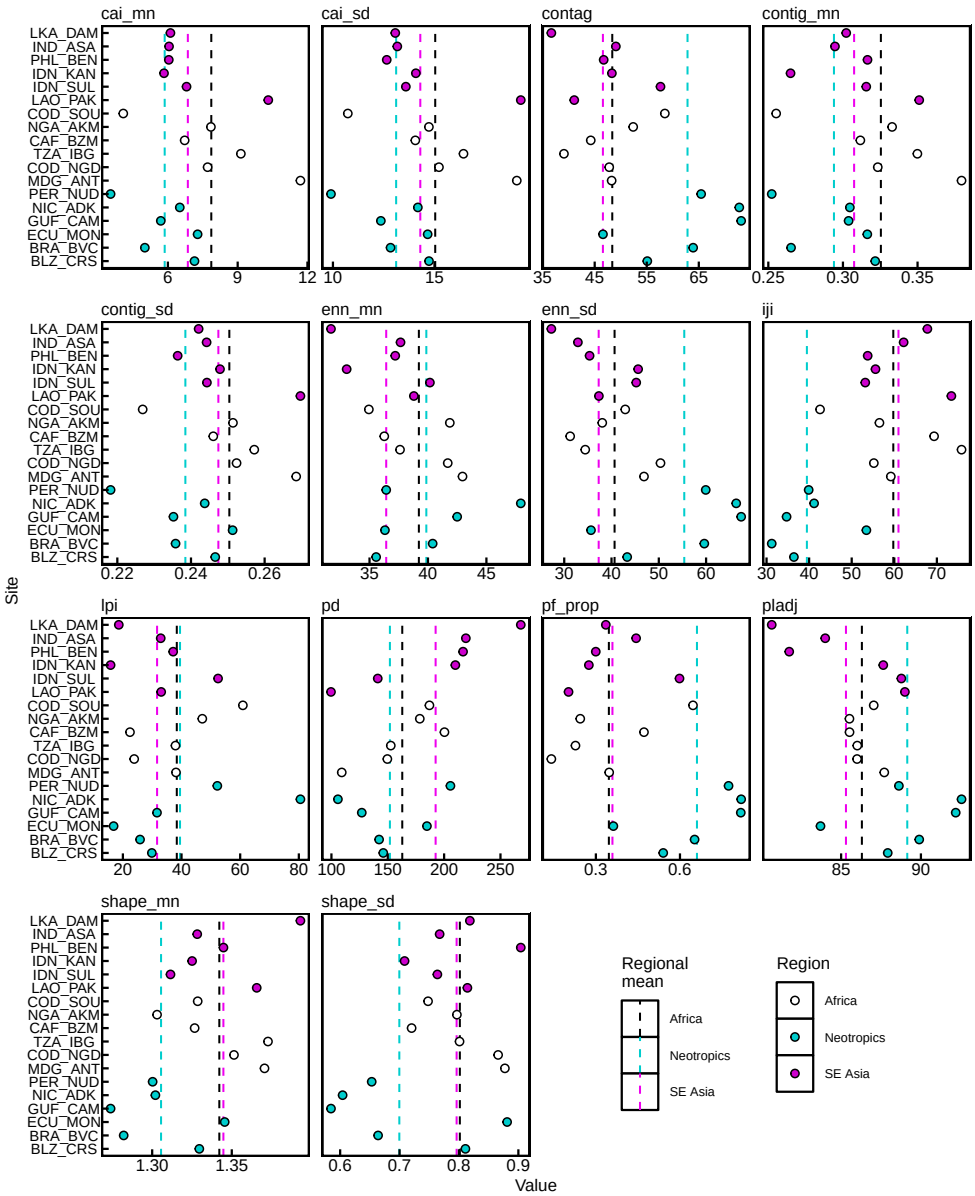

Fig. 4 Landscape metrics summarizing the classification maps for all 18 swidden societies. Dashed lines indicate regional mean values. Sites on the y-axis are ranked by the region mean value of the metrics. Definition of all metrics are provided in the SI under Landscape Metrics and Their Interpretations in Swidden.

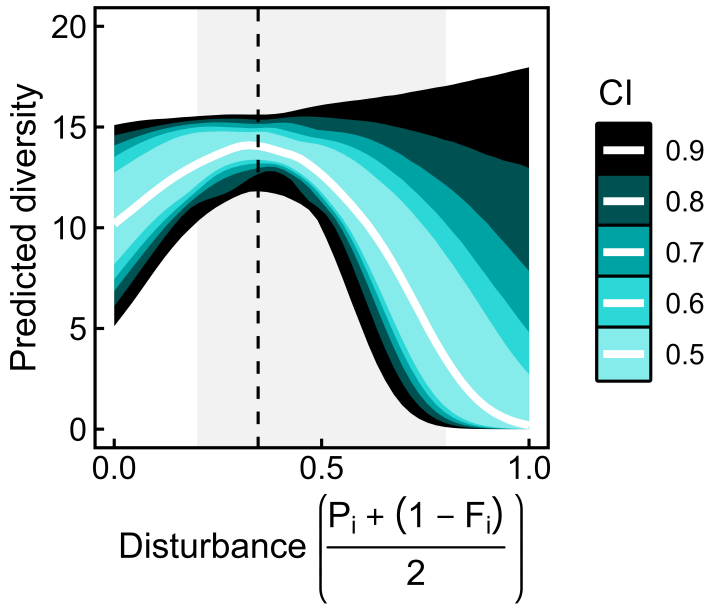

Fig. 5 The average disturbance curve after marginalizing over parameter estimates from all 18 sites. The white curve represents the predicted average curved and the ribbons indicate a range of credibility intervals (CI) to show the variation around this mean. The dashed line indicates the location of the peak (D^*) and the shaded region defines the parameter space between d_1 and d_2 (see SI Analytic Results).

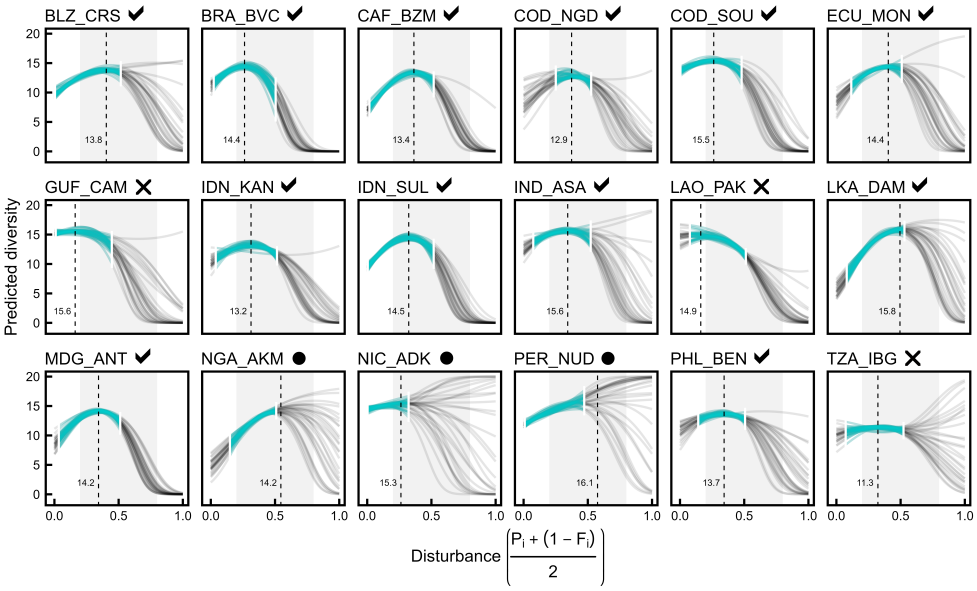

Fig. 6 Predicted disturbance curves for all 18 swidden mosaics. Each line is a single draw from the posterior predictive distribution (50 draws total). The cyan lines shows the data range for each site. Grey lines show the predicted trajectory of the curve beyond the range of observations based on partial pooling of estimates across sites. Dashed lines indicate the location of the peak (D^*) on the average curve and the shaded region defines the parameter space between d_1 and d_2. A peak located within this region supports the IDH (i.e. $D^* \in [d_1, d_2]$) and is denoted by a black check mark. Sites that do not support the IDH or which are inconclusive are denoted by a $\times$ or $\bullet$, respectively.