From plot to landscape scale: linking tropical biodiversity measurements across spatial scales

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Quantitative measurements of changes in tropical biodiversity are sparse, despite wide agreement that maintaining biodiversity is a key conservation goal. Pan-tropical networks to systematically measure plot-level biodiversity are currently being developed to close this gap. We propose that a key component of such networks is the monitoring of human activities at broader scales around plots, to enable interpretation of biodiversity trends. This monitoring goal raises questions about the spatial extent and variables needed to capture interactions between human activities and biodiversity at multiple scales. We suggest a pragmatic approach to delineate and monitor a "zone of interaction" around biodiversity measurement sites to bridge across these scales. We identify the hydrologic, biological, and human interactions that connect local-scale measurements with broader-scale processes. We illustrate the concept with case studies in the Udzungwa Mountains in Tanzania and Ranomafana National Park in Madagascar; however, the framework applies to other biodiversity measurement sites and monitoring networks as well.

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It is widely recognized that land conversion, hunting, forest harvesting, and other human influences are depleting biodiversity. Yet the specific mechanisms through which human activities affect species at particular locations remain poorly characterized. This lack of understanding limits our ability to attribute changes in biodiversity observed at the local scale to processes operating over multiple scales, including local-scale human disturbances, regional-scale land-use change, or global-scale climate variability. Improved understanding of the biodiversity response to human and ecological influences operating over multiple spatial scales is crucial for identifying global trends, focusing conservation priorities, and enabling effective design of community-based conservation efforts.

In a nutshell:

- Biodiversity measured at the local plot scale reflects human activities and ecological processes occurring over larger areas surrounding the plot
- Delineating and monitoring a "zone of interaction" (ZOI) around a measurement plot are needed to interpret possible factors affecting changes in biodiversity
- A ZOI around a plot includes water flows, movements of organisms, and human interactions that strongly influence biodiversity within the plot
- A key component of tropical biodiversity monitoring includes monitoring human activities and ecological processes in the ZOI

Networks for monitoring biodiversity are currently being discussed and implemented (Andelman and Willig 2004; Dobson 2005; Pereira and Cooper 2006; Teder *et al.* 2007). An immediate imperative is to assess progress toward the Convention on Biological Diversity's 2010 goal to "reduce the rate of loss of biodiversity". Existing monitoring networks and long-term plots for measuring biodiversity are generally not coordinated with standard measurement protocols and approaches (Pereira and Cooper 2006). Here, we suggest that monitoring strategies will be most effective in the long run if they monitor not only biodiversity at the plot level but also ecological and human processes that influence the observed biodiversity at multiple spatial scales. Such information facilitates analysis of causal linkages with the many climatic, ecological, and human factors that potentially influence observed biodiversity. This need raises an obvious question: what attributes should be monitored, and over what spatial extent, around plots? Answering this question requires linking plot-level measurements with processes operating over a range of spatial scales. This linkage across scales is generally not incorporated into biodiversity monitoring.

Monitoring human disturbances at the local scale is essential for interpreting biodiversity trends. Observations of diurnal lemurs and human disturbance along

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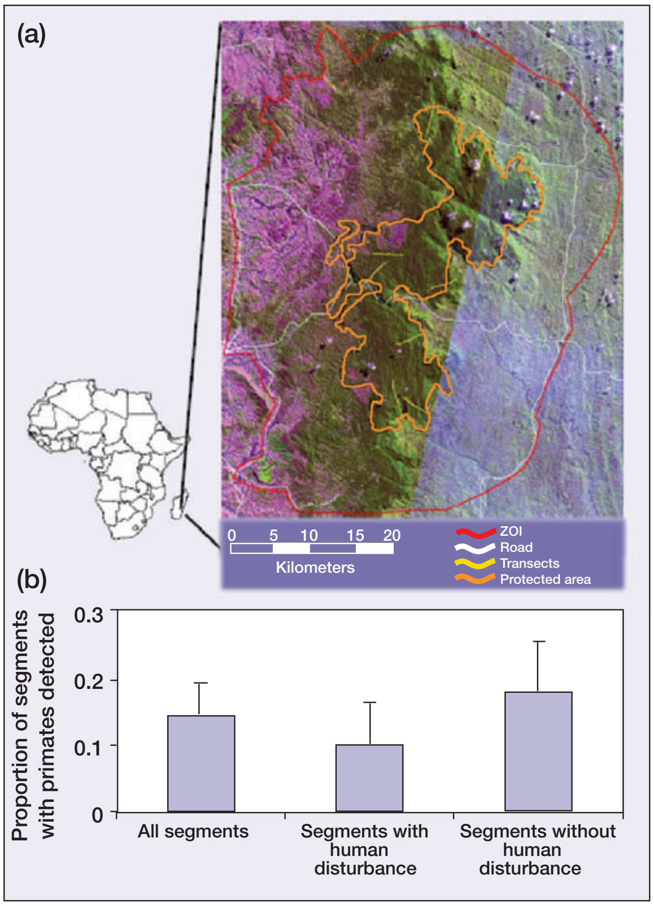

Figure 1. *(a) Location of transects in Ranomafana National Park, Madagascar. Red line is the zone of interaction (ZOI; see explanation in WebPanel 1); inner orange line is the park boundary. Background satellite image mosaic: Landsat Enhanced Thematic Mapper (ETM) path 159, row 075, acquired 29 April 2001 (west) and Landsat ETM path 158, row 075, acquired 22 April 2001 (east). (b) Mean proportion of diurnal lemur detections along 500-m segments in eight 4-km-long transects located from the edge of Ranomafana National Park toward the interior (WebPanel 1) for all segments, segments with human disturbance, and segments without human disturbance (odds ratio for detection without/with human disturbance = 1.78, P = 0.001). Repeated measurements were taken along each transect (transects were walked 22 to 24 times, with 168 to 192 observations per transect). Human disturbance is defined as at least one trail and at least one cut tree observed. Error bar is one standard deviation for means of all transects.*

eight 4-km transects in Ranomafana National Park in southeastern Madagascar illustrate this (Figure 1; WebPanel 1). Based on 22 to 24 repetitions of each transect, human disturbance (signs of at least one trail and one cut tree) had a significant effect on the probability of detecting primates within a 500-m segment, after accounting for transect variability (odds ratio = odds of detecting primates at an undisturbed segment/odds of detecting primates at a disturbed segment = 1.78, $P = 0.001$). Thus, data on local human disturbance are important for attributing fine-scale variability in primate occurrence, as also found by researchers doing a case study in Tanzania (see below). Evidence that species are responding to changes in land use at the regional scale – for example, wildebeest in East Africa (Serneels and Lambin 2001) – and to climate change at the global scale (Thomas *et al.* 2004) illustrates the multi-scale dimensions of interpreting biodiversity trends measured at the plot level.

The mismatch between local biodiversity measurements and broader-scale ecological and human processes arises from a tradition in which ecologists and conservationists view human and ecological processes separately. In reality, these processes are intertwined through exchanges of energy, materials, and organisms (Liu *et al.* 2007b). We address the mismatch in spatial scales through identification of the ecological and human processes that connect local biodiversity measurements with the broader landscape (Figure 2). The framework translates a conceptual understanding of the processes that link scales to a concrete approach for delineating the spatial extent of the interactions. Monitoring ecological and human changes over this spatial extent, or "zone of interaction" (ZOI), forms the basis for interpreting human influences on biodiversity measurements at particular locations. The capability of analyzing changes over large areas through remote sensing and the emerging ability to communicate and analyze standard biodiversity measurements from different locations enables connection across scales.

The framework presented in this paper focuses on the species-rich, humid tropics, where deforestation and other human activities are profoundly affecting biodiversity. The underlying motivation is to monitor the larger landscape surrounding measurement sites in the initial stage of establishing long-term networks for biodiversity measurements.

In the following sections, we first provide a conceptual framework to interpret biodiversity measured at the local scale in the context of ecological and social dynamics operating over larger scales. We then present practical steps for implementing the framework to delineate a ZOI. Finally, we illustrate the application of the ZOI concept using an example from Tanzania.

Conceptual framework for bridging scales

The framework for identifying ZOIs around plot-level biodiversity measurements builds on concepts from ecosystem management (Grumbine 1994; Lindenmayer *et al.* 2008), coupled human–natural systems (Liu *et al.* 2007a, 2007b), and linkages between protected areas and surrounding landscapes (DeFries *et al.* 2007; Hansen and DeFries 2007). An ecosystem management approach incorporates long-distance migrations, natural disturbance, and nutrient cycling over broad scales that extend outside park boundaries. The definition of "greater ecosystems" includes the spatial extent of these interactions. The concept of coupled human–natural systems extends the greater ecosystem to include interactions and feedbacks between ecological, human, and physical processes.

We define the ZOI as the spatial extent of the coupled human–natural system that strongly influences biodiversity measured within a plot. The processes that control the interactions, including movements of water and organisms, link the plot level with the larger landscape (Hansen and DeFries 2007). Interactions also vary across the temporal domain. The ZOI includes seasonal migration routes, water resources used during droughts, and other locations containing resources used only periodically or sporadically in response to climate variability or stochastic ecological processes, such as flowering.

Delineating ZOIs for monitoring around biodiversity measurement sites requires biological and socioeconomic data that often do not exist. We propose here a process for identifying ZOIs based on available data and local expert opinion. The boundaries of a watershed, or road networks, for example, are easily defined. The extent of other human influences is often more difficult to draw on a map and requires local knowledge of the coupled human–natural system.

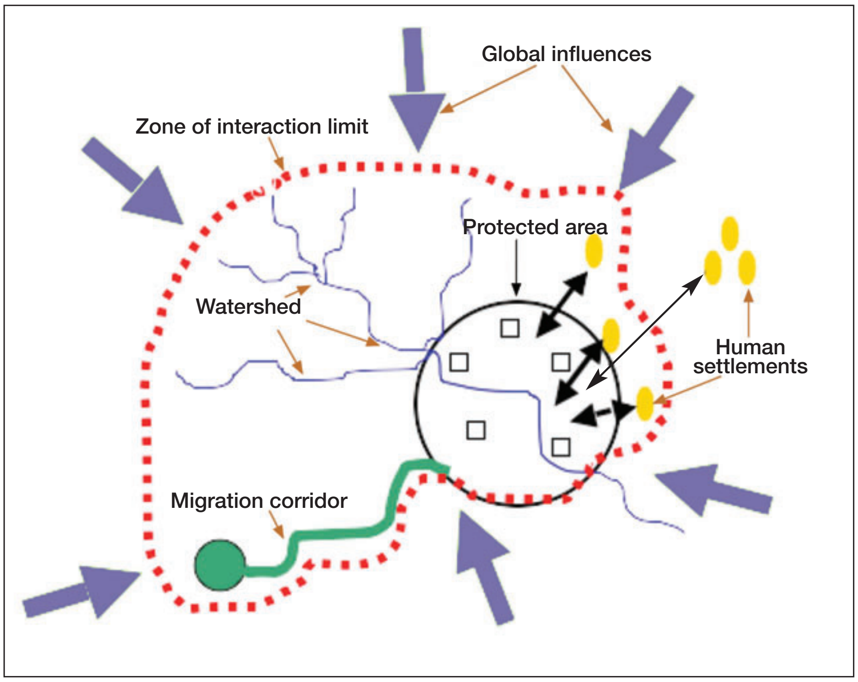

Figure 2. *Hypothetical zone of local and regional interaction (dashed red line) around biodiversity measurement plots (squares) within a protected area (or measurement site encompassing the plots if outside a protected area; black circle). The zone of interaction (ZOI) encompasses the upper watershed (blue tributaries), migration corridors (dark green), and human settlements (yellow). Strong human interactions (thick black arrows) occur between the protected area and nearby settlements, and weaker interactions (thin black arrow) occur with more distant settlements. The ZOI is embedded within global influences (thick purple arrows), such as climate change and nutrient deposition.*

■ Practical steps to define ZOIs

A pragmatic approach to delineating ZOIs associated with biodiversity measurement sites is based on remote-sensing data and other sources of information, such as local expert knowledge of ecological and socioeconomic features. If the measurement plots are located within a protected area, which is often the case, we consider that the protected area defines the minimum extent of the area to be monitored.

We propose the following four criteria for incorporating ecological and human interactions that affect biodiversity at the measurement plots (Figure 3).

Contiguous habitat surrounding the measurement site

Habitat contiguous to the measurement site potentially extends the ranges and number of species found at the site. The contiguous habitat might be defined by topographic features (eg a deep valley of dry habitat separating moist forests), rivers, roads, or boundaries of human land use. Watershed boundaries may also form a natural border, delineating the ZOI where anthropogenic or topographic boundaries are not clear.

Some measurement sites are located in remote areas where habitat is contiguous over a large region. The boundary in these cases is difficult to identify, but several options are possible. The contiguous habitat could be designated according to the home range of a keystone species, as in the case of Yellowstone (Craighead 1979) and Serengeti (Sinclair 1995) National Parks. Alternatively, the area required to maintain a minimum viable population (Traill *et al.* 2007) or number of species, according to species–area relationships (Rosenzweig 1995), can provide guidance on the designation of contiguous habitat. In the subset of cases where contiguous habitat is not bounded by biophysical features and cannot be delineated by ecological interactions, we recommend a minimum (admittedly arbitrary) buffer of 50 km from the protected area's administrative boundary (or the boundary encompassing the measurement site), as used in previous analyses (DeFries *et al.* 2005).

Migration corridors

Migration corridors can be used by species to travel from the measurement site to other habitats. Such corridors can be critically important for survival. Examples include relatively narrow strips of land used by elephants to access feeding areas and seasonally used paths that ungulates use to reach water holes.

For the ZOI, we propose delineating the movement corridor between suitable areas enclosed by an appropriate

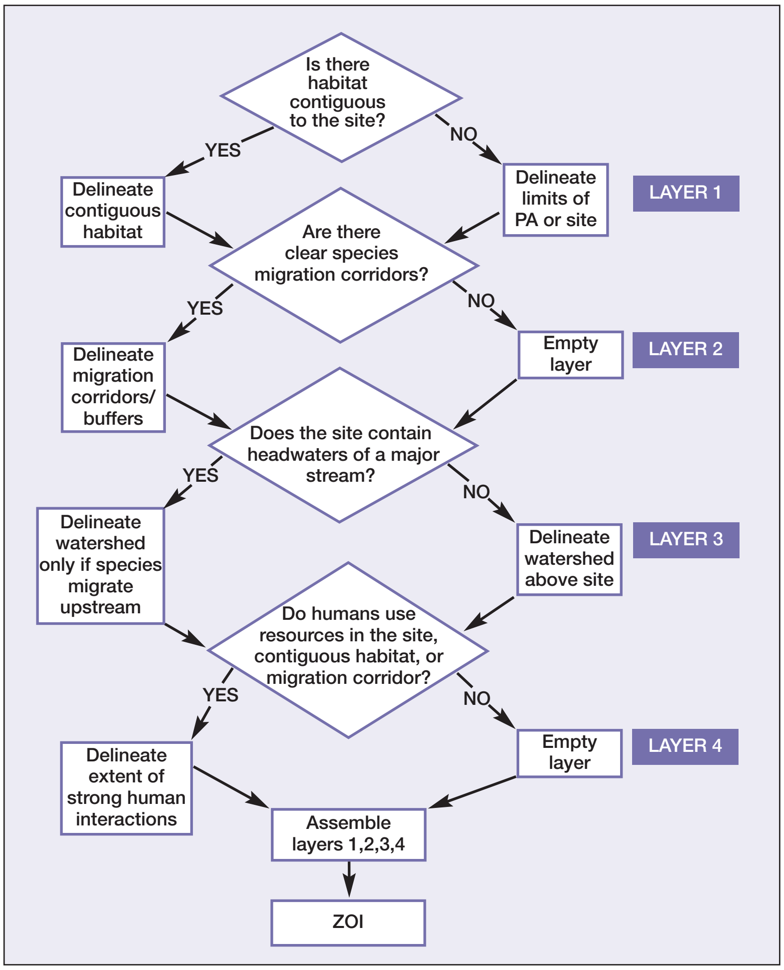

Figure 3. *Steps for delineating a zone of interaction (ZOI) around biodiversity measurement sites. The measurement site includes either the land within a protected area's administrative boundaries (if plots are located within a protected area [PA]) or the area that encompasses the plots (if outside a protected area).*

buffer, eg 5 km. Dispersal needs, habitat suitability, and temporally varying habitat requirements for all relevant species should be considered when delineating corridors.

Some species can migrate over very long distances – for example, birds that migrate over continents. Although it is not practical to include multiple continents in a ZOI, in cases where migratory birds are important components of the ecosystem, the ZOI might need to include key habitats in distant locations.

Watershed boundaries

The area influenced by major water flows will likely impact many ecological patterns and processes around the measurement site. Whether the site is in the upper reach of the watershed (ie water moves out of the site), the middle, or the bottom (ie water moves through the site) is a key factor in controlling these processes. If the plot is located in the upper reach, the site itself is the source of water for other areas in the landscape, so that this component of the ZOI is not relevant. If in the middle or bottom reaches, it is important to determine the boundaries of the watershed, because upstream changes in water flows and quality will impact the site.

In some situations, delineating the lower watershed, below the measurement site, is important because human activities could have an impact on species that migrate upstream (eg fish, shrimp). In this case, the watershed is acting as a corridor and could therefore be delineated under the migration criterion. People also use rivers as transportation corridors, which should be considered under the human-impact criterion for infrastructure.

Human activities with strong influences on the measurement site

The designation of the spatial extent of human influences on biodiversity in the measurement sites is the most difficult and subjective of all the criteria. People living around the site will probably have a direct impact on its biodiversity, through processes such as hunting, land conversion, and extractive activities, and also as a result of domestic animals, and pollutants from factories and other sources. The strength of the influence varies within different cultural practices, restrictions, and protection levels. Consequently, it is misleading to use a fixed buffer width to determine this boundary. Local knowledge is needed to derive the boundaries of the ZOI.

The types of data sources that are potentially useful for this analysis include settlements (eg household number and distribution; Liu *et al.* 2003), population density, infrastructure (roads, rivers, etc), land use, extent of hunting practices and distance travelled for hunting, and locations of factories and mines. Based on knowledge of people's activities in the region, a local expert can delineate a boundary that includes an area where most of these activities will take place. Some of this information could be produced easily from field-based surveys or local maps. Designation of the ZOI according to human activities is likely to result in a fuzzy and dynamic boundary and should be reassessed periodically.

We propose that the four criteria outlined above provide a pragmatic approach for identifying the components of the ZOI. The spatial extents of all the components define the complete ZOI (Figure 3). Monitoring the ZOI then provides a basis for assessing trends in local biodiversity measurements and determining local and global factors that affect biodiversity.

■ Monitoring the ZOI

The attributes that need to be monitored within the ZOI and the frequency of monitoring vary with the socioeconomic characteristics of the region (Table 1). For exam-

Table 1. Categories of socioeconomic settings for defining and monitoring zones of interaction around biodiversity measurement sites within tropical forest protected areas

Socioeconomic setting	*Example site*	*Characteristic landscape features*	*Key criteria for defining ZOI*	*Monitoring needs*		
				Variables	*Frequency*	*Spatial resolution***
Remote, low human population density	Manu (Terborgh 1990); Suriname (Baal *et al.* 1988)	Large tracts of contiguous habitat	Watershed boundaries; contiguous habitat and migration corridors determined by biophysical features	Forest cover	Low	Coarse
Extractive frontier landscape	Udzungwas (Dinesen *et al.* 2001); Manaus (Lovejoy and Bierregaard 1990)	Partially fragmented, rapid change	Watershed boundaries; contiguous habitat and migration corridors determined by biophysical features and existing human impact	Fragmentation, human impact*	High	Coarse large area/fine where heavy impact
Settled human land use surrounding protected areas	Ranomafana (Wright and Andrimuhaja 2002)	Highly fragmented, "island" protected areas	Watershed boundaries; contiguous habitat and migration corridors determined by human land use; human impact boundaries	Human impact*	Low	Fine

*Human impacts include land-use change, fire, number and distribution of settlements, and infrastructure.
**Fine resolution indicates 30-m resolution or finer from Landsat-type sensors; coarse resolution is 100–500-m resolution from sensors, such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS).

ple, ZOIs in remote areas that are not subject to direct human influence require less frequent monitoring of fewer attributes. Conversely, ZOIs in settled regions, where protected areas are effectively "islands", require monitoring of human attributes. Those ZOIs in frontier areas (ie where land use is rapidly changing) require more frequent monitoring and re-evaluation of the delineation of the ZOI.

We suggest that the following attributes be monitored within the ZOIs: (1) land-cover, land-use, and landscape patterns (eg fragmentation, patch size, connectivity); (2) human population density through monitoring the number of settlements and households; (3) infrastructure/access (eg the construction of roads, conversion of road from unpaved to paved, creation of new logging roads, canals, and dam construction); (4) active fire and burned areas; (5) direct human impacts, such as timber harvesting, grazing by domestic animals, and hunting; and (6) surface water and rain quality (eg sediment load, pH, nutrient concentrations, pollutants).

It is possible to monitor some of these attributes, such as land cover, burned areas, and roads, with remote sensing at various resolutions (DeFries 2008). Ground-based knowledge, however, is essential to interpret the remote-sensing data and identify attributes that cannot be detected by remote sensing, such as hunting and wood collection.

Application of ZOI framework

We illustrate the need to monitor human activities and the approach for delineating ZOIs in the Udzungwa Mountains in south-central Tanzania. Direct human influences on the protected areas are strong, as would be expected within an extractive frontier landscape (Table 1).

The Udzungwa Mountains of south-central Tanzania (10 000 km^2, 35°10' to 36°50' E and 7°40' to 8°40' S) contain the largest rainforest blocks of the Eastern Arc Mountains, an area of outstanding biological endemism (Myers *et al.* 2000) composed of mountain forests, where over 70% of the original habitat has been lost (Burgess *et al.* 2007). The area surrounding the Udzungwa Mountains National Park is densely populated (WebPanel 2).

Delineating the ZOI

Following the criteria in Figure 3, we delineate the components of the ZOI as follows:

(1) Criterion 1 (contiguous habitat): contiguous forest habitat outside the protected areas is highly fragmented, with some key, forest-dependent species – such as the Udzungwa red colobus monkey (*Procolobus gordonorum*) – extending their range to isolated fragments. On the eastern side of the Udzungwa Mountains, the contiguous habitat is constrained by the sharp topographic boundary. On the western side, the ZOI includes the remaining forest fragments (Figure 4a).

(2) Criterion 2 (migration corridors): the movements of elephant populations outside the Udzungwa Mountains are restricted to corridors, which are narrow and highly threatened by growing human encroachment

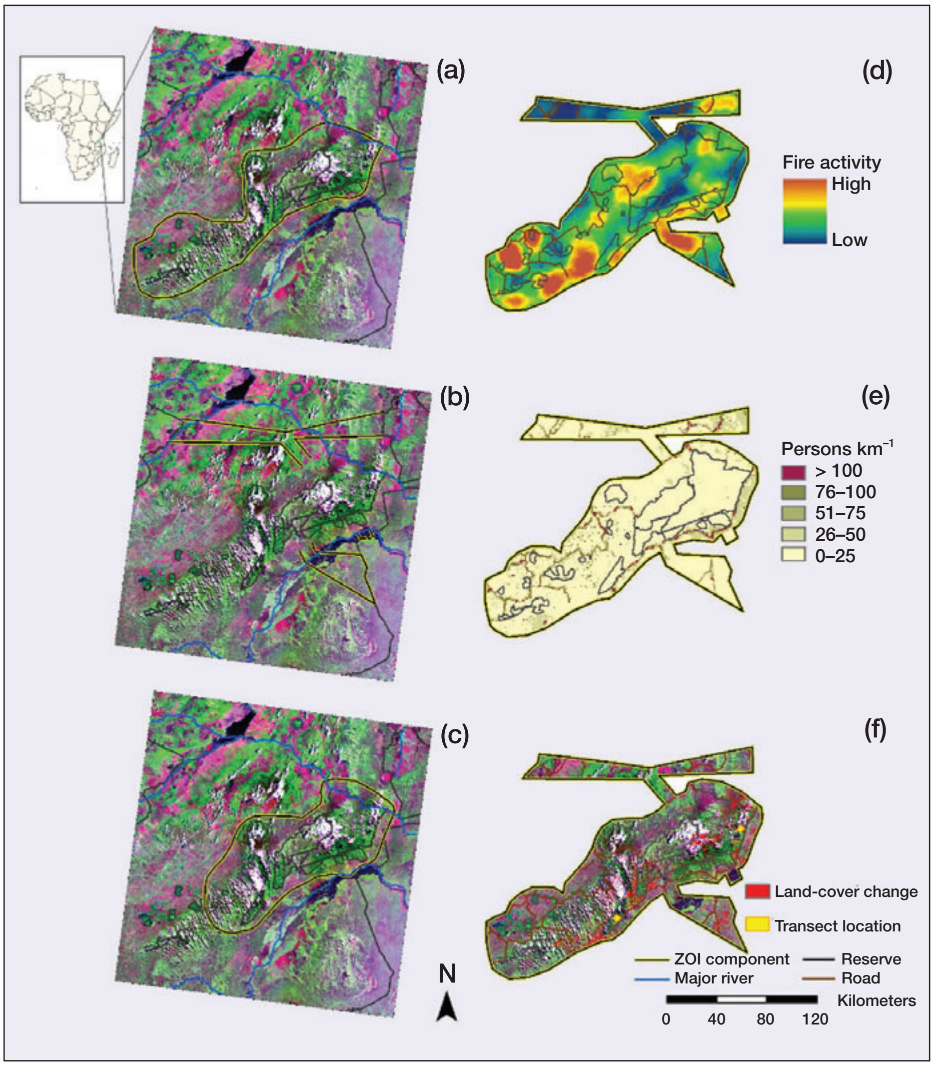

Figure 4. *Zone of interaction defined for monitoring sites in the Udzungwa Mountains of south-central Tanzania, according to the combined spatial extent for (a) criterion 1 (contiguous habitat), (b) criterion 2 (migration corridors), and (c) criterion 4 (human influences). Criterion 3 (watershed boundary) does not apply in this case. (d) Fire activity from Moderate Resolution Imaging Spectroradiometer (MODIS) data (Justice* et al. *2002) for November 2000 through August 2007, highlighting frequency of active fires around each 100-m cell. (e) Population density (Landscan Global Population Database 2006). (f) Changes in forest cover from 1970 to 2000 indicate distribution of human activity in the ZOI (Forestry and Beekeeping Division 2006). Backdrop for (a), (b), and (c) are false color composites (bands 7, 4, 3) for Landsat ETM+ scenes (path167, row065), (path167, row066), (path168, row065), and (path168, row066), acquired 7 July 2000, 10 May 2002, 21 February 2000, and 18 June 2002, respectively.*

(Jones *et al*. 2007). We identify a 10-km-wide strip along the corridor that leads to adjacent protected areas (eg Selous Game Reserve) as the second component of the ZOI (Figure 4b).

(3) Criterion 3 (watershed delineation): the protected area is in the upper reach of the watershed (note the flow of rivers in Figure 4a). The criterion does not apply in this case.

(4) Criterion 4 (strong human interactions): human settlements that directly influence biodiversity are limited to a 5-km zone, which along the eastern side of the mountains is constrained by intensive cultivation and geophysical settings (Kilombero River and Selous Game Reserve). For areas where settlements take up a larger zone, we also identified a 40-km-wide outer zone of indirect human influence (Figure 4c). The resulting ZOI component represents the area affected by direct and indirect human influences.

The combination of these three components constitutes the ZOI. Within this zone, several indicators of human disturbance can be monitored remotely, including fire activity (Figure 4d), population density and infrastructure (Figure 4e), and changes in forest cover (Figure 4f).

Monitoring primates in the Udzungwa Mountains ZOI

The relationships between human disturbance and abundance of primates and other forest mammals illustrate the importance of ground monitoring of human activities within the ZOI in interpreting biodiversity measurements. Human disturbance was low, or moderate, in the Park's Mwanihana forest, whereas it was high in the southern Uzungwa Scarp Forest Reserve (Figure 5a), despite the relatively high human density to the east of the park as compared with that of the southern forests. Data on numbers of primates collected through 23 to 48 repetitions of three transects, each 4 km in length, are negatively correlated with disturbance indicators collected along 20 and 25 randomly placed, 0.5-km-long transects walked from the forest edge toward the interior of the park and Uzungwa Scarp, respectively (Figure 5b). The exception was Sykes' monkey (*Cercopithecus mitis*), which has a preference for secondary forest habitat (WebPanel 2).

It would not be possible to interpret differences in mammal abundances at these sites without collecting data on human activities in the ZOI. The Uzungwa Scarp transects are in the forested escarpment, where population density and access are low. The Mwanihana transects are located where fire activity and population density are relatively high. Changes in forest cover have occurred in close proximity to both sites. Data on human activity within the ZOI, obtained from remote sensing and ground observations, are as critical as the biodiversity data for interpreting whether trends are attributable to local, regional, or global causes.

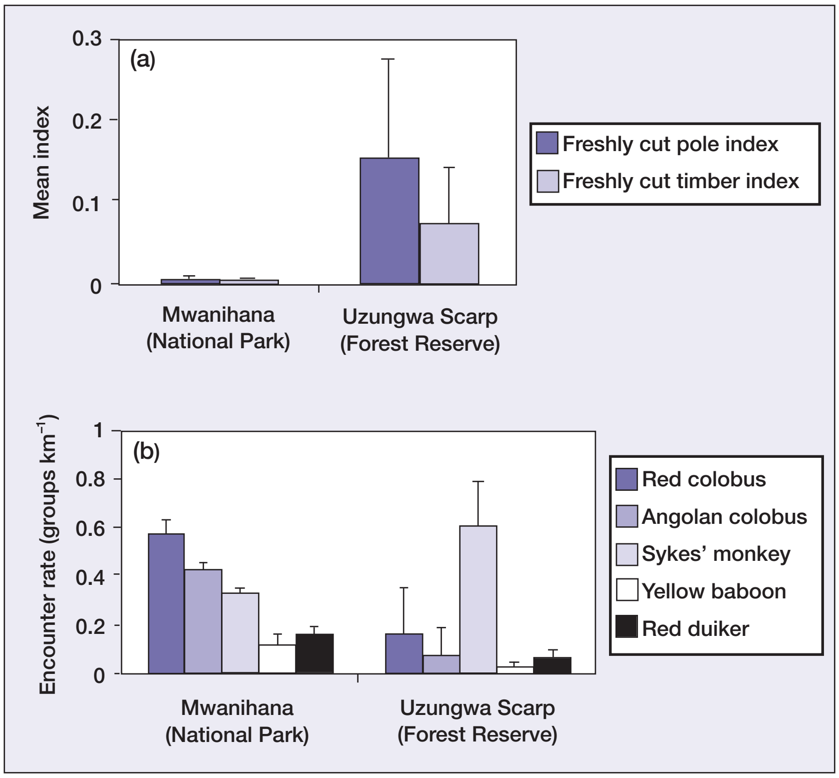

Figure 5. *(a) Indices of human disturbance and (b) mammal encounter rate for Mwanihana forest (National Park) and Uzungwa Scarp (Forest Reserve) in the Udzungwa Mountains of Tanzania. Values are mean and standard deviation of observations from transects running from the forest edge toward the forest interior. For disturbance signs, measurements were taken once along 20–25 0.5-km-long transects. For mammals, measurements were repeated 23 to 48 times along three 4-km-long transects.*

Discussion and conclusion

Monitoring tropical biodiversity is a critical step toward filling the gap in our knowledge concerning where and why species are declining or becoming extinct. An understanding of biodiversity trends is fundamental to assessing the implications for ecosystem services and devising management strategies. Several efforts are underway to establish systematic monitoring networks in tropical regions.

We argue that defining and monitoring the ZOI around measurement sites are essential components in biodiversity monitoring networks, allowing us to evaluate trends and assess conservation strategies. Biodiversity attributes are measured at the plot level for practical reasons, and plots are often located in protected areas. Yet biodiversity measured at any particular site integrates responses to global forces (eg climate change), regional forces (eg land-use change in long-range migration corridors), and local forces (eg hunting or timber harvesting). Attributing observed changes in biodiversity to particular causes requires an understanding of all these forces.

It is unrealistic to try to monitor all the possible human influences at a biodiversity monitoring site. Instead, we propose an approach that bridges across spatial scales, from the local plot level to the broader scale, where strong human and ecological interactions are likely to be important for biodiversity. A global network for monitoring biodiversity is a costly but essential first step toward identifying the most effective approaches for stemming biodiversity loss. Identifying and monitoring the ZOI around each site will provide fundamental measurements for interpreting trends in plot-level measurements.

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