1. Banded Vegetation Patterns and Related Structures

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Introduction

The study of banded vegetation pattern has proceeded in three steps. The first step consisted of a recognition phase. An early reference to plant formation in western British Somaliland was that of Gillett (1941). Most banded vegetation patterns are difficult to identify on the ground, and their spatial extent was not appreciated until the 1950s when the systematic aerial photographic surveys began (Clos-Arceduc 1956). From the air, the pattern is clearly composed of regularly spaced densely vegetated bands interspersed with bare or less densely vegetated areas. Aerial photographic interpretation proceeded at a number of locations at about the same time, leading to a proliferation of local names for banded vegetation (Boaler and Hodge 1964; White 1969; Mabbutt and Fanning 1987; Montaña, López-Portillo, and Mauchamp 1990). Often these bands or arcs cover broad areas of several square kilometers, forming a distinctive pattern similar to the pelt of a tiger, hence its common name of tiger bush in Africa (Figure 1.1). Similar landscape patterns were called mulga groves in Australia (Slatyer 1961) and mogote in Mexico (Cornet, Delhoume, and Montaña 1988). Many preliminary studies were characterized by "observation/description": the scope of published work was somewhat speculative, exploring a range of explanations for a new and enigmatic landform (Clos-Arceduc 1956; Boaler and Hodge 1964; White 1970).

The second phase involved more experimental studies to test hypotheses suggested in the preliminary phase (Slatyer 1961; Ambouta, 1984; Cornet, Delhoume,

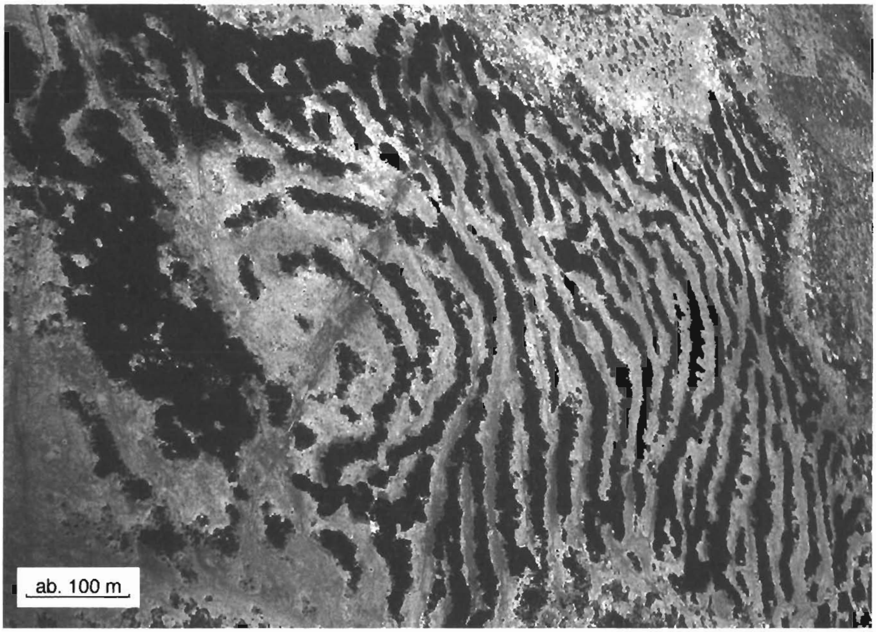

Figure 1.1. Oblique aerial photograph of "typical" tiger bush in Niger, 13°40 N, 2°40 E. (Photo from C. Valentin.)

and Montaña 1988). These included the hydrological functioning (chapters 4 and 5, this volume), ecosystem dynamics (chapters 2, 7 to 9, and 12, this volume), and land management issues (chapters 10 and 11, this volume).

Model building was the most recent phase, and issues such as band initiation and upslope movement were addressed because the field data had been equivocal (chapters 8 and 9, this volume). This step made use of data and hypotheses emerging from the two earlier phases of study to examine the initiation and dynamics of banded landscapes (Mauchamp, Rambal, and Lepart 1994; Thiéry, d'Herbès, and Valentin 1995; Lejeune and Tlidi 1999).

The study of banded landscapes is still somewhat piecemeal. The nature of field work undertaken at different sites reflects the wide variety of available scientific expertise that has been brought to bear on banded landscapes. Progress has therefore been globally uneven. Nevertheless, the state of knowledge now has sufficient maturity to review overall progress and to synthesize the available information.

The aim of this first chapter is to review the main types of banded vegetation patterns at a synoptic scale. As becomes evident, there are many manifestations of vegetation banding, depending on a number of factors. We use a simple classification system based on three simple discriminators:

1. Orientation of the bands with respect to the direction of slope and prevailing wind

2. Degree of contrast between the two phases of the vegetation mosaic
3. Uniformity of the soils beneath the bands and the interbands (Figure 1.2)

Bands Perpendicular to the Slope Direction

Landscapes with Undifferentiated Soils

Landscapes with High Band-Interband Contrast

Tiger Bush. Since the pioneering work of Clos-Arceduc (1956) in Niger, many studies have been devoted to tiger bush both in West Africa (White 1970; Ambouta 1984; Thiéry, d'Herbès, and Valentin 1995; Couteron et al. 2000) and in East Africa (Greenwood 1957; Worral 1960; Wickens and Collier 1971). Typically, five zones were distinguished along transects through tiger bush pattern, extending from the downslope edge of the vegetated band to the core of the next lower vegetated band (Figure 1.3a, b; Thiéry, d'Herbès, and Valentin 1995; Valentin, d'Herbès, and Poesen 1999; chapters 4 and 5, this volume.

The bands aligned with the contour support distinctive communities of annual grasses and forbs, mainly at the upslope margin of the band (Seghieri et al. 1997), with shrubs and trees in the core of the band. The interbands are nearly completely devoid of vegetation. There is little or no difference in soil type between the band and interband (Bromley et al. 1997). Commonly, the bare interband is more steeply

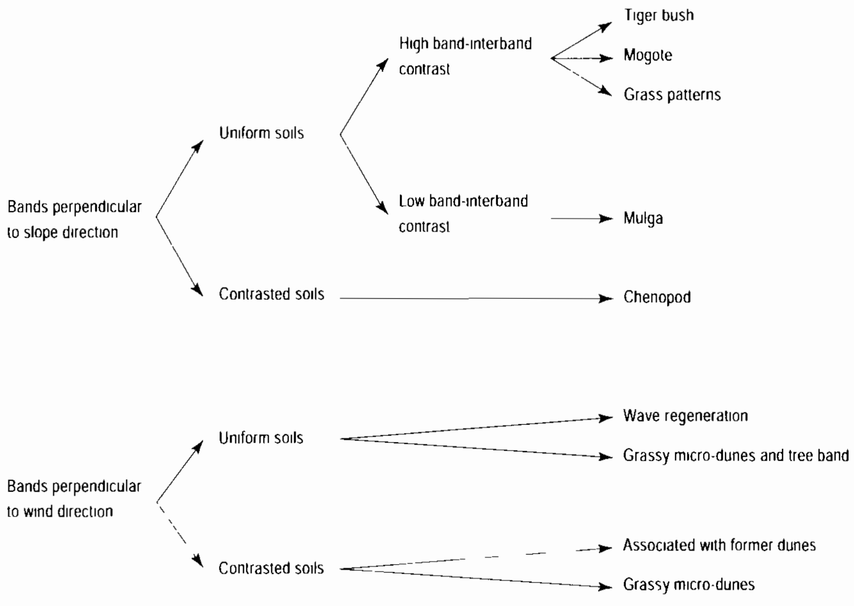

Figure 1.2. Classification of the principal types of banded vegetation pattern.

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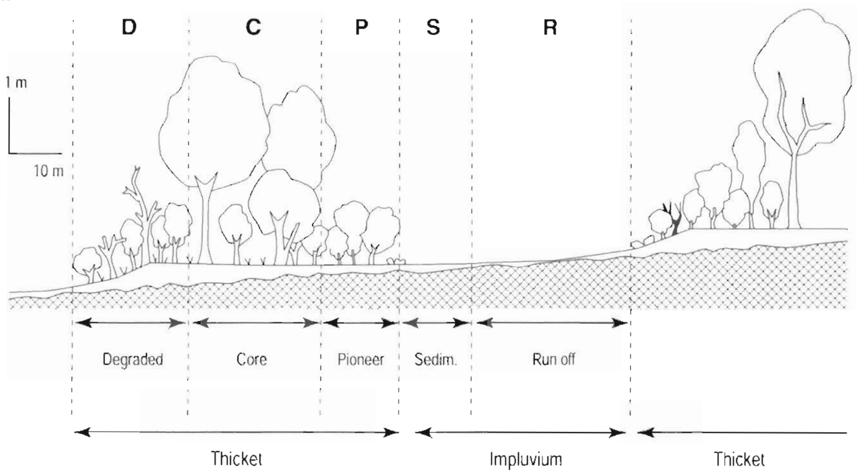

Figure 1.3a. Schematic diagram of a typical transect through the tiger bush in Niger. (Adapted from Thiéry, d'Herbès, and Valentin 1995; Hiernaux and Gérard 1999.)

b

Figure 1.3b. Lateral ground-level view of a degraded downslope edge of tiger bush in Niger. (Photo from C. Valentin.)

sloping than the vegetated band, but there can be local exceptions to this topographic distinction (Chappell et al. 1999). Deposited alluvium at the downslope edge of each interband can result in the formation of a small ridge that acts as a barrier to runoff.

In West Africa, typical tiger bush is found mainly in southwestern Niger, in northern Burkina Faso, and in the adjacent Gourma region in Mali (Figure 1.4). The mean annual rainfall of these regions ranges from 300 to 700 mm yr^{-1} Tiger bush develops on sites with a common array of factors: a semiarid climate, internally draining sites with an underlying sedimentary or metamorphic geology (Leprun 1999).

In Niger, the tiger bush covers 1 million h (chapter 11, this volume) on ferruginous plateaus where the ancient sand deposits have been removed by erosion. When there is a sand cover in Niger or in Mali, banded vegetation does not occur (Figure 1.5; Leprun 1992, 1999; d'Herbès and Valentin 1997).

Variations in band wavelength, band width, and contrast between bands and interbands occur on these plateaus (Figure 1.6, Valentin, d'Herbès and Poesen 1999).

Typically, the wavelength of the bands increases with decreasing slope (d'Herbès, Valentin, and Thiéry 1997; Eddy et al. 1999). Mixtures of band wavelengths can be discerned in close proximity, due to subtle slope differences (Figure 1.7). However, below a critical threshold of slope gradient (0.2% in Niger), the banded

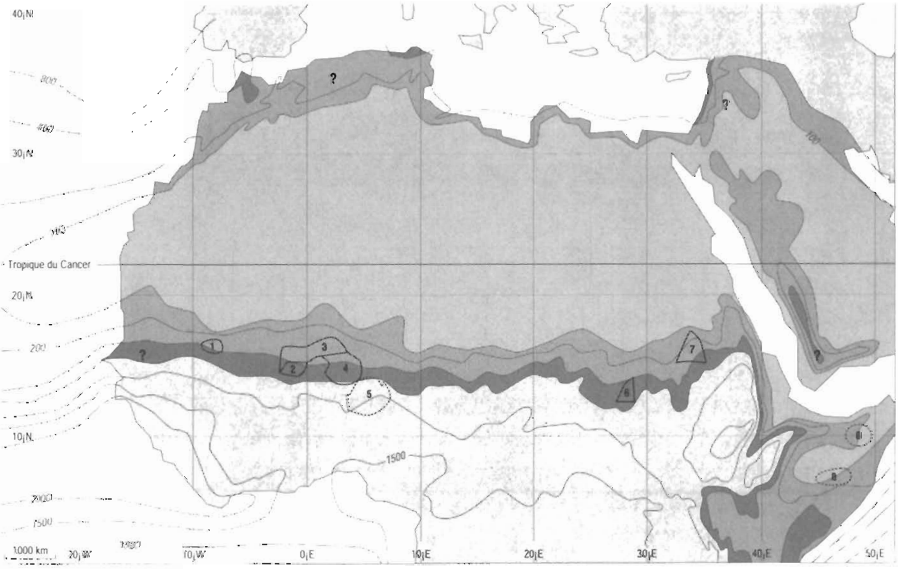

Figure 1.4. Distribution of the tiger bush in northern semiarid zone of Africa according to mean annual precipitation (P). Light gray for P <400 mm ; dark gray for 400 mm < P < 600 mm. Location of banded patterns from (1) Audry and Rossetti 1962; (2, 3, and 4) Leprun 1992, 1999; (5) Zonneveld 1999; (6) Wickens and Collier 1971; (7) Worral 1959; (8) Macfayden 1950. (Adapted from Wickens and Collier 1971; Leprun 1999.)

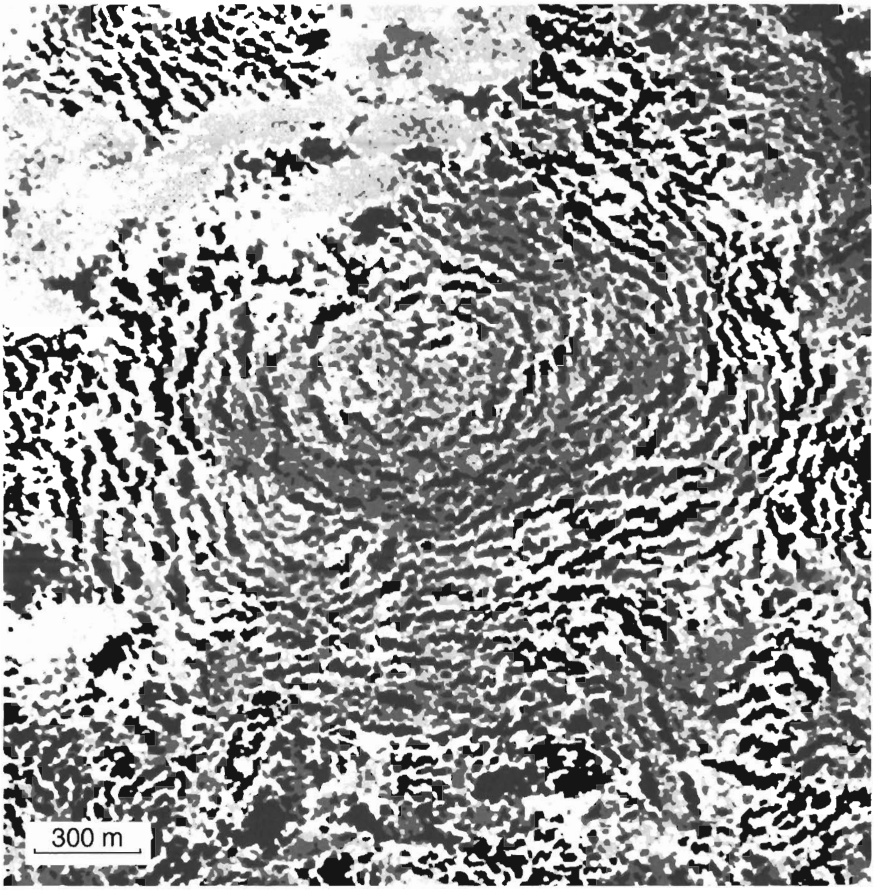

Figure 1.5. Aerial view of tiger bush in Niger on a ferruginous plateau. (Système Probatoire d'Observation de la Terre [SPOT] Panchromatic, 1991.)

pattern disappears and the vegetation assumes a "spotted" distribution (see Figure 1.6). Aguiar and Sala (1999) also report this in Argentina. The slope threshold tends to increase with mean annual rainfall (Valentin, d'Herbès, and Poesen 1999).

The interband/band ratio decreases exponentially with increasing rainfall, varying from 2 under 300 mm of annual rainfall to 0.5 under 700 mm (Valentin and d'Herbès 1999). This relationship was assessed in Niger along a rainfall gradient as well as over a 30 year time sequence (Figure 1.8; Valentin and d'Herbès 1999; Wu, Thurow, and Whisenant 2000). Concurrently, the width of the vegetated bands tends to be reduced with decreasing mean annual rainfall, forming a "dashed" pattern (Ambouta 1984).

Conversely when mean annual rainfall increases, the contrast between the bands and the interbands becomes either less pronounced (fuzzy patterns, Figure 1.9) for slopes gradient of about 0.3% or less banded (dense spotted patterns, Figure 1.9)

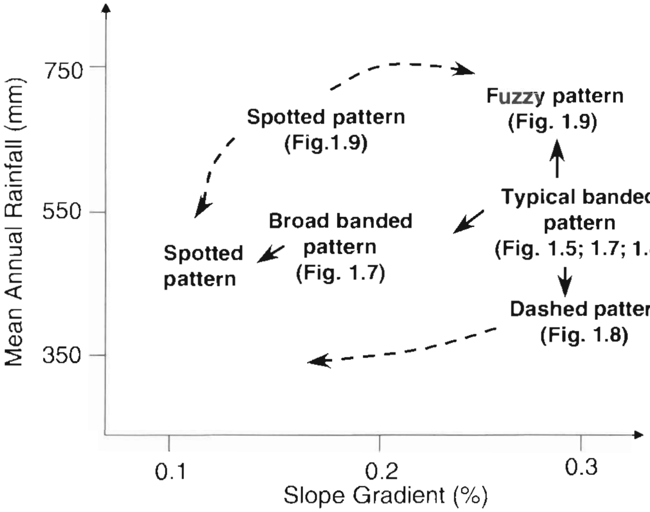

Figure 1.6. Schematic classification of main vegetation patterns in Niger, according to mean annual rainfall and slope. Dark arrows indicate potential transition between pattern types; dashed arrows represent potential spatial extension of the pattern. (Adapted from Valentin, d'Herbès, and Poesen 1999.)

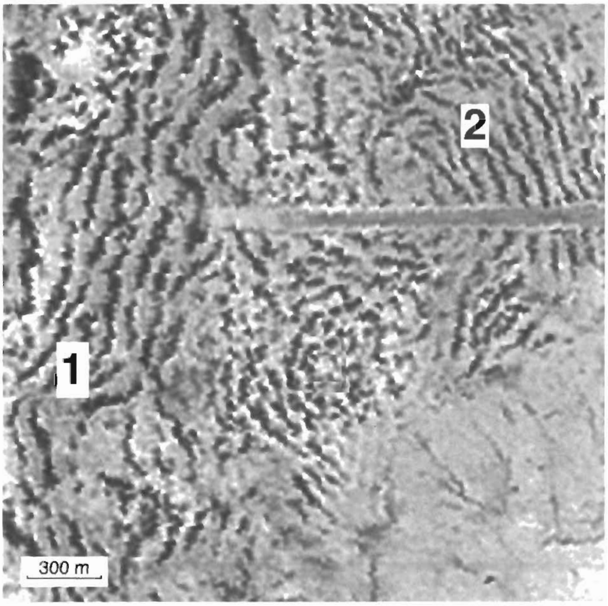

Figure 1.7. Co-occurrence of "broad banded" (zone 1: slope < 0.20%) and "typical" (zone 2: slope 0.25%) vegetation patterns on the same plateau in Niger (mean annual rainfall, 60 mm). (SPOT Panchromatic 1991.)

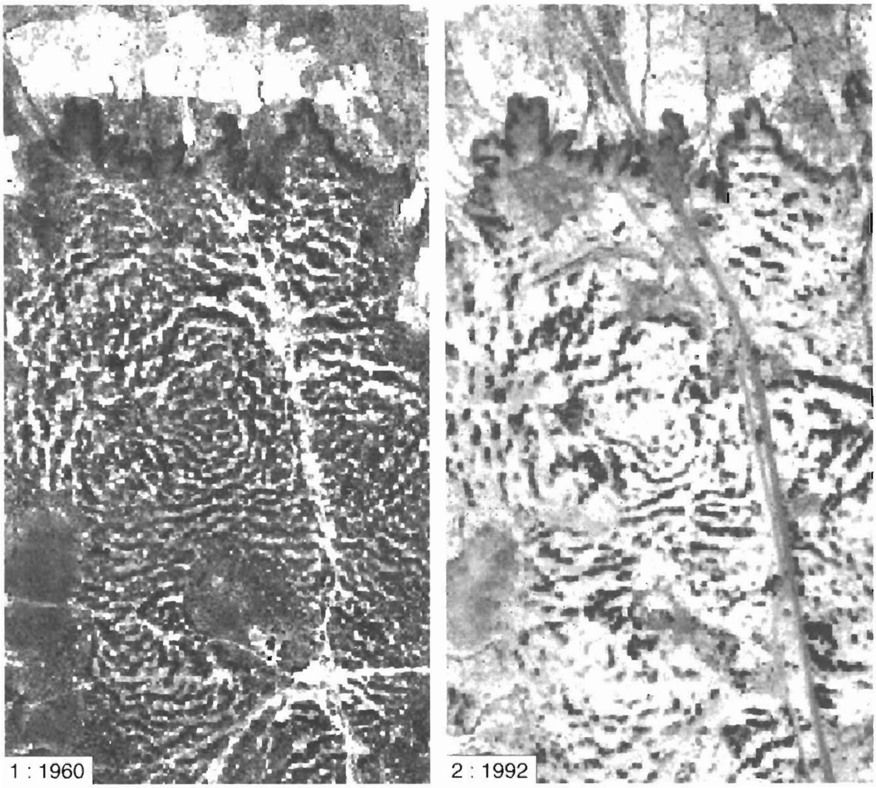

Figure 1.8. Degradation of a "typical" tiger bush pattern (1, 1960) to a "dashed" pattern (2, 1992) due to greatly increased anthropic pressure in terms if firewood collection and a decrease in mean annual rainfall. (From Wu, Thurow, and Whisenant, 2000. Permission courtesy of Blackwell Science Ltd.)

The Mogote. Mogote is the local name for the banded vegetation pattern studied in the Chihuahuan Desert of northern Mexico (Cornet, Delhoume, and Montaña 1988; Montaña, López-Portillo, and Mauchamp 1990; Cornet et al. 1992; Montaña 1992; Mauchamp, Rambal, and Lepart 1994; Delhoume 1995; López-Portillo and Montaña 1999). This pattern is very similar to tiger bush (Figure 1.10) but develops under more arid conditions than in West Africa.

The region is located at about 1100 m above sea level, receives a mean annual rainfall of only 283 mm (variation coefficient of 23%; Mauchamp and Janeau 1993). These banded patterns occur in the lower part of the hillslopes on slope gradients of about 0.5%. The substrates include alluvia and colluvia. The soil texture varies from clay to sandy-clay loam with similar surface crusts to those observed in tiger bush (Figure 1.11; Janeau, Mauchamp, and Tarin 1999). There is no difference in soil type between the bands and the interbands except for gilgai microrelief in the upper layers of the vegetated bands (Delhoume 1995). The trees of the

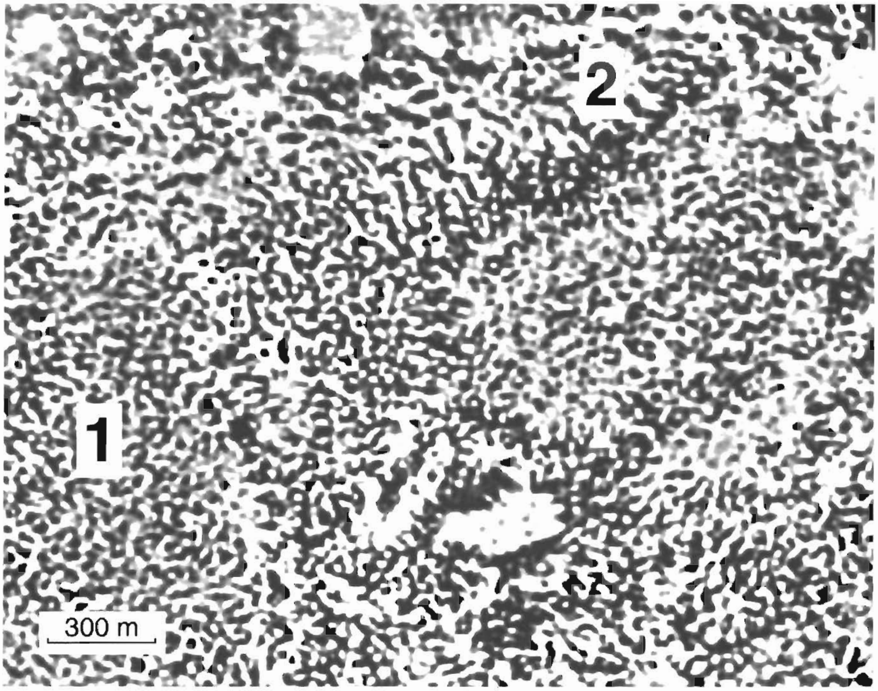

Figure 1.9. Co-occurrence of "spotted" (zone 1, slope = 0.20%) and "fuzzy" (zone 2, slope = 0.35%) patterns on the same plateau (680 mm annual rainfall) in Niger. (SPOT Panchromatic 1991.)

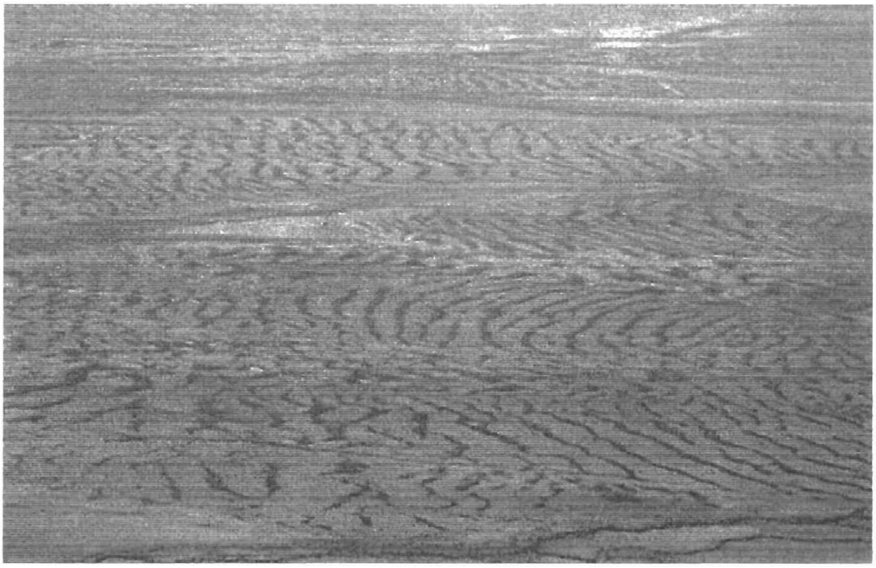

Figure 1.10. Oblique aerial view of the "mogote" pattern in northern Mexico. (Photo from J.P. Delhoume.)

Figure 1.11. Ground-level lateral view of the upslope fringe of the vegetation band in the mogote banded vegetation pattern in northern Mexico. (Photo from C. Valentin.)

mogote are shorter than in West Africa (2.5 m compared with 7 m) and the grass is perennial rather than annual (chapter 5, this volume). The interband/band ratio (3 to 4) is much higher than in Niger.

Grass Patterns. Vegetation patterns consisting of alternating bands of grass and almost bare soil oriented on the contour in the Sudan and Somalia (Macfayden 1950; Worrall 1959; Boaler and Hodge 1964; Hemming 1965) were among the earliest recognized banded landscapes. There are no differences in soil type reported for the grassy and the bare bands, a similar situation to tiger bush and the mogote. These banded landscapes are located on very gentle slopes of about 0.5% under arid and semiarid conditions (100 to 400 mm rainfall yr^{-1}). Soil textures range from loam to sand. The interband/band ratio of 2 is similar to that of the drier tiger bush regions in West Africa.

Landscapes with Low Band-Interband Contrast

Mulga. There are extensive banded landscapes in Australia where the tree component is dominated by mulga (*Acacia aneura*), with canopy covers between 20 and 40% (Figure 1.12). These lands have characteristics typical of banded landscapes everywhere: low slopes (0.2 to 2%), sheet-flow of runoff water and annual rainfall between 200 and 500 mm. Rainfall seasonality varies between uniform to summer dominance. Landforms range from slightly convex through planar to slightly concave. Some landscapes are located on tertiary residual plateaus, similar to those in Niger, whereas others are on piedmont slopes and alluvial plains

Figure 1.12. Oblique aerial view of groved mulga in Australia. (Photo from G. Griffin.)

(Mabbutt and Fanning 1987). The soil textures vary from clayey-sand to sandy-clay and are generally acid, with a slight increase in texture with depth. Parent materials are sandstones. Physical crusting of the surface soil is ubiquitous. Typically, banding is narrower on finer-textured soils. At the higher rainfall end, the bands, or groves, the common name in Australia, have a dense perennial grassland on the upslope edge of the band (Figure 1.13a, b). At lower rainfalls, there may be a sparse (<4% cover), unpatterned perennial grass or shrub understory. Intergrove zones are typically bare (Figure 1.13b) but may grow ephemeral herbage after rain. There are large areas in Western Australia where the banding is underlain by a silica-cemented hardpan (Bettenay and Churchward 1974) varying from 15 to 100 cm below the surface.

Banded Pattern with Differentiated Soil Types

Chenopod Shrublands

Extensive areas of banded chenopod shrublands occur in eastern Australia, associated with the Barrier Range (Figure 1.14). These occur on typical landforms and climate for banded vegetation: gentle planar slopes associated with outwash plains from the ranges, which are a maximum of 300 m above the surrounding plain, 200 to 250 mm annual rainfall. The slopes extend to the east and west of the range, which is oriented north–south. These banded landscapes are unusual in having distinctively different texture profiles associated with the vegetated band and the bare interband. The former zone is characterized by deep cracking self-mulching calcareous clays with gilgai microrelief, whereas the interband zone is composed of a

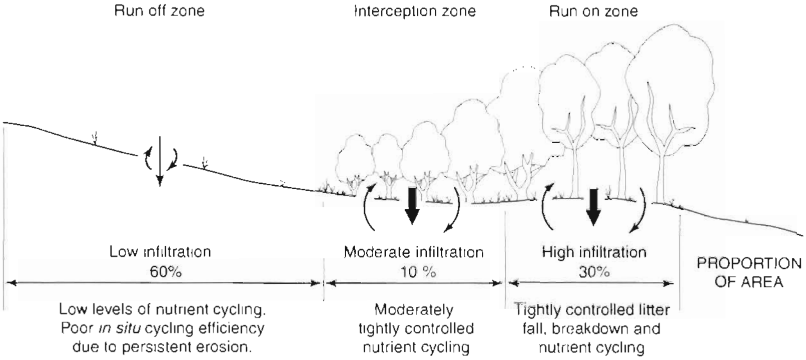

Figure 1.13a. Schematic diagram of a typical transect through groved mulga in Australia. (Adapted from Noble, Greene, and Müller 1998; Tongway and Ludwig 1990.)

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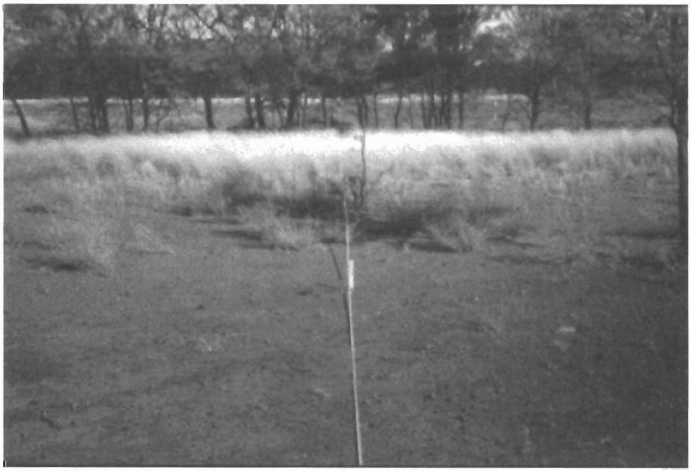

Figure 1.13b. Lateral ground-level view of groved mulga in Australia. (Photo from D.J. Tongway.)

a texture-contrast soil with a noncalcareous loamy A horizon about 10 cm deep, overlying a red well-structured clay (Wilson, Tupper, and Tongway 1982). The interband is frequently covered by stone and is bare of vegetation. There is a large differential in infiltration rate between these soils, and runoff water feeds the vegetated band from as little as 4 mm of rain (Dunkerley and Brown 1995). Typically, chenopod shrubs, *Atriplex* and *Maireana* species, occupy the band, but when infrequent summer rains occur, dense stands of the perennial grass *Astrebla* germinate and persist as long as the soil water supply remains. The clay materials were deposited by aeolian action about 16,000 years B.P. and have their origin in ancient lake basins to the west (Chartres 1982).

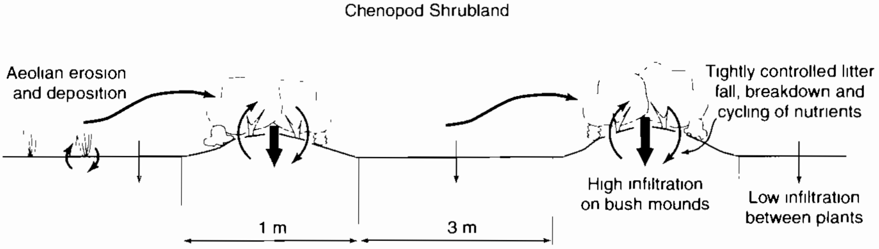

Figure 1.14. Schematic diagram of a typical transect through chenopod. (Adapted from Tongway 1993.)

Bands Perpendicular to the Wind Direction

Landscapes with Undifferentiated Soils

Wave Regeneration

Wave-regenerating forests consist of stripes of trees perpendicular to the prevailing wind direction, with older and dying trees in the windward edge and a seedling regrowth on the lee side of each band. These patterns have been recognized in northeastern United States (Sprugel 1976; Sprugel and Bormann 1981), central Japan (Kohyama 1988; Sato and Iwasa 1993), and eastern Tierra del Fuego (Puigdefábregas et al. 1999).

Using a model based on a cellular-automata simulation, Sato and Iwasa (1993) assumed that trees die if they are taller, by a critical threshold value, than their windward neighbors (Figure 1.15). The major cause of death was the desiccation of canopies in winter. A similar model (Puigdefábregas et al. 1999) also generated bands from initially random patterns. The authors hypothesized that tree clusters produce cone-shaped wind shadows that protect larger clusters on their leeward side, this process being repeated and enlarged through a positive feedback mechanism. The model showed that the higher the tree growth, the longer the wavelengths and the higher the wave propagation rates. More lethal winds led to shorter wavelengths and lower propagation rates.

Alternating Microdunes and Bands

More complex banded patterns have been reported in Mauritania by Audry and Rossetti (1962), in Mali by Leprun (1992, 1999), and in Australia by Mabbutt and Fanning (1987). These consist of a band system oriented nearly perpendicular to the wind direction comprising a sandy grass-covered microdune (Figure 1.16), a bare sloping crusted band, and a dense vegetated band including some trees or shrubs. These patterns have been attributed to alternate wind action and sheet water flow, perhaps representing climatic variations over decade to century time scales.

Figure 1.15. Schematic diagram of a typical transect in a wave regenerating forest. (From Sprugel 1976.)

Bands with Soil-Type Differentiation

Bands Associated with Former Dunes

In semiarid regions, to account for banded patterns that maintained their spatial orientation irrespective of topographic variation, they have been associated with leveled former dune fields (Figure 1.17). These have been described mainly in northern Nigeria (Clayton 1966, 1969; Zonneveld 1999) and in the Kimberley district of northwest Australia (Goudie, Sands, and Livingston 1992).

Grassy Microdunes

Desert ripples in the Salt Lake Desert (United States) are small transverse dunes, 9 to 150 m long, 25 to 90 cm high, with a crest interval of 3 to 15 m. They are par-

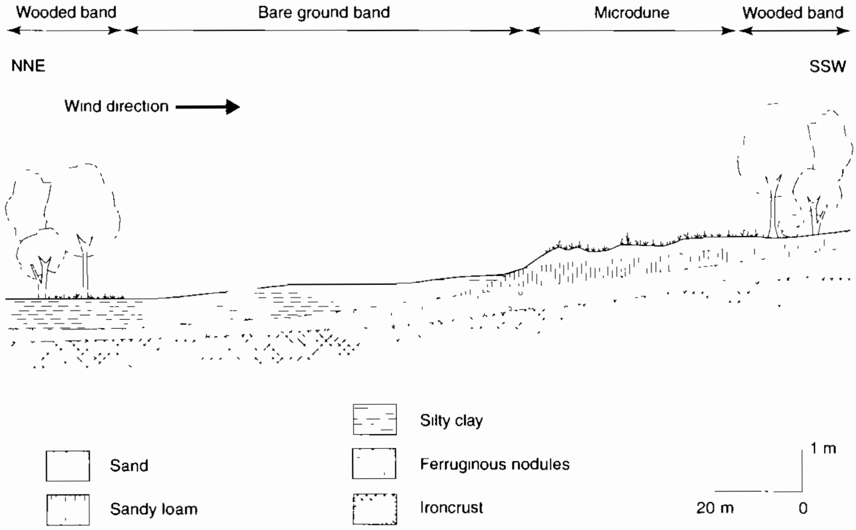

Figure 1.16. Schematic diagram of a typical transect alternating microdunes and bands in Mali (Adapted from Leprun 1999.)

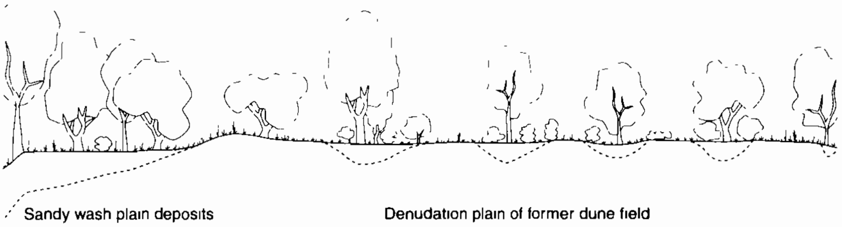

Figure 1.17. Schematic diagram of a transect in banded vegetation associated with former dunes in Nigeria. (Adapted from Zonneveld 1999.)

tially stabilized by vegetation cover on the ripple crests and by caliche plating of the trough floors (Figure 1.18). Ives (1946) invoked conventional aerodynamic theory to account for the aeolian origin of these features, where sand accumulated around obstacles in a characteristic ripple pattern. Similarly, White (1969, 1971) suggested that the accumulation of aeolian sand trapped material by isolated plants as shadow dunes might act as a nucleus of the development of grassy microdunes over saline and alkaline alluvial soils in Jordan. He also observed similar patterns in the Iraq-Syrian border areas.

Other Banded Patterns

Mediterranean terracettes (Figure 1.19) develop on steeper slopes (10 to 60%) and at finer scales but are strongly analogous with the high-contrasted banded vegetation patterns on uniform soils (see Figure 1.2). They have been described in southeastern Spain under mean annual rainfall ranging from 300 to 400 mm (Puigdefábregas and Sanchez 1996; Bergkamp, Cerdà, and Imeson 1999).

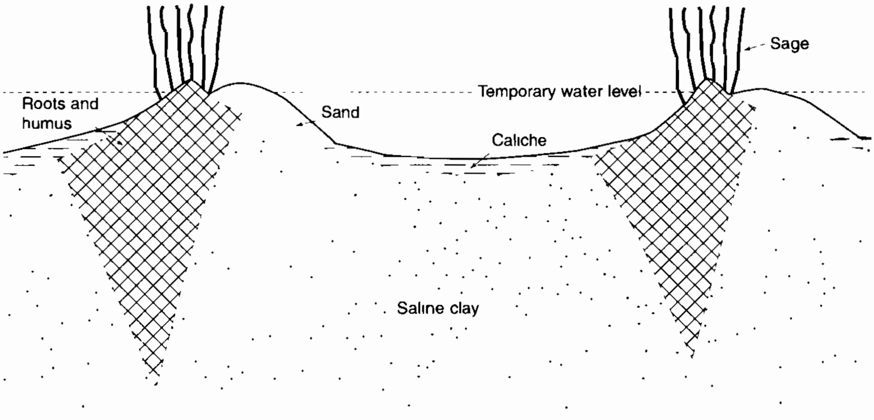

Figure 1.18. Schematic diagram of desert ripple morphology associated with small transverse dunes on caliche. (After Ives 1946. Reprinted by permission of the *American Journal of Science.*)

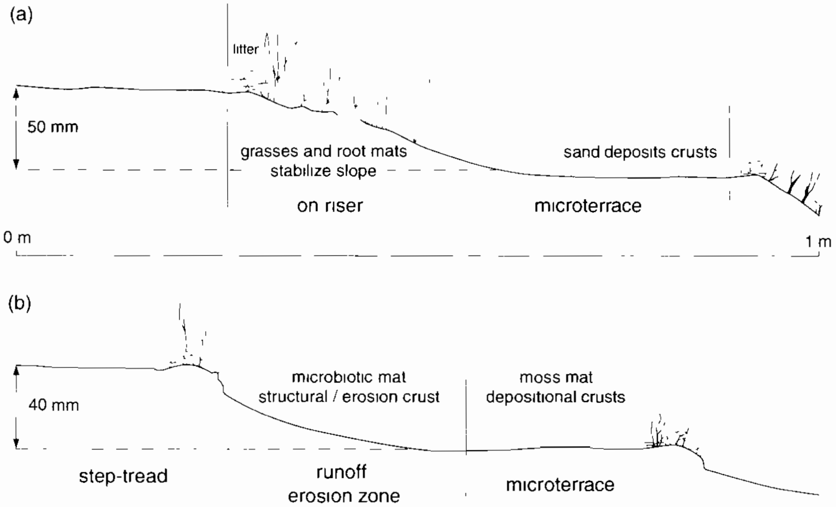

Figure 1.19. Schematic diagram of litter dams structures (a) with vegetation located on the slope and (b) with vegetation located at the edge of the terrace. (Reprinted from Catena 37(1/2), Eddy et al., Vegetation arcs and litter dams: Similarities and differences, pp. 57–73, Copyright 1999, with permission from Elsevier Science.)

Even smaller-scaled vegetation bands patterns have been reported from a number of locations, such as those associated with litter dams (Eddy et al. 1999) and sediment deposition (Bryan and Brun 1999). In both cases, slope profiles and crust distribution along the transect lines are similar to those observed in the tiger bush, suggesting similar controlling processes (Figure 1.20). It is possible that these structures are meta-stable transitional states on a degradation gradient.

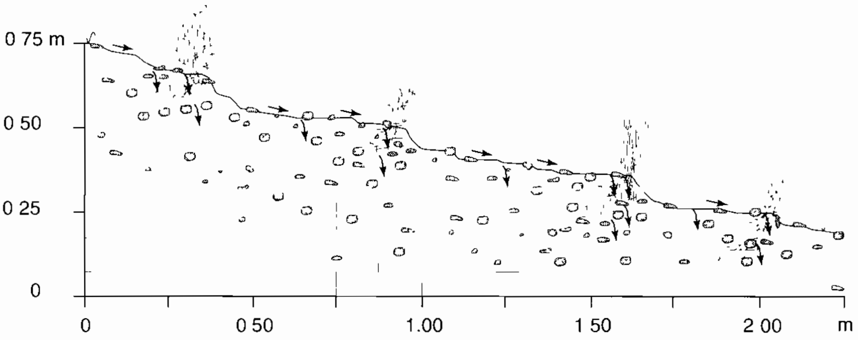

Figure 1.20 Schematic diagram of a microterrace structure in southern Spain. (Reprinted from Catena 37, Bergkamp, Cerdà, and Imeson, Magnitude-frequency analysis of water redistribution along a climate gradient in Spain, pp 129–146, Copyright 1999, with permission from Elsevier Science.)

Summary

This chapter has described the range and global distribution of banded vegetation landscapes that have been reported in the literature to date. There are similar landscape patterns on different continents (e.g., the tiger bush and the mogote) and different pattern types in neighboring regions (e.g., the groved mulga and the patterned chenopod shrubland). The variety of expressions of the banded landscape phenomenon probably accounts for apparently conflicting theories about the origin and functioning of these strikingly geometric landscapes. The following chapters of this volume provide a synthesis of what is currently known, linking the scientific information with management imperatives.

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