Fragmentation and changes in hydrologic function of tiger bush landscapes, south-west Niger

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Summary

1 Fragmentation of tiger bush landscapes in south-west Niger between 1960 and 1992 is evidenced by a reduction of percentage woody vegetation cover, changes in the spatial attributes of vegetation patches, and an increase in the spatial heterogeneity of the landscapes. The spatial patterns and dynamics of these landscapes were effectively captured using a combination of selected patch-based landscape metrics that measured specific aspects of the spatial pattern.

2 Derived from the spatial distribution of the alternating bands of vegetation and bare ground, lacunarity curves provide a particularly effective quantitative measure of the spatial pattern and dynamics of tiger bush landscapes in terms of percentage vegetation cover, spatial heterogeneity, and the domain of scale of the landscape. Lacunarity curves can be used to characterize landscapes in areas with different climates and topographic settings, and are an effective and parsimonious indicator of the fragmentation of tiger bush.

3 The dynamics of the vegetation bands during the fragmentation process was anisotropic. A significantly larger proportion of woody vegetation reduction occurred in the downslope than upslope portions of woody patches, while the opposite was true for woody vegetation expansion. These results corroborate the hypothesis that tiger bush bands migrate upslope due to the upslope-downslope resource gradient across the vegetation band.

4 Fragmentation of the tiger bush landscapes reduced retention of water on site, significantly increasing the landscape permeability to surface flow. When vegetation bands were well connected in 1960, no transects were found that allowed surface water percolation. That is, no path travelling through the bare ground areas was found to connect the upslope edge and downslope edge of any of the 200-m long transects, regardless of their width (50, 100 or 150 m). By 1992, within the same but now severely fragmented landscapes transects of all widths allowed water to percolate across them (44% if 50 m wide to 89% if 150 m wide). This increased landscape permeability to surface flow may have reduced the water available to the remaining fragmented vegetation bands and accelerated their degradation.

Key-words: banded vegetation, lacunarity analysis, landscape permeability, spatial dynamics

Introduction

Landscapes consisting of alternating bands of vegetation and bare ground aligned parallel to contours of gentle, uniform slopes (0.2–2%) is widespread throughout and semi-arid (50–750 mm annual rainfall) regions (Valentin et al. 1999). Considerable research has been conducted on, and two recent special issues of *Catena* (Volume 37(1–2) 1999) and *Acta Oecologica* (Volume 20(3) 1999) have been devoted to, the structure and dynamics of such banded vegetation (Montana et al. 1990, Tongway & Ludwig 1990; Montana 1992), their interaction with soil and hydrologic process (Slattery 1961; Greene 1992; Wallace & Holwill 1997; Seghieri &
Galle 1999), and their genesis and dynamics using approaches such as process-based simulations (Ludwig et al. 1994, 1999), cellular automata (Thierry et al. 1995; Dunkerley 1997a, >b) and analytical models (Lejeune & Lejeune 1997; Lejeune & Titi 1999, Lejeune et al. 1999). Apart from the simulation modelling and some remote sensing-based studies (Gouterbo et al. 1997) carried out at landscape or regional scales, most information is derived from small-scale field investigations. These have been few attempts to quantify the spatial pattern of complete areas of naturally occurring banded vegetation (Ludwig & Tongway 1995), note to quantify how fragmentation occurs over time, and few to evaluate the effects of its fragmentation on landscape processes (Ludwig et al. 1999).

Plant composition and woody biomass vary across each band, reflecting a gradient of water availability (Casenave & Valentin 1992; Cornet et al. 1992; Seghier et al. 1997). For instance, in the bands of 'tiger bush' vegetation of Sahelian Africa, an upper pioneer zone usually contains colonizing plants, a central zone shows vigorous woody growth, and the lower zone is degrading. It has been hypothesized (Thierry et al. 1995) that plants in the upper part reduce resources for the lower part of the band (Galle et al. 1999) so that tiger bush bands migrate upslope, and evidences of such behaviour has been reported recently (Chappel et al. 1999; Guillaume et al. 1999, Leprun 1999). We hypothesize that the cross-section of variation in structure and resource gradients will lead to vegetation bands showing an anisotropic (direction-dependent) response to disturbances, such that landscape fragmentation would lead to a greater reduction of vegetation cover on their downslope than that on their upslope side.

Sediments, plant residues and aeolian deposits often accumulate at the upper edge of the band (Thierry et al. 1995), and pooling above these counter-slope dams during the intensive storms is evidenced by the presence of sedimentary crusts in these areas (Valentin & Bresson 1992; Bromley et al. 1997; Galle et al. 1999). Livestock trails through banded vegetation or the harvest of fuelwood may lead to fragmentation and water in the pools can then flow through breaks in the vegetation. We hypothesize that the landscape thus becomes more 'permeable' to surface flow, reducing the amount of water retained on the landscape and thus available to vegetation, and leading to further degradation of the vegetation bands, particularly in sections near the breaks.

The structure of the tiger bush landscape and its fragmentation over time can be quantified using landscape metrics (Gustafson 1998) and geographical information system (GIS) modelling. Approaches similar to percolation modelling, as used in many studies of the dispersal of plants and animals and the spread of disturbances across heterogeneous landscapes (Gardner et al. 1989; O’Neill et al. 1992; Lavorel et al. 1995), can assess the effect of fragmentation on the percolation of surface flow across tiger bush landscapes.

The objectives of this study were: (i) to quantify the spatial structure of tiger bush landscapes in Niger and to assess how it changes as a consequence of fragmentation; (ii) to examine the spatial dynamics of the woody cover across the landscape in relation to vegetation band structure and associated resource gradients, and (iii) to assess the effect of fragmentation on surface hydrological processes of the tiger bush landscapes.

**Materials and methods**

**STUDY AREA**

Tiger bush vegetation in Niger occurs in a zone about 250 km wide extending from approximately 12°30' N to 15°N (White 1970) covering about 22,000 km², or one third of Sahelian Niger (Galle et al. 1999), but is restricted to laterite-capped plateaus on shallow gravelly soils and very gentle slopes (< 0.3%). Annual rainfall varies from about 200 mm in the north to 750 mm in the south and falls mainly in the summer months (Bromley et al. 1997). The width of the alternating vegetation bands and the bare areas vary with the precipitation gradient and local variations in topography and soils. Our study site (13°34'N, 2°33'E) is located near Hamdallaye, approximately 35 km north-east of Niamey, the capital of Niger (Fig 1). The long-term average of the annual rainfall is 480 mm, most of which falls as high intensity storms between June and September. The tiger bush vegetation in this area has been subjected to many years of heavy cutting, burning and grazing so that most of the larger trees have been harvested for fuel wood and timber and most of the perennial grasses and palatable shrubs have also been removed (Manu et al. 1994). The vegetation bands are 10–40 m wide and consist of a central portion dominated by relatively small woody species (2–5 m thigh) such as Combretum macrosanthis, C. nigricans and Acacia macrostachya, with herbaceous species such as Cenchrus elegans and Pennisetum pedicellatum occurring towards the edges (Manu et al. 1994). The bands are separated by at least 30 m of essentially bare interband areas.

We used six functionally independent landscapes with characteristic tiger bush vegetation pattern ranging in area from 13.33 ha to 37.1 ha (mean 25.4 ha). Black and white aerial photographs covering these landscapes, taken in 1960, 1979 and 1992, were scanned with a nominal resolution of 1 m. These scanned images were co-registered, and the spatial scale was verified with ground features of known dimensions. Areas of the six selected landscapes
were classified using an iterative self-organizing clustering algorithm (ERDAS ISODATA) that classified the pixels of each landscape into 40 classes based on their spectral similarity (ERDAS 1997). The 40 classes generated for each landscape were then grouped into three vegetation classes, woody, herbaceous, and bare ground, based on visual interpretation of the aerial photo images and other field photos. Subsequent spatial analyses were conducted using ArcView Spatial Analyst (ESRI 1998) and FRAGSTATS (McGarigal & Marks 1995) software.

Figure 1 (a) Location of the study area and (b) aerial photos showing fragmentation of tiger bush (black bands) between 1990 and 1992 in an area close to the edge of a plateau and crossed by roads.

**Fragmenation of Tiger Bush Landscape**

The spatial structure of the landscapes and their temporal changes were quantified with a number of landscape metrics (Gustafson 1998). Percentage woody cover was used to measure the overall changes in the amount of tiger bush vegetation within a landscape. The spatial characteristics of woody patches were measured with a set of patch-based metrics, including patch density, mean patch shape index, edge density, and mean nearest neighbour distance (McGarigal & Marks 1995). Patch shape index, defined as a quarter of the ratio of the perimeter to the square root of the area of a patch, is a measure of the complexity of the shape of a particular patch (a square patch would have an index of 1 and elongated or interconnected bands will have higher values than patches of fragmented ones). The edge density metric is defined as the total length of the edges of all patches of a particular type divided by the overall area of the landscape, and is therefore a measure of the amount of interface between the bands and bare interband areas. The mean nearest neighbour distance metric, the average distance between a woody patch and its nearest neighbouring woody patch, reflects the spatial arrangement of woody patches and is related to the width of the bare areas between vegetation bands. As the banded structure becomes increasingly fragmented, one would expect the percentage cover as well as density, shape index and edge density of woody patches to decrease and the nearest neighbour distance of woody patches to increase. Similar landscape metrics were calculated for bare ground patches and were expected to show opposite trends to those for woody patches. All metrics were calculated using FRAGSTATS software.

Herbaceous vegetation, which was generally distributed along edges of woody patches, occurred in discrete patches only in isolated sections of vegetation bands at their last stage of degradation and was not therefore analysed with patch-based metrics. The amount of the herbaceous cover can also be highly variable throughout a season and from year to year depending on the pattern of precipitation. Bare ground areas were generally separated from the woody patches by a band of herbaceous vegetation and a distance matrix was therefore generated to measure the shortest distance from each pixel representing herbaceous or bare ground to adjacent woody vegetation, and thus to assess the spatial arrangement of such cover relative to woody patches.

**Spatial Heterogeneity and Domains of Scale**

The lacunarity metric (Plotnick *et al.* 1993, 1996) was used as a further measure of the overall spatial pattern of the landscapes and its change over time. Lacunarity is a scale-dependent measure of spatial heterogeneity or texture of a landscape (Plotnick
Lacunarity enables parsimonious analyses of landscapes and their comparisons in terms of overall cover of a particular element, spatial heterogeneity or contagion of a landscape at different scales, and domains of scale. It can also indicate the presence of self-similarity and the existence of functional hierarchy (Plotnick et al. 1993). Unlike most other landscape metrics (Gustafson 1998), the results of lacunarity are not sensitive to map boundaries, but are sensitive to scale, and can be used for the analysis of very sparsely occupied maps. Lacunarity can be used with both binary and continuous data of any dimensionality, such as 1-D transects, 2-D surface and 3-D space. It allows determination of scale-dependent changes in the spatial structure of a landscape, which can provide insights into the underlying processes operating at different scales (Plotnick et al. 1996). Lacunarity (A) was determined using a gliding box algorithm (Allain & Cloutier 1991; Plotnick et al. 1993). The gliding box of a given size (r) was first placed at one corner of a landscape and the 'box mass' S(r), the number of pixels that were woody, determined. The box was then systematically moved through the landscape one pixel at a time and the box mass determined at each location. The lacunarity for box size r is calculated by adding one to the ratio of the variance and the mean square of the box mass: A(r) = var[S(r)]/E[S(r)]^2 + 1. The lacunarity curve, a log-log plot of lacunarity A(r) against box size r, was then used to quantify spatial heterogeneity of a landscape at different scales and the domains of scale. ArcView Spatial Analyst was used to calculate lacunarity for each of the landscapes.

PERMEABILITY OF THE LANDSCAPES

A percolation study was conducted to assess the permeability of these tiger bush landscapes and evaluate the effect of landscape fragmentation on the surface hydrologic process. A system of 200-m long belt transects, 50, 100, or 150 m wide, oriented along the general flow direction was used to assess the percolation of water through the landscapes. A transect was considered percolated if a continuous path across bare ground areas connected its upslope and downslope edges. The first transect was located at one end of the upslope boundary of the landscape and additional transects were located by moving in 25-m steps perpendicular to the general flow direction; the procedure was then repeated moving down in 100-m steps parallel to the general direction of flow until the entire landscape had been covered. All transects that had over 95% of their area within the boundary of the landscape were included in the analysis. Percentage of transects that percolated were determined for the transects of each of the three widths in each of the six landscapes in each of the 3 years.

RESULTS

FRAGMENTATION OF TIGER BUSH LANDSCAPE

There was a significant reduction in the woody vegetation cover and a significant expansion of the bare ground cover on these landscapes over the 32-year period (Fig. 2a) indicating severe fragmentation of the tiger bush landscapes. The average cover of woody vegetation decreased from 53% in 1960 to 24% in 1979 and 14% in 1992, while bare ground increased from 14% in 1960 to 53% in 1979 and 72% in 1992. Herbaceous cover was therefore about 33% in 1960, decreasing to 23% in 1979 and 13% in 1992. It is noticeable that herbaceous cover tracked woody cover and that once the vegetation bands became well separated, the two vegetation types were similar in extent. There was a close spatial association between herbaceous and woody vegetation (Fig. 3a). The majority of the herbaceous vegetation (c. 75%) was within 5 m of woody vegetation. Small amounts of herbaceous vegetation were distributed further away and the maximum separation increased from 1960 to 1979-92 due to isolated late-stage degrading patches with no apparent woody vegetation. In contrast, the majority of the bare ground areas (c. 95%) was at least 4–5 m away from woody vegetation (Fig. 3b), from which it was separated by herbaceous vegetation. As the tiger bush landscape became increasingly fragmented, the total amount of bare ground increased and a larger proportion of the bare ground was distributed farther away from woody vegetation.
As the woody cover decreased, the vegetation bands became increasingly fragmented as reflected by the changes in the spatial characteristics of woody patches. The reduction in woody cover between 1960 and 1979 (by more than 50%) was associated with the division of long and often interconnected vegetation bands into shorter and rarely interconnected patches. Many small woody patches also disappeared so that overall, there was a slight (but statistically insignificant) increase in woody patch density (Fig. 2b). The isolated bands, however, were relatively simple in shape and fragmentation, therefore led to a significant decrease in both mean value and variance in shape index of woody patches (Fig. 2c). By 1992, many of the remaining small woody patches had disappeared and the longer bands had shrunk or been further fragmented, leading to a significant decrease in woody patch density. The more rounded shapes of the shortened bands were reflected in their significantly decreased mean shape index. The very marked decrease in density of bare ground patches from 1960 to 1979 was due to isolated patches coalescing as the vegetation bands became disconnected and fragmented (Fig. 2b). As the vegetation bands further fragmented from 1979 to 1992, all the bare ground areas in each landscape coalesced into one or a few large patches within which woody patches were embedded. The resulting very high perimeter:area ratio led to a large increase in the mean shape index of bare ground patches (Fig. 2c).

Woody edge density decreased almost linearly from 1960 to 1992 (Fig. 2d). The pattern for bare ground was more complex: the low percent cover in 1960 was made up of isolated patches and edge density increased significantly from 1960 to 1979 as the vegetation bands fragmented, but then tracked the decrease in woody edge density as the vegetation bands further fragmented (Fig. 2d). Since the bare ground areas were separated from the woody areas by the surrounding herbaceous vegetation (Fig. 3), the amount of bare ground edges (i.e. the border

Fig. 2 Mean values and standard deviations of landscape metrics for six tiger bush landscapes in 1960, 1979 and 1992. Statistically significant differences (P < 0.05) are indicated by different letters next to the data point.
between bare ground and herbaceous vegetation) should be greater than, and track, the amount of woody edges (i.e. woody-herbaceous borders) if the vegetation bands are well separated from each other. This was not seen in 1980 when there was high woody cover with coalesced vegetation bands. Approximately half of the length of the bare ground edges would represent functional edges for the interception of surface flow. The large amount of woody vegetation (53% cover) recorded in 1980, supported by low level of intercepting edges and bare run-off surface, was greater than that expected from most reports for this general region (White 1970; Seghieri et al. 1997). The connectiveness of tiger bush band structure, an indicator of the efficiency of water retention of such landscapes, might therefore be an important factor in determining the amount of woody vegetation that they can support in addition to climate gradients and local topoedaphic conditions.

The mean nearest neighbour distance between woody patches both increased significantly and became more variable as the vegetation bands fragmented (Fig.2e) because disappearance of woody patches also degraded the regular alternating pattern. Although the percentage cover, density and shape complexity of bare ground patches changed greatly over the three decades, there was no significant change in their mean nearest neighbour distance (Fig.2e) since the width of the surviving vegetation bands stayed relatively stable.

**SPATIAL HETEROGENEITY AND DOMAINS OF SCALE**

Spatial heterogeneity of the tiger bush landscapes, as measured by lacunarity of the landscapes, changed significantly as a result of the fragmentation of the vegetation bands (Fig.4). The spatial heterogeneity was the lowest for the landscapes in 1960 when there were regular alternating vegetation bands and bare interband areas. The spatial heterogeneity increased significantly over time, across all spatial scales in all six landscapes, as fragmentation of the vegetation bands resulted in the banding becoming increasingly irregular and bare ground gaps more variable.

Lacunarity analysis captured spatial configuration and dynamics of structure for individual landscapes that were difficult to deduce from patch-based metrics (Fig.4). Landscape 1 was the most heterogeneous in 1960, with the others showing similar levels. All showed an increase in spatial heterogeneity between 1960 and 1972, by which time there were little differences between the landscapes. Increases in spatial heterogeneity between 1979 and 1992 were higher for landscapes 4, 5 and 6 than the other landscapes. This was due to fragmentation creating extended areas of bare ground of variable size on landscapes 2, 4 and 6 compared to fragmented but relatively well distributed bands with a narrower range of bare ground gaps on the other landscapes (1, 3 and 5).

These different degrees of fragmentation were partially characterized by the patch density and mean patch shape index calculated for all patches (i.e. both woody and non-woody) for each landscape in 1992 (Fig.5). These metrics were considered particularly effective for measuring landscape fragmentation (Fibon 1998) and did separate the landscapes into two groups with different levels of fragmentation. Landscapes 2, 4 and 6 had smaller mean patch shape indices (because they had simpler shapes and more isolated, shorter woody patches) and lower patch density (fewer surviving woody patches), indicating higher levels of fragmentation, than landscapes 1, 3 and 5. These metrics did not, however, measure the size distribution of the patches and, most importantly, the spatial arrangement of the patches on a landscape, and therefore the ranking of degree of fragmentation within each group in Fig.5 was not consistent with that in Fig.4. Although a combination of patch-based metrics (Fig.2) could be used to provide a description of the spatial configuration of a landscape, lacunarity analysis was much more efficient and intuitive in quantifying the overall spatial pattern of a landscape. Additionally, and perhaps more importantly, lacunarity analysis
measured spatial heterogeneity at multiple scales and could yield information on the domain of spatial scale.

The lacunarity analysis revealed information on the domains of scale of the tiger bush landscapes as well as their temporal change. The domain of scale of a tiger bush landscape is determined by the dimension of the regular alternating structure, i.e. the width of a vegetation band plus an interband and its variability. When the sampling scale (sliding box size) is smaller than the scale of the landscape pattern, the variance among the percent woody cover values at different locations and thus lacunarity would be high. As the sampling scale exceeds the scale of the landscape pattern, this variance would approach zero and the lacunarity value approach one. Mean lacunarity approached zero at a scale of about 60 m in 1960 and at some value above 100 m in 1979, but was still far from zero at this scale in 1992 (Fig. 4). The domain of scale for the 1960 landscape reflected the width of a typical vegetation bands plus its adjacent interband. Many vegetation bands had thinned and broken into shorter sections by 1979 but only a limited number of woody patches disappeared completely and the domain of scale was therefore changed moderately. The elimination of many vegetation band segments by 1992 created a range of large bare ground gaps and resulted in a significant increase in the domain of scale for the landscapes.
Fig. 5 Patch density and mean patch shape index of all woody and non-woody patches for six tiger bush landscapes (denoted by L-1 through L-6) in 1992.

**ANISOTROPY IN TIGER BUSH FRAGMENTATION**

About 42% of the woody cover reduction from 1960 to 1992 occurred in areas downslope of the remaining woody patches, significantly \((P < 0.01)\) more than the amount (17%) that occurred in upslope areas (Fig. 6). Although these downslope and upslope area measurements were approximate because the flow directions at different locations might not be exactly the same as the general flow direction for the landscape, the downslope portion of the vegetation bands were clearly more sensitive to disturbances presumably as a result of the upslope-downslope gradient of resources, particularly moisture (Cornet et al. 1992). The results also showed that a significantly \((P < 0.01)\) larger proportion of the woody vegetation expansion occurred upslope (52%) than downslope (11%) of the 1960 woody patches. These anisotropic dynamics with woody plants tending to colonize the adjacent upslope areas and to die back in the downslope portion of the bands corroborate the hypothesis that tiger bush bands migrate upslope. Reduction and expansion in other directions probably indicate that local surface flow patterns, probably modified by the vegetation bands themselves, are complex and may deviate from the general flow direction.

**PERMEABILITY OF THE LANDSCAPES**

Fragmentation of the tiger bush vegetation significantly increased the landscape permeability to surface flow (Table 1). In 1960, when the vegetation bands were well connected, none of the 200-m transects on any of the landscapes percolated, i.e. no path travelling in the bare ground areas was found to connect the upslope edge and downslope edge of any of the transects regardless of the width of the transects. The tiger bush landscape effectively maintained low landscape permeability to surface flow, which helped retain water on site. As the vegetation bands began to fragment, the landscapes became more permeable to surface flow. Although an average of 6% of the 200 × 50 m transects on the 1979 landscapes percolated, the rates varied between landscapes and the mean was not significantly different from zero. By this time both of the wider (200 × 100 m and 200 × 150 m) transects were more perme-

<table>
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<tr>
<th>Moving transect (length × width)</th>
<th>Proportion of transects allowing percolation (mean ± SD, %)</th>
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<tbody>
<tr>
<td>200 × 50 m</td>
<td>0.0 ± 0.0^a</td>
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<tr>
<td>200 × 100 m</td>
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<tr>
<td>200 × 150 m</td>
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<td>59.0 ± 5.5^a</td>
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<td>252.0 ± 14.3^a</td>
<td>75.4 ± 17.9^a</td>
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<tr>
<td>430.0 ± 17.0^a</td>
<td>88.5 ± 13.2^b</td>
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able and all widths showed significantly greater percentage percolation in the severely fragmented 1992 landscapes than in 1979 (Table 1).

In both 1979 and 1992, the percent of transects percolated increased significantly with transect width. Increased width allowed more tortuous percolating paths to be included in the transects. Although increasing degree of tortuosity in flow paths might reduce the surface flow through a landscape, in tiger bush, the effect might not be significant given the sheet flow pattern resulting from the high intensity rainfall and very gentle slope of the landscape, as well as frequent pooling upslope of the vegetation bands. The degree of fragmentation, i.e. the density, width and spatial distribution of the breaks along the vegetation bands is therefore likely to have the most influence on surface flow retention.

Discussion

FRAGMENTATION AND HYDROLOGIC PROCESSES

Fragmentation of tiger bush landscapes, characterized by a reduction in the amount and changes in the spatial configuration of the vegetation bands, can have significant influence on the hydrologic process and primary productivity at landscape-scales (Ludwig et al. 1999). As demonstrated in fine-scale studies on hydrologic processes associated with vegetation band structure on tiger bush landscapes, rainfall run-off from crusted interband areas was captured by the vegetation bands which have a markedly different surface and subsurface soil structure and very high infiltration rates (Bromley et al. 1997; Seghieri et al. 1997; Galle et al. 1999). As a landscape becomes fragmented, the amount of vegetation and thus the interception of the surface flow is reduced, and the decreased connectivity of the vegetation bands exerts a significant further effect as shortened bands and the bare ground breaks increase the permeability of the landscape to surface flow. This can significantly reduce the amount of water available to the remaining vegetation bands, given the characteristic high intensity of seasonal monsoon rainfall and significant sheet flow and pooling in the interband areas. There may exist a threshold level of landscape permeability; once this threshold is passed, rapid degradation of the fragmented vegetation bands may occur and lead to irreversible changes of tiger bush landscape.

METRICS FOR QUANTIFYING SPATIAL PATTERN AND CHANGE

Many landscape metrics, showing varying degrees of intercorrelation and redundancy, have been developed to measure different aspects of landscape pattern (Gustafson 1998; McGarigal & Marks 1995). The spatial patterns and dynamics of the tiger bush landscapes were effectively captured using a combination of selected patch-based landscape metrics and lacunarity analysis provided an effective quantitative measure, which is parsimonious compared to combinations of patch-based metrics. More importantly, lacunarity analysis measured spatial heterogeneity at multiple scales and yield information on the pattern of the spatial scales.

The spatial dimensions of the vegetation bands and interband bare ground determine the domain of scale for a tiger bush landscape, which may be used to characterize landscapes in different climatic zones at regional-scales and topographical settings at landscape-scales (White 1976; Valentin et al. 1999). Given the complexity in the banding pattern within landscapes, lacunarity curves will likely provide more adequate characterization of landscape structure than simple measurements of average dimensions of the typical banding structure at local-scales.

Changes in the amount of vegetation cover, the level of spatial heterogeneity and the domain of scale of tiger bush landscapes, which occur during fragmentation by breaking up and reducing the vegetation bands and increasing the amount and the range of widths of interband bare ground, were effectively captured by lacunarity analysis (Fig 4). Comparison of the lacunarity curves for a tiger bush landscape at different points of time, or to that of a relatively undisturbed landscape, can be therefore used to measure the degree of fragmentation and the dynamics of the fragmentation process.

POSSIBLE CAUSES OF FRAGMENTATION

Widespread evidence of degradation of native vegetation communities has been documented in many regions of the Sahel over the past several decades, with much of this degradation attributed to drought and climate change (Le Houerou 1996). However, ecosystem responses to climatic variability cannot be interpreted independently of the land-use pressure. This pressure is associated with a dramatic increase in regional human population which has been growing at a rate of about 3% per year (WRI 1992), and the concurrent increase of the livestock population (Case 1981) and fuelwood harvesting (Fig. 7). Valentin & d’Herbès (1999) found a strong correlation between the interband vegetation band ratio of tiger bush systems and mean annual rainfall (15-year average) across both the south-north precipitation gradient in Niger (300–750 mm) and temporal variations in the last four decades, indicating remarkable adaptability of tiger bush landscapes to the variations in precipitation that are intrinsic to and semi-arid regions. The human and livestock populations in Niger started to increase dramatically (Fig. 7) during the period when historical aerial photography indicates that the tiger bush landscapes
became significantly fragmented, which strongly suggests that human disturbances may have been the major cause of the degradation. Indigenous knowledge of the community elders on the study site corroborate that they attribute degradation of the banded vegetation pattern to increased grazing and fuelwood harvest pressure that opened runoff pathways through the tiger bush. They noted this change because they started to have gullies cut through the cultivated lands downslope from the degraded banded vegetation rangelands.

These anecdotal statements, the corresponding population statistics and the ecological theory of the hydrologic function of the vegetation bands combine to make a circumstantial case in support of the hypothesis that vegetation bands maintain the hydrologic balance within the system. Once the bands are broken, the accelerated rate of runoff through the system results in an acceleration of the senescence and fragmentation of vegetation bands which is reflected in our analysis of the aerial photographs. This hypothesis is further supported by the success of restoration techniques that targeted re-establishment of the vegetation bands as a way to stop downslope gully erosion (Manu et al. 1999).

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