3. Specific Methods of Study

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Introduction

Banded vegetation is composed of two interacting and interdependent "phases": a vegetated phase and a more-or-less bare phase. Both phases are oriented along the contours and alternate along the main slope. As an array of bands in a landscape, the product is a system operating to display unique larger functional properties (Archer and Smeins 1991). The bare (or sparsely covered) soil zone acts as an impluvium because it generates a high proportion of runoff (Peugeot et al. 1997). The densely vegetated zone downslope (runon or sink area) intercepts and absorbs runoff water due to high infiltration rates (Delhoume 1992; Green, Kinell, and Wood 1994; Galle, Ehrmann, and Peugeot 1999). The two combined phases constitute the basic functional unit of the banded landscape, repeated many times across the landscape.

In Africa, banded landscapes have been reported from Mauritania to Somalia and Sudan (Macfadyen 1950; Clos-Arceduc 1956; Boaler and Hodge 1964; White 1970; Wickens and Collier 1971; Boudet 1972; Lawesson 1990; Leprun 1999). They have also been studied in Mexico (Cornet et al. 1992) and Australia (Slatyer 1961; Mabbutt and Fanning 1987; Ludwig and Tongway 1995).

In banded landscapes, structure and function are particularly strongly linked, but they can be affected by stress or disturbance, either from their natural environment (e.g., drought) and/or from human pressure such as grazing pressure or wood harvesting (chapter 11, this volume). It is the objective of this chapter to discuss some potentially useful field procedures and data analyses to address the four most frequently asked questions about banded landscapes:

- What is the geomorphological context of their occurrence?
- What is the fine-scale structure within the bands and its variation in space and time?
- What are the dominant biotic and abiotic properties and processes involved?
- Do the vegetation bands move upslope over time?

Banding is a simple, clear-cut example of ecosystem heterogeneity. Consequently, many methods developed to study heterogeneity in landscapes generally are useful in banded landscapes (Whittaker 1975; Greig-Smith 1983; Forman and Godron 1986; Turner and Gardner 1990; Kolasa and Pickett 1991; Dale 1999). The vegetation bands are sometimes asymmetric: the boundary of the upslope edge tends to be sharp, whereas the downslope edge tends to be more diffuse. In terms of resource distribution, this corresponds to a sharp increasing gradient in resource availability from the upslope edge to the core and the reverse extending from the core to the downslope edge. Vegetation structure mirrors this. Most of the methods used to detect, locate, and analyze ecotones or boundaries from ground-level survey data can be used (Forman and Godron 1986; Ludwig and Cornelius 1987; Johnston, Pastor, and Pinay 1992). The second section discusses some useful ground-based methods of data collection and the most appropriate spatial statistical analyses to assess the pattern properties in banded landscapes.

Understanding the processes by which the landscape transfers, accumulates, and uses its vital resources is of considerable importance in understanding overall function (Tongway and Ludwig 1997). Hydrological processes have been recognized as driving and controlling the structure and the dynamics of the vegetation at different spatial and temporal scales (chapters 4 and 5, this volume). Different ways to assess and to verify these, mainly hydrological, processes involved are summarized in the third part of this chapter.

Upslope migration of vegetated patches was often presumed or deduced from the spatial organization of the biota and the inferred runoff/runon processes in action (Ambouta 1984; Cornet et al. 1992; Montaña 1992; Mauchamp, Rambal, and Lepart 1994; Thiéry, d'Herbès, and Valentin 1995). Positive proof has not been forthcoming in the period these landscapes have been studied, and the issue is still being scrutinized. Methods used to address upslope migration are reviewed and considered in the fourth section.

Coarse-Scale Observations and Analysis

The first distinct feature of banded vegetation ecosystems is that most of the heterogeneity of the pattern is expressed in the horizontal plane. The first investigators recorded the distinctive pattern from aerial photography (Ives 1946; Macfayden 1950; Clos-Arceduc 1956). They were able to use this imagery to derive information on patch density, size, shape, edge morphology, location, and spatial distribution of bands in the landscape (e.g., more or less random, regular, or aggregated). They proposed some causes for the occurrence of banded landscapes. Ives (1946) related pattern orientation to the dominant wind direction, whereas Clos-Arceduc (1956) observed that the bands were parallel to the terrain contours.

More recently, remote sensing allowed quantification of the structure from digitized photographs (Mougenot and Hamani 1997; Wu, Thurow, and Whisenant 2000). Digitized aerial photographs have had limited use until now, although substantial future developments are expected as pixel size becomes smaller and image registration becomes more reliable. Valentin and d'Herbès (1999) associated broad-scale banding character with a rainfall gradient, comparing different sites along a latitudinal transect. Jacqueminet and associates (1989) characterized the class distribution of vegetated patch size on a binary picture. Couteron (1998) used spectral analysis by a Fourier transformation (Mugglestone and Renshaw 1996) to compare the periodicity and the dominant orientation of more-or-less banded vegetation landscapes. Also, a model based on the interplay between short-range cooperative interactions and long-range self-inhibitory interactions inside the vegetation community has been calibrated with the Fourier transform of a digitized aerial picture of a banded landscape in Burkina Faso (Lejeune, Couteron, and Lefever 1999; chapter 9, this volume).

Remotely sensed images from aircraft or satellites provide information on spatial or temporal changes in patch configuration through multisite or multidate analysis (White 1969). They allowed investigators to characterize, classify, and quantify patch cover over time at coarse scale. Recently, more attention has been paid to coarse scale as new analytical techniques are developed, and the need to follow trends over time increases in response to climatic or anthropic stress (Couteron 1998; Wu, Thurow, and Whisenant 2000). The task for future investigations is now to fill the gap between local field observations and data from remotely sensed imagery to establish an unbroken information continuum between the different scales (Bastin et al. 1993). Indeed, there is an urgent need to extrapolate ground-based interpretation to coarser scales and test cross-scale relationships.

Ground-Based Characterization and Quantification of the Pattern Properties

Data Collection

Grid surveys provide the most rigorous technique for the collection of data to characterize and quantify the heterogeneity of patterned landscapes. The resulting "map" of the landscape enables the two-dimensional character to be appreciated and provides incontrovertible proof of banding. Although useful for both symmetric and asymmetrical internal band structure, grid surveys require big data sets and need more complex data manipulation for landscape analysis. It is thus somewhat more costly in the expenditure of time, effort, and measuring equipment than simple transects (Tongway and Ludwig 1990; Cornet et al. 1992; Montaña 1992).

The linear transect, a special case of the grid, enables the collection of parameters or variables reflecting spatial changes in banded vegetation with economy of time and effort. The most widely used transect type in banded landscapes is the gradient-oriented transect ("gradsect") specifically aligned to reflect the effect of the strongest environmental gradient (Gillison and Brewer 1985; Ludwig and Cornelius 1987). In the case of banded vegetation, the gradsect crosses the vegetated bands from upslope to downslope. Most of the complexity of the biotic and abiotic features in banded landscapes can be revealed on such gradients. Gradsects are effective in providing data relating ecological features to causal physical processes and establishing spatial connectivity in the landscape due to the distributive flows of water, sediments, dust, nutrients, propagules, and so on (Tongway and Ludwig 1990). More generally, gradsects are the basic method of data collection to quantify ecotones (Johnston, Pastor, and Pinay 1992) because they are amenable to a variety of vegetation patch shapes.

There are many variations of gradsects in practice. They can be linear with point or segment data (Slatyer 1961), or in the form of a belt, using quadrat data (Ludwig and Tongway 1995; Couteron, Mahamane, and Ouedraogo 1996). Gounot (1969) used the segment method along linear transects to assess foliar cover and thus obtain the comparative cover and/or biomass of each group of plants. Different widths of transect have been combined (Montaña, López-Portillo, and Mauchamp 1990; Mauchamp et al. 1993). Couteron and colleagues (2000) used quadrats of two sizes along the same transect to measure the density of plants of widely different abundance. This practice enables economy in data collection effort.

Lateral variation within vegetation bands can be studied with transects oriented on the contour, where heterogeneity is much less pronounced than with gradsects (Worral 1960a; Boaler and Hodge 1964; Montaña, López-Portillo, and Mauchamp 1990). Erhmann (1999) studied differences of structure and function between convex and concave boundaries alternating along the upslope boundary of a thicket. She compared these data with the vegetation distributions in gradsects oriented down the slope, crossing the thicket.

Transects are flexible enough to permit the collection of data at a range of time and spatial scales ranging from small to large (Delcourt and Delcourt 1992). The technique has been used at local scales such as one-patch or across-patch boundaries (Montaña, López-Portillo, and Mauchamp 1990; Cornet et al. 1992; Seghieri et al. 1997). It has also been used to understand linear data dependence on the repetitive pattern (Ludwig and Tongway 1995). In this case, the sampled area must be sufficiently large to include repetitions of the basic functional elementary unit a sufficient number of times (Tongway and Ludwig 1990; Ludwig and Tongway 1995; Couteron, Mahamane, and Ouedraogo 1996). A very wide range of ecological data can be collected by using transects as the spatial reference.

Analysis of Spatial Data

There have been few temporal changes or intersite quantitative comparisons of banded landscape pattern reported in the literature (Valentin and d'Herbès 1999;

Couteron et al. 2000; Wu, Thurow, and Whisenant 2000). Frequently, only descriptive information was provided, and various visual criteria were proposed but rarely defined. Statistical tests are essential to explore detailed questions about pattern (Keddy 1991). We therefore focus here on the statistics of spatial data to analyze banded vegetation pattern.

Several statistical tests of varying complexity are available for spatial data analysis that have been elaborated in a number of standard texts. Cormack and Ord (1979), Greig-Smith (1983), and Sokal and Rohlf (1995) concentrate on the statistical analysis per se, whereas other works focus on the application of spatial statistics to general ecological problems such as landscape ecology (Turner and Gardner 1990), heterogeneity (Kolasa and Pickett 1991; Dale 1999), or landscape boundary detection (Hansen and Di Castri 1992). Few of these were developed specifically for banded vegetation. Statistical analysis of data derived in banded landscapes was a major component in Montaña (1992), Mauchamp and co-workers (1993), Ludwig and Tongway (1995), and Couteron, Mahamane, and Ouedraogo (1996). Despite spatial analysis being able to confirm nonrandom population distributions, the ecological interpretation was not always clear (White 1971; Couteron et al. 2000).

The scope of spatial statistics is too large to be comprehensively reviewed in several pages, nor is it the aim of this chapter. The following section reviews some examples of the main types of spatial statistical procedures that have actual or potential use for banded vegetation analysis. The choice of method depends on the nature and quality of the field data, the ultimate use of the results, and hence the balance between information accuracy and interpretation complexity. Table 3.1 summarizes spatial statistical analysis developed above according to the needs.

Quantification of the Structure Scale

Assessing the scales at which every component exhibits patchiness is crucial to a good understanding of ecological processes and resource utilization (O'Neil et al. 1986, 1988; Pickett et al. 1989; Wiens 1989; Gosz 1993). Despite the obvious

Table 3.1. Classification of Some Spatial Statistical Techniques According to Their Efficiency for a Given Aim[a]

	Quantification of structure scale	Location of boundaries	Delineation of homogeneous areas
Blocking	++		
Autocorrelations/ cross-correlations	++		
Global ecotone detection	+	++	+
Local edge detection (edge detection filters)		++	+
Smoothing filters	+	+	++

[a] Useless if nothing, + can be used, ++ useful

repetitive structure of tiger bush, not all species contribute to the same extent to the pattern perceived at coarse scale. Several species have been noted as taking little or no part in banded pattern. This is the case of *Prosopis glandulosa* in Mexico (López-Portillo and Montaña 1999) and *Pterocarpus lucens* in Burkina Faso (Couteron, Mahamane, and Ouedraogo 1996). The techniques described in this section enable the size and periodicity of the repetitive pattern to be characterized with statistical rigor and to determine which variables contribute to pattern.

Greig-Smith (1952) proposed a "blocking technique" that originally used field data derived from a grid of contiguous quadrats. Kershaw (1957) later adapted the method for use on linear transects. In this procedure, field data from a pair of contiguous quadrats are grouped into a block. All other quadrats are treated similarly. These blocks in turn are grouped, pairwise, into another set of larger blocks. This grouping process continues until only two blocks remain, each containing one half of the total data set. This creates a nested hierarchy of block sizes, with respective means and variances calculated at each block size. An analysis of variance is then performed for each block size in the hierarchy of blocks, the variance being partitioned between and within block size. The relationship between block size and mean square variance is then plotted, resulting in peaks and troughs emerging. Peaks correspond to block sizes in which adjacent blocks are dissimilar, whereas troughs represent block sizes in which adjacent blocks are similar (Goodall 1974). Although being criticized, mainly because the "treatments" are not independent as they should be in analysis of variance, the technique underwent a number of improvements (Ludwig and Goodall 1978; Turner et al. 1990).

The development of statistical tests to determine whether the spatial distribution of organisms along a resource gradient deviate significantly from random distribution led to the use of techniques that partition variance into spatial lags (Turner et al. 1990). For example, an autocorrelation test can be applied to see whether the observed value of a variable at one location is significantly dependent on values of the same variable at other locations. It assumes that the variables are normally distributed (Sokal and Oden 1978). This approach has the advantage that the locations as well as the attributes of data points are taken into account. Autocorrelation is suitable for parameters whose value varies at local scale. It does not account for regionalized variables that are too irregular to be modeled by smooth mathematical functions (Johnston, Pastor, and Pinay 1992). Repetitions of sequence are found by computing a measure of self-similarity in the data. The one sequence is compared at successive positions, as in the moving window technique. The degree of similarity between adjacent parts along the transect is computed, and every point is compared with every other to reveal the positions of strong similarities. These methods require large data sets and need very consistent autodependencies within the data sets to be powerful discriminatory tools (Ludwig, pers. comm.). Thus, it is appropriate for use in banded vegetation in which autodependency is expected. Other techniques that partition variance into spatial lags were presented by Turner and associates (1990). Cross-correlation has been applied to Mexican banded vegetation (Mauchamp et al. 1993) and semivariograms for regionalized variables in Burkina Faso (Couteron, Mahamane, and Ouedraogo 1996). The relative contribution of different shrub species to the banded pattern was thus verified. Dominant species were found to contribute the most to the banded pattern but not all the others.

Parameters of banded pattern based on periodic functions such as Fourier analysis (Renshaw and Ford 1984) have been used in Burkina Faso (Couteron 1998). This approach is particularly useful in comparing different banded landscapes or the distribution of various components within the same site because of the strong periodicity of the vegetated bands. This periodicity is conventionally thought to be the result of the dynamic balance between functional properties of vegetation and abiotic factors. One can test whether given components actually contribute to the overall periodicity measured by applying a Fourier analysis to each component. This is helpful, for instance, to address the role of the biological factors on the natural maintenance of the pattern or in discussing the effect of management on landscape function.

Detection and Location of Boundaries Between Pattern Elements

The location of boundaries between contiguous elements of banded pattern needs to be determined objectively and quantitatively to compare the pattern on different sites or on the same site over time. Location of the boundaries can be addressed through three types of method.

1. *Optimal limits.* Godron (1966) described an analysis based on the information theory using species presence along a transect to define boundaries in terms of "optimal limits." The method involves the use species presence/absence data on consecutive points, segments, or quadrats along a transect, the calculation of a relative value of heterogeneity ("information") for each species at each transect location. The heterogeneity value is plotted against the location on the transect. The optimal limit occurs where this heterogeneity value is at a maximum. The calculation can be computed for one, several, or all the species recorded. An analysis of the species distribution along the transect in relation to the "optimal limit" location gives the relative contribution of each species to the limit. This method has not been tested yet on banded vegetation patterning but was used on a less markedly heterogeneous pattern in a wet savanna in the Ivory Coast (Godron and Bacou 1975). "Global zonation" is a similar approach that also searches for edges in blocks of data by breaking the whole transect into segments that are as internally homogeneous as possible and as distinct as possible from adjacent segments (Davis 1986). Turner and co-workers (1990) discussed this method in some detail in relation to the quantification of landscape heterogeneity in general. Global zonation makes no assumptions about the repetitiveness of a pattern but is applicable to landscapes with abrupt transitions. It assumes that the landscape is composed of discrete homogeneous patches of any size. This makes it a useful spatial statistic to be applied to banded vegetation and also to other vegetation patch types (chapter 1, this volume).
2. *Edge detection filters.* This method is simple but powerful and useful in the analysis of ecological discontinuities (Niblack 1986). A moving split window

is laid over equal numbers of equally spaced sampling units, and an index of similarity or dissimilarity is calculated at each location of the window center (Ludwig and Cornelius 1987; Johnston, Pastor, and Pinay 1992). It permits the detection of landscape boundaries from one-dimensional data or to locate positions of high heterogeneity. It consists in calculating the "dissimilarity" (i.e., statistical distance) between values of a given attribute on either side of a moving split window of arbitrary width (Ludwig and Cornelius 1987). The approach is now in common practice (Turner et al. 1990; Kolasa and Pickett 1991; Johnston, Pastor, and Pinay 1992). The dissimilarity between attribute values of two parts of the split window is calculated at each location and computed successively along the entire transect length. A boundary is signaled when maximum values of the "statistical distance" metric occur. This indicates that the rate of change of the landscape attribute is at a maximum or peak. When these values are plotted against the respective positions on the transect, the location, the physical width, and "strength" of the boundaries are displayed. High and narrow peaks represent abrupt boundaries, whereas wider and lower peaks characterize more diffuse boundaries (Ludwig and Cornelius 1987; Johnston, Pastor, and Pinay 1992). The analyst can alter window widths at will to look at landscape organization at different scales. The ultimate quality of the boundary analysis depends on the resolution of the data used and the innate characteristic variation in the attributes involved (Turner et al. 1990). For assessment of band boundaries in banded vegetation, Ludwig (pers. comm.) used first a window width as small as possible (although this generates a plot with quite a lot of "noise"). He then slowly increased the window size until distinct peaks, denoting the landscape pattern elements, emerged from the noise. Too large a window as a first choice might have "smoothed" the analysis excessively. Johnston, Pastor, and Pinay (1992) used the method to locate and to assess the stability of the location and of change in several soil water attributes in Minosota. Ludwig and Tongway (1995) used it to assess the spatial organization and the functional connectivity in Australian landscapes of varying pattern clarity. A wide range of ecological data may be used as the input data.

3. *The "median smoothing filter"* is a method somewhat the reverse of the second approach (Niblack 1986). It consists in using a moving split window to locate homogeneous vegetated patches instead of to locate the position of maximum heterogeneity. Couteron and colleagues (2000) used it to compare two African banded landscapes differing only in the soil properties. They compared the thicket sizes and spatial distribution between a banded landscape in Burkina Faso and another one in Niger. A thicket was defined as "a stretch of consecutive quadrats for which the proportion of quadrats occupied by at least one mature woody plant is 'sufficiently' high." Variables used, such as plant "maturity," the size of the moving window, and the threshold of frequency of occupied quadrats in each window were defined from an existing knowledge of species growth and of coarse pattern nature. This smoothing technique does not alter the location of the boundary. It is especially useful when boundaries are not distinct.

Processes Within the Structure

Most of the biological processes such as seed dispersal, plant recruitment, competition, succession, role of soil microfauna, predation, and their spatial relationships within and between general patched vegetation can be found in Forman and Godron (1986) and Forman (1995). Most of the biological processes have not yet been extensively studied in banded vegetation patterns (Mauchamp 1992; Mauchamp et al. 1993; Couteron, Mahamane, and Ouedraogo 1996; Ouedraogo 1997; chapters 6 and 7, this volume). However, they were recognized as being important factors in maintenance and regulation of hydrological processes (runon, infiltration) and in the capacity of banded landscapes to conserve resources and biological and soil processes (Greene, Kinell, and Wood 1994; Tongway and Ludwig 1996; Ludwig et al. 1997).

Runoff and runon processes, which are crucial in banded landscapes, are the result of different infiltration rates in the " source" and "sink" areas, respectively. Runoff transfers water, soil, and litter from the source area, and infiltration and deposition processes recharge the fertile areas (Tongway and Ludwig 1997).

Quantification of the Local Water Balance

In arid and semiarid environments, consistent differences in available soil moisture are one of the main causes of the spatial heterogeneity of the landscape (Yair and Danin 1980; Olswig-Whittaker, Shachak, and Yair 1983). High infiltration in the vegetated band is responsible for establishing and maintaining vegetation pattern, as well as controlling the dynamics of the structure and its components by providing water for plant growth (chapters 5 and 7 to 9, this volume). To establish and quantify the efficiency of vegetation bands in intercepting, storing, and conserving water, the measurement of infiltration processes is fundamental. This is true both in the short term, in terms of resource supply to living organisms, and in the longer term and at coarser scales when dynamics and stability of the entire landscape structure were considered (Ludwig and Tongway 1997). An overview of the advantages and disadvantages of most of the techniques used to measure soil moisture content is described in Noble (1973). We discuss below the techniques that have been already used in banded landscapes.

Direct Measures

Monitoring the soil moisture content directly in different landscape pattern elements provides concrete verification of differential infiltration processes. The measurement locations (generally along a transect normal to the contour lines) and recording frequency need to be appropriate for the space and time scales being specifically addressed. Gravimetric techniques, and after calibration, neutron or gamma probes and time-domain reflectometry (TDR) all record the soil water storage in different soil layers. TDR measures volumetric water content absolutely. It is restricted to shallow depths as the measuring nods are delicate and easy to distort. The neutron probe is probably the technique the most used in tiger bush sites

(Delhoume 1992; Greene, Kinell, and Wood 1994; Peugeot et al. 1997; Galle, Ehrmann, and Peugeot 1999). The advantage of this technique is that once an access tube is properly installed, there is no further disruption of the soil and moisture content can be recorded as frequently as required. Repeated gravimetric sampling tends to destroy the site or at least alter the characteristics. The most suitable measurement regime is one in which the intervals between readings gradually increase after the rainfall event and the soil moisture decreases (Galle, Seghieri, and Mounkaïla 1997; Seghieri et al. 1997; Galle, Ehrmann, and Peugeot 1999; Seghieri and Galle 1999). However, the quantitative evaluation of the water status in the soil can be deduced only if appropriate calibration has been undertaken (Noble 1973).

Indirect Measures

Methods of measuring the water potential, which is directly linked to moisture status, are essential to study the water–soil–plant relationships and the derivation of moisture retention curves. In the field, one of the main tools in assessing water stress in plants is by measuring water pressure with a psychrometer or a pressure chamber (Seghieri and Galle 1999), and in the soil, tensiometers are commonly used (Peugeot et al. 1997). However, measuring water tension gives indirect measure of the reserves of the soil water storage because of the large changes in potential occurring at very short time distance intervals. Rather, it characterizes the potential transfers of water within the continuum soil-plant-atmosphere (Noble 1973). Soil tensiometers need to be buried in the soil, and the excavation of the soil types commonly found in tiger bush is extremely hard. The size of the soil samples required, to be representative, is large. Indeed, large stone fragments mainly located in the runoff zone and macropores located in the thicket center, create preferential flow paths (Bouma and Dekker 1981; Laurent et al. 1988; Ritsema and Decker 1996). In addition, the soil is generally hard to dig despite extreme variations of the soil resistance found by Dunkerley and Brown (1999). Those authors showed 400% change in soil unconfined compressive strength, measured in kilo-Pascals (kPa). It ranged from peaks of 4,000 kPa, immediately upslope of thickets on a hard setting duplex soil, to an average of 500 kPa within the thickets less than 10 m away on a self-mulching clay.

Other techniques, such as electrical, thermal, acoustic, or cohesive properties of the soil, measure water indirectly in the sense that they measure or sense some physical or chemical properties of the soil that is dynamically related to changes in soil moisture (Noble 1973; Valentin, d'Herbès, and Poesen 1999).

Runoff assessment

Runoff-runon processes caused by differential infiltration rates in landscape zones has long been recognized as the primary controlling factors of banded vegetation patterning (Worrall 1959; Slatyer 1961; Boaler and Hodge 1962, 1964; White 1969; Wickens and Collier 1971; Ambouta 1984; Tongway and Ludwig 1990; Cornet et al. 1992; chapter 4, this volume). Runoff-runon flows also mediate erosion/deposition processes between "source" and "sink" zones (Ludwig et al. 1997).

Although there was general acceptance of the runoff-runon proposition, there are relatively few studies in which the nature of the runoff flow was observed and described (Boaler and Hodge 1964). Barker (1992) used drops of dye to study flow patterns of sheet runoff during rain and observed diffuse thin flow moving at about 0.5 m s^{-1}, with low stone and sediment transport. He also noted that when water flow was confined in rills (on a degraded part of his site), the velocity increased by fourfold, compared with the sheet-flow, easily transporting stones weighing up to 80 g. Recently, studies by Greene (1993), Greene, Kinell, and Wood (1994), Peugeot et al. (1997), and Galle, Ehrmann, and Peugeot (1999) measured the runoff flow rates from bounded runoff plots (100 m^2 or larger in size) during rainfall events. This technique can be used to measure both water and sediment carried by runoff and is more fully described by Greene, Valentin, and Estève in chapter 4 of this volume. When the plot exceeds 10 m^2, both sheet-flow and channel water flow may be taken into account. The value of this procedure is to measure with some precision the quantity and dynamics of runoff generated from the experimental area. The study plot could examine the behavior of either a bare or a vegetated zone alone or, preferably, the basic functional unit composed of a paired runoff-runon complex. Hudson (1993) noted that these methods measure the total amount of water running off the bounded area but do not necessarily identify the origins of the flow within the plot.

Microplots of 1 or 2 m^2 may be appropriate research tools to characterize and compare the infiltration/runoff potential of different locations within a banded landscape complex, relating the data to different soil surfaces (e.g., different soil crust types). The method is relatively inexpensive, and multiple replications are possible. The use of rainfall simulators on such quadrats enables the use of controlled rainfall characteristics (e.g., intensity and duration) and also to collect data in dry field conditions (Mauchamp and Janeau 1993; chapter 4, this volume). However, runoff data (and sediment yield if desired) is interpretable only at the scale of the plot: scaling the results up to quantitatively represent whole landscape performance is not possible due to nonlinearity in the relationships when going from fine to coarse scale. Data from small plots tend to overestimate erosion measured at landscape scale. However, these methods are useful in making intersite comparisons or comparing the same site over time.

In most of these studies, the plots have specifically installed barriers or boundaries to confine runoff and define the area from which the runoff and soil are being collected, but there are some cases in which it is appropriate to use unbounded plots (Planchon 1991). They used a small collecting gutter, let into the soil surface and oriented on the contour, and connected to a collection container on the downslope side. This arrangement permits the measurement of the amount of water crossing a watershed section defined by the width of the gutter after each rainfall event. The gutter length must be chosen to represent the average distance between plants likely to intercept runoff flow (Planchon and Janeau 1990). Various degrees of refinement are possible with this approach, but often a simple design yields adequate data. The method requires and is amenable to multiple replications to overcome the uncertainties arising from the lack of plot boundaries and to account for site variations in terms of microtopographic features and rills (Barker 1992). This technique was used in banded vegetation in Niger to evaluate the rainfall conditions (intensity and amount) under which the runoff can cross the thicket (Ehrmann 1999).

Casenave and Valentin (1992) used an indirect technique that classified soil surface crust types into groups representing a range in runoff capability in semiarid areas of West Africa. They showed that it is possible to subdivide the soil surface type into a number of distinct, internally homogeneous hydraulic units, called "unit surfaces." Owing to the large number of possible combinations of these surfaces, the concept of "surface features unit" was defined to characterize a small watershed composed of differing unit surfaces (i.e., a group within which interactions occur), as it is the case in banded landscapes (Seghieri et al. 1997). Mapping the units facilitates modeling of the hydrological behavior of the basic functional unit, when the parameters of runoff production are combined in proportion to the surface area occupied (Janeau, Mauchamp, and Tarin 1999; Valentin and d'Herbès 1999; Valentin, d'Herbès, and Poesen 1999; chapter 4, this volume).

Another indirect technique is to use microtopography to predict the runoff-runon behavior at unit surface scale. At the fine scale, the roughness of the soil is of great significance for the behavior of surface runoff and erosion-deposition processes. It was recently used to characterize surface runoff as one of the many factors that differentiates the various components of the mosaic (Dunkerley and Brown 1999). Tongway (1994) and Tongway and Hindley (1995) used very similar assessments of soil microtopography in implementing routine monitoring procedures for assessing the functional status of banded landscapes in Australia.

Experiments and Techniques Used to Verify the Processes

Some processes have been deduced from description of spatial pattern alone. Keddy (1991) proposed to statistically test the relationships between state variables (e.g., biomass and species richness or competition and biomass) from data describing organism distribution. However, even if the properties of every species were known, they might not allow us to understand and predict the whole system behavior. Relationships between sets of dependent variables relating to organisms (i.e., biomass, cover, density) and state variables relating to resources (i.e., soil water, nutrients, and organic matter contents or seed stock) could be tested or related to soil characteristics (i.e., soil surface features, porosity, infiltrability, hydraulic conductivity). Even so, such relationships tend to reflect past circumstances in a static sense and do not inherently enable a predictive understanding to be developed.

Applied experimental treatments have been helpful to effectively and quickly validate or refine hypotheses and assumptions about landscape function that follow from observations in natural conditions. As an example, in Sudan, Worrall (1960b) anchored palm leaf mats to the ground in the bare soil zone at the beginning of the rainy season to simulate the role of natural vegetation cover in collecting water. At the end of the rainy season, the mats had not only collected more rainwater than the bare ground but also much sand and dust, so that they had become firmly anchored in the ground without the need of stakes. From testing a simple hypothesis about water accumulation, Worrall (1960b) acquired information about other processes such as sediment deposition after a single rainy season. A similar procedure was used at Lake Mere in Australia (Tongway and Ludwig 1996; Ludwig and Tongway 1997; Noble, MacLeod, and Griffin 1997). "Brush piles" on the ground quickly succeeded in trapping runoff water, soil sediments, and litter, thereby creating new fertile patches with greatly improved biological, chemical, and physical soil properties compared with the controls composed of untreated, bare, stony slopes. Experiments, therefore, may achieve faster and more precisely interpretable outcomes due to the specific control of landscape processes than observations of natural processes under ambient conditions. For instance, Mauchamp and Janeau (1993), when using a rainfall simulator, applied concrete to the base of shrubs in banded vegetation of Mexico. They demonstrated the role of the shrub canopy in decreasing the kinetic energy of the raindrops and in creating stem flow that channeled water into the base of the shrub: the lower the rain intensity, the greater the "harvesting" effect, due to less vigorous flow rates Two independent experiments investigated the restriction of runon into vegetated bands. In Niger, Seghieri and Galle (1999) built a wall at the upslope boundary of a thicket to restrict runon. Responses in terms of infiltrated water, vegetation phenology, and physiology were assessed. Differential responses from distinct zones and species were found. The experiment verified the necessity of the runon water, quantified its benefit to the vegetation, also showing that the gains were spatially heterogeneous. In Australia, Noble, Greene, and Müller (1998) prevented runon water infiltration in replicated plots in the interception zone by sheet metal barriers buried in the ground, with 30 cm exposed. They recorded a severe inhibition of the herbage dry matter production (see Figure 11.2, this volume). The requirement for upslope runoff to sustain downslope vegetation had been widely accepted in principle before this work, but its significance had not been experimentally demonstrated. Keddy (1991) advocated an experimental approach to verify the presence of particular trends in those processes and their constraints or boundary conditions.

Dynamics of the Banded Vegetation Patterns

A review of the accumulated knowledge on vegetation dynamics in banded patterns is given in chapter 7 of this volume. Temporal changes are affected by both natural (mainly climatic) and human influences (grazing, wood harvesting), sometimes in combination with a synergistic effect on the landscape. Some studies analyzed the status of the ecosystem as consequences of human activities but without monitoring the temporal changes per se (Orr 1995; Achard 1997). A new and effective methodology enabling the long-term survey of the dynamics of the vegetation bands at the whole landscape scale has been reported in Wu, Thurow, and

Whisenant (2000) in Niger. It is based on the quantitative comparison of remotely sensed images, seeking evidence of landscape fragmentation. This study showed that serious fragmentation of the vegetated bands occurred between 1960 and 1992 and that only small increments of band were evident. These increments only occurred on the upslope edge of the band, and no evidence of "defragmentation" or lateral extension of the bands was found.

Upslope migration of the vegetation bands is one of the most debated questions about the long-term functioning of banded landscapes. Evidence and predictions of both movement and refutation of the possibility of movement are common in the literature (chapter 2, this volume). As the detailed studies of banded landscapes have been over only short time spans, evidence of either movement or stationarity may well be confused by inadequate data to properly support either position. For example, movement may be part of a cyclic expansion-contraction phenomenon ("pulsation"), driven by cyclic variations in rainfall. Consequently, techniques to rigorously verify (or deny) migration and then to measure the rate of movement over long time scales are required to ascribe more certainty to this controversy.

Direct Measures

Ground benchmarks are the most direct technique to check whether movement (either migration or pulsation) of the vegetated patches can be measured and the rate estimated. This was done by Worrall (1959) for annual grass bands in Sudan (0.3 to 1.5 m yr^{-1}) and by Leprun (1999) for upslope expansion in Mali (0.1 to 0.75 m yr^{-1}). Cornet and associates (1992) and Montaña (1992) studied migration by using multi-annual surveys of plant population frequency in the upslope and downslope borders of thickets within a grid of contiguous quadrats. They were unable to measure a migration rate in the more than 5 years of their study. Clearly, the time scale of observations should be commensurate with the expected time scale of the system dynamics. It is possible that migration is a stochastic process, depending on climatic or other circumstances not yet clearly defined.

Indirect Measures

Indirect assessments of band movement have largely been concerned with evidence provided by vegetation dynamics inferred from the spatial pattern of seedling/dead trees across the band (i.e., along the resource availability gradient) (Couteron et al. 2000) or by tree age distribution (Mabbutt and Fanning 1987; Tongway and Ludwig 1990; Ichaou and d'Herbès 1997). Mabbutt and Fanning (1987) used the depth of siliceous hardpan to counter propositions of movement. Under the mulga bands, the hardpan was deeper than in the open bare areas, thus providing a larger soil water store for the long-lived mulga trees to use. The spatial distribution of natural isotopes of carbon may provide evidence of the long-past presence of plants in the bare zone and thus be helpful in providing insights into long-term dynamics (Chappell et al. 1999; Guillaume et al. 1999), but the evidence is not yet compelling.

Summary

The literature reviewed here provides a wide range of techniques useful in the study of banded landscapes, ranging from simple to complex, cheap to expensive, and from static to dynamic. Research in banded landscapes has only recently moved on from descriptions of pattern to assembly and response rules (Keddy 1991) to provide a predictive understanding of landscape function and the effects of perturbation. Many of the published studies have addressed simple disconnected aspects of soil physical, chemical, and hydraulic properties and vegetation distribution. Future studies need to integrate these aspects and to address issues such as competition and facilitation processes in a holistic way. This chapter provided an overview of techniques used to date in banded landscapes and refers the reader to concepts and procedures that would facilitate future studies of these aspects.

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