Chapter 12
Vegetation Mosaics of Arid Western New South Wales, Australia: Considerations of Their Origin and Persistence

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Abstract The drylands of Australia contain areas of striking and spatially extensive patterned vegetation. The difficulty in understanding emergent structures in dryland eco-geomorphology springs in part from a fundamental challenge of separating function or operation in a system once fully-developed from the processes that drive the initial emergence of patterning. There is an additional challenge over much of the Australian drylands, connected with the very marked inter-annual variability in rainfall, which drives large swings in soil moisture, plant cover, and floristics, as well as in herbivore grazing pressure, abundance of soil biota, and other factors. There are reasons to believe that the rainfall variability, including particularly the ecosystem impacts of the dry years lying near the extremes of the annual series, is important to the emergence of vegetation and soil patterning. In the study area of western New South Wales discussed in this chapter, soil characteristics are tightly linked with the evolution of vegetation patterning. Diverse kinds of vegetation mosaics are present in the study area, ranging from gilgai-like depressions and mounds, in which plants surround the moist depressions, to irregular patches or groves lying within bare soil or stone mantled soil, to strikingly regular, contour-aligned vegetation banding. Groves are favourable locations for plant growth because of the combined role of the enhanced infiltrability generated within groves, and the increased soil water availability that is created by the crabholes and other shallow closed depressions. Field data suggest that crabholes and closed depressions are more likely to account for the presence of shrubs than the reverse. The production of overland flow in the intergroves within patterned vegetation can be remarkably efficient. Consequently, groves are not uniform hydrologically, and the upslope margins receive runon water more frequently than the lower parts of the groves. For the field context of western NSW, existing models fail to touch upon key mechanisms that appear to be pivotal

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to the development and operation of emergent vegetation patterns, including soil shrink-swell and spatial differences in soil shear strength. In order to explore in a general way the development of vegetation banding of the kind seen in western NSW, a cellular automaton (CA) model was employed. Crabhole formation during very dry years and runs of years appears to be a very important aspect of the mechanisms that create and sustain the banded mosaic vegetation communities of the study area. Thus, it may be that soil pattern development is the leading process, and the emergence of patterned vegetation is an effect consequent upon the soil behaviour. It is likely, also, that the vegetation patterning establishes a feedback process to further strengthen the hydrologic compartmentalisation resulting from the soil collapse processes.

12.1 Introduction

The drylands of Australia contain areas of striking and spatially extensive patterned vegetation. In all cases, the vegetation patterning is associated with mosaics of differing soils and surface and subsurface hydro-geomorphic processes. Though some aspects of form and process in these landscapes have been researched, knowledge is far from complete, and this chapter will highlight some of what has been learned as well as what remains to be understood. The difficulty in understanding emergent structures in dryland eco-geomorphology springs in part from a fundamental challenge that is encountered in many fields of endeavour, namely, the task of separating function or operation in a system once fully-developed from the processes that drive the initial emergence of patterning. This is a classic 'chicken or egg' problem. There is an additional challenge over much of the Australian drylands, connected with the very marked inter-annual variability in rainfall, which drives large swings in soil moisture, plant cover, and floristics, as well as in herbivore grazing pressure, abundance of soil biota, and other factors (van Etten 2009; Letnic and Dickman 2010). The ENSO-related fluctuations in annual rainfall that occur strongly over much of eastern Australia (Suppiah 2004) cause conditions in many drylands there to swing from extreme drought with scant plant cover to exceptional wetness and plant cover through irregular quasi-cycles lasting some years. In this area, rare exceptionally wet years associated with La Niña conditions occur at intervals of perhaps some decades, and alternate with occasional El Niño periods of extreme dryness. In such an environment, it is not immediately clear how to characterise or parameterise the rainfall environment, nor to see clearly whether very dry or very wet years are responsible for driving the most fundamental ecosystem and landscape adjustments. As will be shown below, there are reasons to believe that the rainfall variability, including particularly the ecosystem impacts of the dry years lying near the extremes of the annual series, is important to the emergence of vegetation and soil patterning. If this is correct, then the emergence of enduring vegetation patterns in the area of eastern Australia discussed in this chapter cannot be accounted for simply by reference to mean climatological dryness or the mean annual level of water scarcity within the ecosystem; it also involves inter-annual variability as a key driver. But it will be argued below that in the study area, soil characteristics are tightly linked with the evolution of vegetation patterning.

The following discussion is limited primarily to the patterned landscapes of western NSW, Australia, though work in other environments is referred to. (For a broader review of ecogeomorphology in the Australian drylands, see Dunkerley 2010). The chapter contains three sections, which briefly consider the form and composition of the patterned landscapes, some of the eco-hydrologic factors that operate on and within them, and some explorations of their developmental pathway and persistence in the face of climate change and land-use pressures.

12.2 The Patterned Dryland Landscapes of Western New South Wales, Australia

The landscapes of western NSW considered here are all used for pastoral production, and the pressure of herbivory adds to the climatic stresses on plant cover (Read 2004). Grazing, primarily by sheep, has been carried on since the middle of the nineteenth century in many areas. In addition to the direct effects of grazing stock and introduced feral pest animals such as rabbits and goats, considerable impacts in these landscapes undoubtedly arose in the early days of European settlement from the cutting of trees for fence posts, for fuel, and for use in the mining industry. Grazing pressures are selective according to season and the palatability of various taxa, and it is therefore clear that the ecosystems studied today are to some extent modified from the conditions that would have existed prior to European settlement, in terms of floristics, ground cover, and other parameters. The probable extent of change is difficult to assess or quantify, owing to the absence of baseline data. In pre-European times, human impacts from the indigenous peoples and from native herbivores would have been of quite low intensity, though there may have been effects from the use of fire by people for clearing grass and shrub vegetation after years of very high rainfall and fuel accumulation.

Diverse kinds of vegetation mosaics are present in the area, ranging from gilgai-like depressions and mounds, in which plants surround the moist depressions, to irregular patches or groves lying within bare soil or stone mantled soil, to strikingly regular, contour-aligned vegetation banding (Fig. 12.1) such as that described by Dunkerley and Brown (1995).

The environments in which patterned vegetation occurs conform to the ranges that are reported for most global occurrences (low topographic gradients, broad relatively un-dissected surfaces, mean annual rainfalls of a few hundred millimetres or less; e.g. Lefever and Lejeune 1997). The patterned plant communities in western NSW are dominated by chenopod shrubs (e.g. Atriplex spp.), or by native perennial grasses such as Astrebla spp., but elsewhere in the Australian drylands, the most widespread patterned vegetation, including striking and extensive contour-aligned vegetation banding, is developed in woodlands of Acacia spp. with a grassy understory (Dunkerley 2002).

Fig. 12.1 Contour-aligned banded vegetation in arid western New South Wales, Australia. The *upper photo* is an aerial view, and the *lower* presents a ground-level view looking downslope. The line of trees on the horizon marks the position of an ephemeral stream channel

12.2.1 Soil Characteristics and Shrink-Swell in the Mosaic Landscapes

An aspect of the western NSW landscapes that is distinctive is their soils. These contain exogenous silts and clays delivered by aeolian transport from more arid areas of the Australian inland lying to the west (upwind). In the Barrier Ranges – Fowlers Gap area, which forms the focus for this chapter, and where many of the ridge-forming rocks are highly resistant quartzites that generate little or no soil fines, the aeolian input of exogenous clays and silts has been a key influence upon soil depth, texture, mineralogy, and physical and hydrologic behaviour (Chartres 1982). Accumulation of windblown dusts through arid glacial cycles is considered to have resulted in significant blanketing of the areas such as those flanking the low uplands of the Barrier Range, whose elevation forms a topographic barrier that lies across the path of the dominant westerly dust-transporting winds. Exogenous wind-blown fines have been reported from soils in various parts of eastern Australia. Along the Murrumbidgee River in the Wagga Wagga area, Chen et al. (2002) reported depths equivalent to up to 80 cm of dusts intermixed with dune sands, and inferred rates of dust accumulation of up to 5 cm per ka through the last glacial maximum. From the Namoi area in northern NSW, Cattle et al. (2002) reported deposition equivalent to 20 cm of dust in the last 13 ka. The dusts had illite-smectite mineralogy, and a modal diameter of 40–50 μm. Both of these locations are located much further downwind than the area discussed in this chapter, and presumably received a reduced dust flux. Dryland dusts from the Australian inland have been reported from other locations, including NW NSW (Tate et al. 2007) and Antarctica (Revel-Rolland et al. 2006).

Since the time of its accumulation in the Barrier Ranges, overland flow on the hillslopes has reworked much of this material into piedmont slopes and low-angled alluvial fans, and fluvial transport has spread it across the extensive floodplains and outwash plains of the ephemeral channel systems. Consequently, many of the areas of patterned vegetation are developed not on the relatively thin soils of the rocky hillsides but flanking footslopes on deep alluvial-colluvial soils of broadly loamy texture, which contain exogenous illite-family clay minerals. These soils exhibit marked shrink-swell behaviour, desiccation cracking, and surface seal and crust development. Many of the soils and sediments slake very rapidly when in contact with water, but the soil surface is commonly stabilised against wind and water erosion by biological soil crusts. Lichen and bryophyte crusts are locally abundant, but cyanobacterial crusts are virtually ubiquitous. Resistance to erosion by overland flow also arises from dense veneers of resistant stones, including vein quartz and quartzite, which rest on the soil surface over large areas. In extreme droughts, wind abrasion progressively disrupts and fragments the biological crusts, and undercutting and the lifting of crusts fragments become widespread.

Upton (1983) confirmed that Fowlers Gap soils also contain illite minerals, with the clay fraction tending to increase with depth. Upton's linear shrinkage tests showed that the uppermost 15 cm exhibited linear shrinkage of 1.6 %; the 15–20 cm depth, 9.2 %; and the soil below 30 cm (often to >100 cm) showed shrinkage of 11.6 %. Volumetric contraction would be approximately three times that of the linear shrinkage, or about 30 % in the subsoils. (Coefficients of linear shrinkage are often about 15 % (e.g. Greacen and Huon 1953) though Akpokodje (1985) reported linear shrinkage of up to 20 % for heavy-textured soils at Fowlers Gap, suggesting that locally, very large volume changes would be associated with wetting and drying cycles). Observations by the writer suggest that dry conditions are required in order for deep subsoils to dry and shrink. Thus, in El Niño years especially, marked

Fig. 12.2 Typical appearance of crabholes in vegetation mosaics of arid western NSW. The *upper right* images shows a small collapse encircled by tension cracking (see text for details)

volumetric contraction of the subsoils (where the clay content is high) results in a loss of support for the soil above, and collapse features then occur, locally called ‘crabholes’ (Fig. 12.2).

Crabholes and shallower closed depressions arising from subsidence form highly efficient traps for overland flow. Crabholes are sometimes ringed by tension cracking (Fig. 12.2) which offers a second pathway for overland flow to enter the deeper soil than would readily occur from the infiltration of rainfall through the soil matrix. Shrink-swell behaviour of the soils in some cases results in gilgai undulations in the soil surface, which may be semi-permanent. Closed depressions often result, and these gather water in wet years that follow drying and shrinkage in preceding droughts (Fig. 12.3). This is likely to prime the deep subsoils for renewed contraction when they next dry out. This effect is probably amplified by the more abundant vegetation that is able to grow in and around the water-filled depressions.

Though there are no relevant field data, it can be considered possible that the ENSO quasi-cycle is associated with a parallel quasi-cycle of shrink-swell in the deeper subsoils. Crabhole abundance and location are currently being monitored, and data to date suggest that crabholes and closed depressions that were abundant in the drought of the decade to 2009 have largely disappeared following the exceptional rainfall of 2010, which therefore appears likely to have allowed subsoil materials to increase in volume.

Fig. 12.3 Examples of closed depressions in vegetation mosaics of arid western NSW. Both photos are taken looking upslope across closed depressions that contain water from recent rain. The vegetation in each case is dominated by chenopod shrubs. Intergroves are veneered with pebbles

Table 12.1 Crabhole and closed depression volumes, Fowlers Gap Arid Zone Research Station

Grove number	Number of closed depressions (area mapped m^2)	Areal density (pits per m^2)
1	31 (75)	0.41
2	20 (37.5)	0.53
3	17 (25)	0.68
4	16 (25)	0.64
5	18 (25)	0.72

Data collected under drought conditions in March 2009, when the value of the SOI was +0.2

A key observation pertinent to understanding the hydrologic operation of these vegetation mosaics is that crabholes and closed depressions are only found within the groves. A hypothesis to account for this is that enhanced infiltration attributable to one feature (plants or closed depressions) favours co-location of the other. Mechanisms for crabhole formation have been outlined by Upton (1983) and the literature on gilgai contains many accounts of the formation of closed depressions (e.g. Knight 1980). The presence and potential importance of crabholes in the development of vegetation mosaics have been mentioned previously in the literature (Dunkerley 1997a, b; Dunkerley and Brown 1995) and will be addressed further below.

12.2.2 *Field Data on Crabholes and Shallow Closed Depressions*

In order to assess the capacity of crabholes and closed depressions to contribute to depression storage and the capture of runon water, estimates of pit and depression volume were made in the field. This was done by lining crabholes and depressions with thin, soft plastic sheeting, and filling with measured amounts of water until level with the surrounding soil surface. Table 12.1 presents some indicative data from this work.

With a mean density of about 0.5 crabhole or closed depression per m^2, and a mean volume of 3.7 l (standard deviation 1.6 l), these pits have the capacity to intercept the equivalent of about 2 mm of rainfall across the area of a typical grove. Some of the pits measured were quite large, the maximum recorded volume being 8.5 l. This static measurement using plastic sheeting is an underestimate of the true water-trapping capacity of the crabholes, neglecting as it does the unmeasured narrow crack network extending deeper into the soil, and also the ongoing seepage of water into the walls of the pit and the crack network during rainfall. Nevertheless, given that these closed depressions arise in dry years, and vanish in wet years when the subsoils are re-wetted, their significance is twofold: first, they present a large capacity to trap and retain water within the groves. Crabholes are never seen within the drier intergroves, presumably because there the subsoils are never wetted, and therefore do not display major volumetric shrinkage in dry years. Second, the crabholes are important because they compensate for the loss of vascular plant cover and litter that occurs in dry years. Crabhole formation represents the development of marked water trapping in subsequent rainfall events that has little directly to do with the vascular plant cover. Thus, in dry years, when surface plant cover becomes scant, subsoil shrinkage results in crabhole formation, and this ensures that overland flow is trapped with great efficiency even though the surface may be quite bare. In this way, the scare water resource is conserved, and conditions favourable to the persistence or re-establishment of vascular plant cover are created once adequate rainfall occurs.

Thus, an important argument of this chapter is that the groves are favourable locations for plant growth because of the combined role of the enhanced infiltrability generated within groves, and the increased soil water availability that is created by the crabholes and other shallow closed depressions. Crabholes are undoubtedly water traps and enhance the entry of water into the subsoil. In contrast, it is clear that water entry is not always enhanced in the presence of shrubs, which may in fact result in diminished soil water contents at sub-canopy sites (Moran et al. 2010). In light of the wide spacing of vascular plants in groves of the study site, which would appear to eliminate shading, sheltering from wind, or other benefits that might arise in denser groves, crabholes and closed depressions seem more likely to account for the presence of shrubs than the reverse.

12.2.3 El Niño – Southern Oscillation (ENSO) Rainfall Variability

The other distinctive feature of western NSW is its marked inter-annual rainfall variability. ENSO-related phenomena result in marked quasi-cycles of variability in annual and seasonal rainfall amounts across much of eastern Australia (Verdon et al. 2004) such that many areas show wet years in association with La Niña conditions, in which the rainfall is 50–100 % greater than in El Niño years. For much of western NSW, 1974 was the year of record rainfalls in the period of European settlement. The Southern Oscillation Index (SOI) for that year was around +20 for the late summer months (that is, trans-Pacific pressure differences were about two standard deviations from their long-term mean for those months). For September 2010, the SOI value was even higher, at +25; it was high for a number of months following June. In contrast, for much of the summer and autumn of 2010, the SOI was in the range −10 to −15. In 1974, Fowlers Gap 1974 experienced the highest annual rainfall on record (629 mm) and 2010 was the second wettest year, with 523 mm. However, the complex behaviour of annual rainfall can be illustrated by observing that 1987 was also an exceptionally wet year (408 mm) but the SOI was moderately negative all of that year. In dry years (well exemplified by 1983, when the SOI in summer lay in the extreme range −28 to −33), plant cover becomes very much reduced, and sand and dust storms become common. As mentioned earlier, sandblasting of the cyanobacterially crusted soil surface fragments or eliminates the crust over large areas. Soil moisture falls to extremely low levels (less than a few percent by volume) and occasional rainfall events result in highly sediment-laden ephemeral streamflows. In the same way, plant cover in the vegetation mosaics becomes extremely low, and only scattered individual woody plants, such as chenopod shrubs, remain, largely in a dormant condition and with diminished canopy cover. Ephemerals and grasses are completely absent. Many research questions remain about the causes of major, lengthy drought periods the affect parts of the Australian drylands, including the study area. The long and severe 1995–2010 dry period, termed the “Big Dry”, is an example (Ummenhofer et al. 2009).

12.2.3.1 The Rainfall of Fowlers Gap

When rain stops only briefly – perhaps for a few minutes – and then resumes, it is appropriate to count both periods of rain as a single storm. But as a gap in rainfall grows to many hours, perhaps with sunshine and drying winds during the gap, it makes more sense to tally two separate events. This process is customarily made rigorous by defining a minimum inter-event time, or MIT, which is a rainless period that must be reached or exceeded for two periods of rain to be counted as separate storms. There is a wide range of MIT criteria in use, but often it is set to about 6 h (Dunkerley 2008a).

Using such a definition, the Fowlers Gap rainfall record at Fowlers Gap shows that there are on average about 25 storms per year that deliver a depth exceeding 0.5 mm, and that these typically last for around 4.5 h, delivering 8.1 mm of rain at an average intensity of 3.8 mm/h. The distributions of all of these parameters exhibit strong positive skew (Fig. 12.4). However, these low rainfall intensities and moderately short storm durations in an environment of low relative humidity mean that the drying of wet foliage consumes a large fraction of the arriving rain.

Owing to the entrainment of dry air from beyond the localised rainfall cells, intra-storm evaporation can proceed at quite high rates (Dunkerley and Booth 1999; Dunkerley 2008b). Rain is registered in defined events for only about 1.3 % of the time, and the mean waiting time between successive rainfall events is about 10 days, though in the extreme it can extend to months. Owing to the low rainfall rate in this environment, and the fully dry soil surfaces and plant canopies encountered at the start of events, the effective rainfall, the part that infiltrates into the ground to add to soil moisture, will be significantly less than the gauge rainfall owing to ongoing intra-event wet canopy evaporation. Rainfall events of longer duration are therefore likely to be very important to the recharge of deep soil moisture in this environment, and hence to volumetric expansion of the subsoil clay minerals.

Annual rainfalls at Fowlers Gap can be fitted by a two-parameter gamma distribution having scale parameter of 48.83 and a shape parameter of 4.71, though the number of high-rainfall years such as 1974 and 2010 is too small to offer great confidence in the fitting of the positive tail of the distribution.

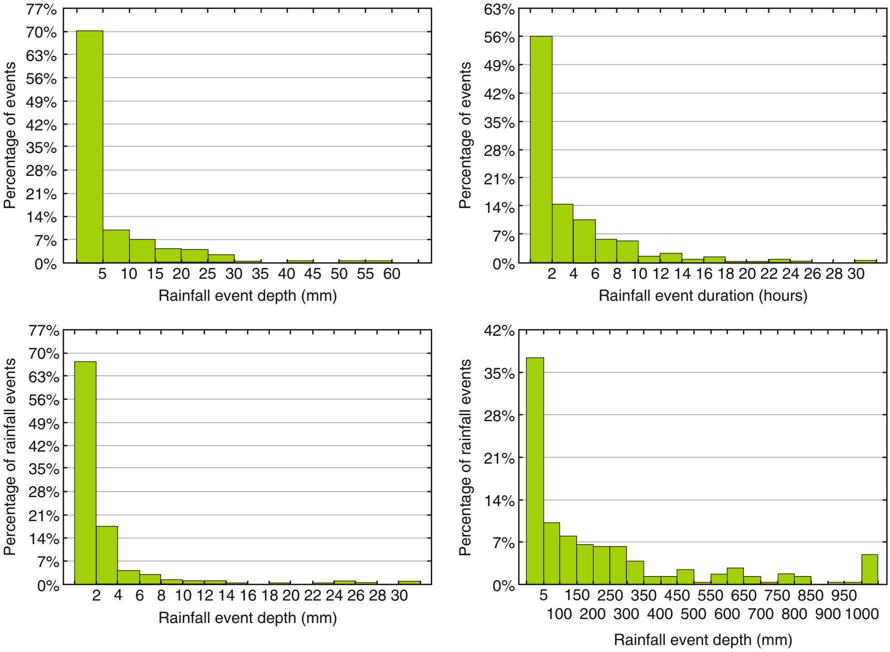

Fig. 12.4 Distribution of rainfall event depths (*top left*), rainfall rates (*bottom left*), event durations (*top right*) and event waiting times (*bottom right*) for Fowlers Gap Arid Zone Research Station. The data span 8 years of record

12.2.4 Plant Cover in the Patterned Landscapes

Plant cover in the patterned landscapes is very variable through time, as a consequence of variations in seasonal and annual rainfall, especially through the ENSO quasi-cycle just discussed. Foliar cover is low, often only reaching values of 20 %, even with the 'groves' or more densely vegetated phases of the mosaics. In chenopod mosaics, individual plants are not located sufficiently closely that there would be any significant synergistic or shading effect of one plant on another; rather, the plants are widely spaced. The plants are generally of low height, typically reaching no more than 30–60 cm. During very dry years, the above-ground parts of many chenopod shrubs appear brown and dead, but many individuals are capable of recovering once soil moisture is replenished, and in general these plants are long-lived. In wetter years, abundant ephemerals emerge, along with native grasses, and in suitable locations along floodplains, foliar cover can approach 100 % for short periods before dry conditions return. In the case of larger chenopod shrubs, measurements have confirmed that soil infiltrability is higher near the stem, and declines into the shrub interspace (Dunkerley 2000). Moreover, some plant-related increase in infiltrability persists even beyond the edge of the plant canopy.

12.2.5 Runoff and Runon in the Patterned Landscapes

Soil surfaces vary systematically through the vegetation mosaics. Within groves, soils are soft, and the surface is often broken by shrink-swell behaviour; biological crusts are also less developed in groves. These soils belong to the class of soils known as ‘self-mulching’, and they exhibit desiccation cracking (Pillai-McGarry and Collis-George 1990a, b). Infiltration rates based on cylinder infiltrometry and the application of simulated rainfall at realistic rain rates to bounded runoff plots (Dunkerley 2008c, 2009a) suggest infiltration rates of 15–30 mm/h in groves. Intergroves have soils which grade upslope somewhat diffusely into grove soils, but which become very hard and impermeable toward the lower intergrove. At lowermost intergrove locations, infiltration tests suggest rates of up to 5 mm/h. Observations made during and after rainfall have confirmed that overland flow arises on the intergroves, where shallow ponding and flow are widespread, and from there drains toward and into the groves, where soils are wet but where surface ponding is much less extensive. Surface water is primarily seen within groves at locations where preferential flow paths deliver trickles of overland flow from the intergrove lying upslope (Fig. 12.5).

The overland flow shown in Fig. 12.5 resulted from prolonged but low rate rainfall on 4 March 2010, amounting to nearly 40 mm. It is clear that ponding is primarily a feature of the impermeable intergroves, and that water is strongly absorbed within the groves. The figure also makes it clear that many plants within the grove stand on mounds and that water entering the groves passes between, rather than directly onto, the plants. Consequently, the soils exhibiting the highest infiltrability (located close to the stem) are not able to become directly active in the absorption of runon water, though in much of the literature, this effect is claimed to be a key process favouring plants in groves. For example, Yizhaq et al. (2005) include in a model of vegetation patchiness the presumption that the presence of a vascular plant induces local infiltration larger than would occur in the absence of that plant. This role for plants is cited as a key factor needed to account for the emergence of vegetation patterns.

The production of overland flow in the intergroves within patterned vegetation can be remarkably efficient. Observations by the writer have shown substantial runon water arriving at groves from the immediately upslope intergroves, from rainfall events of <3 mm depth, falling at low rain rates. Soils along the upslope margins of some groves were visibly wet when inspected 12 h after one rainfall event of just 2.8 mm depth, while downslope within the grove, soils appeared dry. In other words, these mosaic landscapes can result in important accessions of water to plants in groves that would not arise in an unstructured landscape. But clearly, groves are not uniform hydrologically, and the upslope margins receive runon water more frequently than the lower parts of the groves.

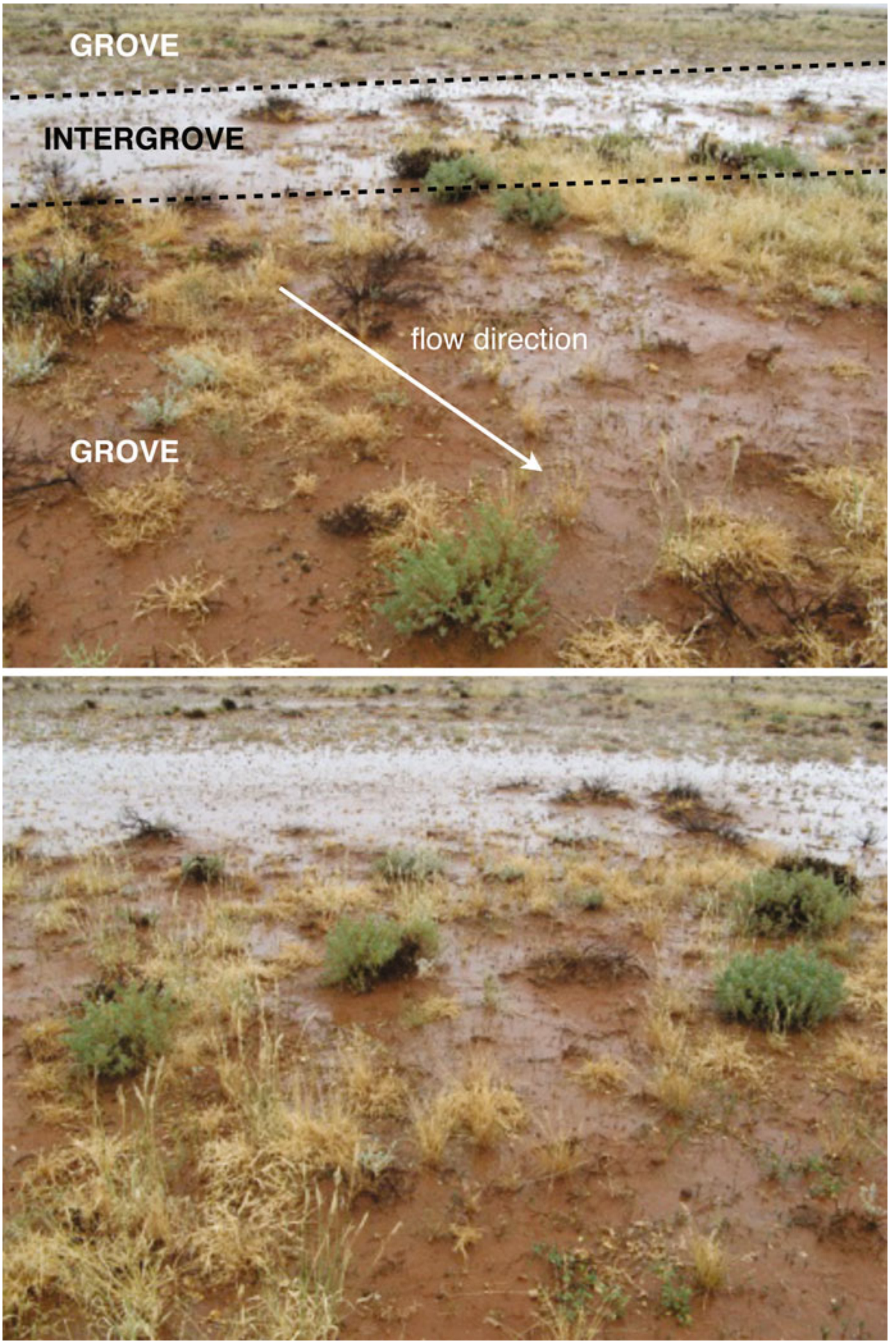

Fig. 12.5 Two examples of overland flow behaviour in a vegetation mosaic in arid western NSW. Both photos are taken looking upslope, and show a single intergrove that carries shallow surface flow, and groves upslope and downslope where ponding is virtually absent. Note the extent of bare soil event within the groves

12.3 Exploring the Origin and Development of the Patterned Landscapes

Having presented a brief outline of some of the environmental characteristics affecting patterned vegetation in western NSW, we now turn to consider what can be said about the origin of this striking mosaic of vegetation and soils.

In recent years, many hypotheses have been advanced seeking to account for the emergence of stable vegetation patterns such as those of the Fowlers Gap study sites and others in western NSW. A recent overview of some approaches was provided by von Hardenburg et al. (2010). Among the plethora of hypotheses, some consider patterns to be the outcome of an interaction of competitive and facilitative interactions among plants, acting at different spatial scales (Borgogno et al. 2009); other approaches stress the pivotal importance of the positive feedback provided by the link between vascular plant cover and soil infiltrability (Okayasu and Aizawa 2001). Some workers envisage a critical role for the nature of the rainfall climate, including seasonality and the annual variability in rainfall amounts (D'Odorico et al. 2006; Ursino and Contarini 2006; Kletter et al. 2009), while others adopt an unchanging annual rainfall or do not treat rainfall explicitly at all (Kéfi et al. 2007, 2010). Some models attempt to incorporate 'process' representations, such as canopy interception loss (Borgogno et al. 2007) or the dispersal of propagules (Thompson et al. 2008) but include no data on the properties of the soils and of the overland flow field, including infiltrability, flow depth, and flow speed, as controlled by rainfall event structure. Many theoretical approaches envisage a bistable distribution whose end-members are fully vegetated or bare states, with landscape processes of various kinds yielding a stable intermediate condition (Lejeune et al. 2002).

A striking feature of much of this literature is the extent to which it is has evolved without reference to data from particular field locations and conditions, and the extent to which hypotheses have been advanced without being constrained by validation. In particular, in light of the field context of western NSW, existing literature fails to touch upon key mechanisms that appear to be pivotal to the development and operation of emergent vegetation patterns, including soil shrink-swell. The challenge here is worth illustrating. For instance, some workers (e.g. Lefever and Lejeune 1997; Yizhaq et al. 2005; Esteban and Fairén 2006) argue, on the basis of model output, that banded vegetation patterns incrementally and progressively migrate upslope. However, there are few or no reliable data confirming this process, much less examining the mechanism or rate of the supposed upslope migration. Additionally, the models cited do not include any consideration of soil development. In the banded vegetation of western NSW, lower intergrove soils exhibit a shear strength that is far too high to allow root development, and they are so impermeable that the exceptionally dry soil environment is hostile to any propagules that might lodge there. Moreover, the system of crabholes and closed depressions tends to promote re-wetting of subsoils, and hence the future formation of new crabholes in the same location repeatedly. Through processes of this kind, it

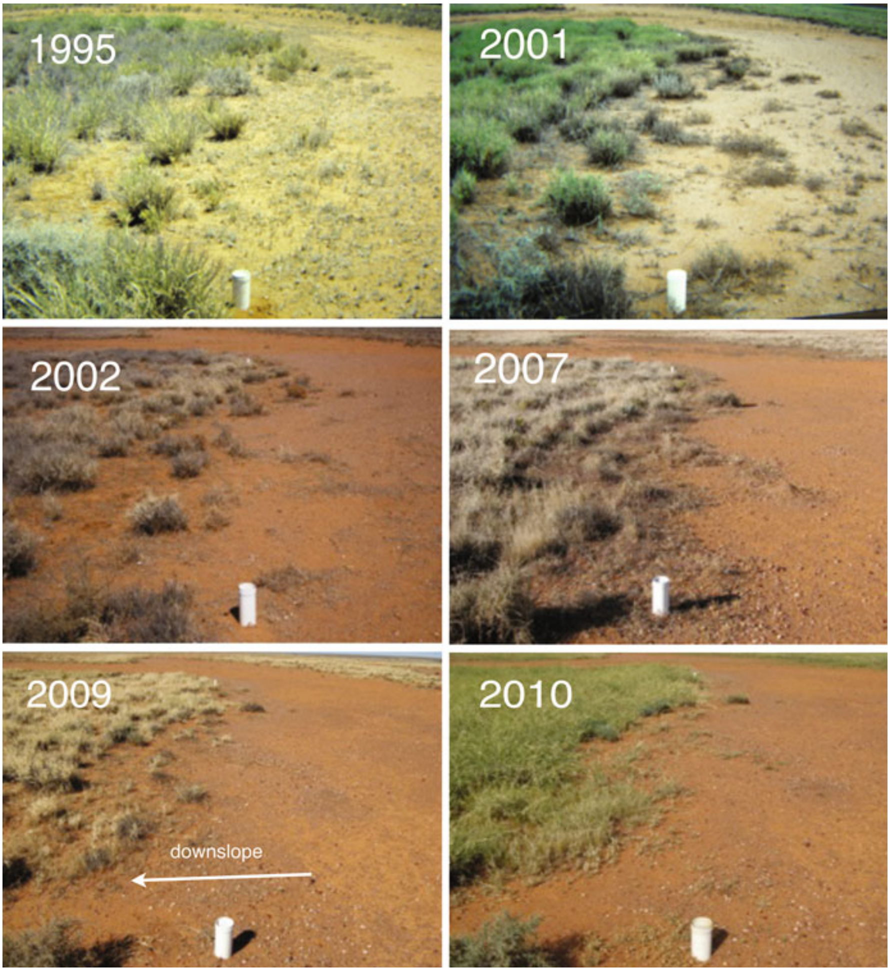

Fig. 12.6 Time series of photographs of a grove-intergrove margin in a contour-aligned banded vegetation mosaic in arid western NSW. In 1995, the upslope edge of the grove was marked with two PVC pipes 30 m apart. Though individual shrubs and grasses have been replaced during the 15 years of monitoring, there is no evident shift in the location of the grove margin

has been argued that the vegetation bands are effectively locked in a fixed position by pedologic controls (Dunkerley 2009b). By considering soils in this way as an essential component in any model dealing with vascular plants, it is possible to envisage mechanisms which would mitigate against the upslope migration of vegetation bands. More than 15 years of repeat surveys of band margins in western NSW (e.g. see Fig. 12.6) show no detectable shift in these bands, despite the notable inter-annual rainfall variability of this area, mentioned earlier.

In light of the supposed rates of upslope migration (Sherratt 2010 refers to rates of 0.2–1.0 m/a) the upslope displacement in the period of observation ought to lie in the easily detectable displacement range 3–15 m. Clearly, no such upslope displacement has occurred at the monitored locations. In considering these landscapes further, yet other inconsistencies with models divorced from field locations and field data emerge. For instance, Yizhaq et al. (2005) predicted that the spacing of vegetation bands would undergo adjustment, widening (via the elimination of some groves) when rainfall declined. Repeat surveys of 30 wavelengths of the regular vegetation banding shown in Fig. 12.6 over 15 years have shown no detectable change in grove and intergrove dimensions, despite very marked rainfall variability. Under exceptionally dry conditions, grove foliar cover declines, but grove locations do not change. This kind of discord between models and field data suggests that many models have failed to capture key ecosystem processes, and require better validation, so that modelling efforts can incrementally be developed further.

Another significant issue can be mentioned here. It has also been argued on the basis of numerical models that landscapes containing patterned vegetation may be at great risk from climate change (Kéfi et al. 2007), and this influence may be combined with increasing pressures arising from human use of these landscapes for purposes such as pastoral production. Whether this is true or not remains to be seen. In the case of the striking banded vegetation in western NSW, long-term local residents have described these areas in extreme drought as being almost bare, and yet the groves re-appear when rainfall returns to ordinary levels. Soil microtopography associated with the vegetation bands (e.g. Dunkerley and Brown 1995, 1999) and the crabhole processes already described, may well account for this stability, since they affect the retention of overland flow whether or not plants are present. Certainly, in western NSW, widespread banded grassland systems are valued by pastoralists for their resilience and productivity under climatic and grazing pressure, and this certainly does not seem to be a system under threat of imminent collapse. Some models do indeed suggest this kind of resilience. HilleRisLambers et al. (2001) used a numerical analysis to suggest that high levels of herbivory are not likely to be associated with the collapse of plant cover in patterned ecosystems. This emphasises the need for models used for scenario development to be fully tested and validated, so that their applicability in actual landscapes and ecosystems can be properly evaluated.

12.4 Development of Mosaic Vegetation in a Cellular Automaton Model

In order to explore in a general way the development of vegetation banding of the kind seen in western NSW, a cellular automaton (CA) model was employed. This modelling approach is suitable for exploring the outcomes of a range of possible drivers of vegetation pattern development, without being so demanding of data that it cannot be fully parameterised. The application of models of this kind in ecological work was reviewed by Dunkerley (1999). The model used here consists of a tessellation of 10,000 cells (100 × 100) each taken to represent perhaps a plant or a few neighbouring plants, growing on a gradient sufficient to drive overland flow or seepage across the tessellation. The model was run on time steps taken to represent a year, in the sense that the annual rainfall was delivered to the tessellation at a single model time step. These same general conditions have been widely adopted in the literature on emergent patterns in dryland vegetation (e.g. Bailey 2010). This approach completely fails to capture rainfall event properties and their role, but really too little is known about the fate (infiltration, overland flow, evaporative loss) of rainfall events of varying sizes in this landscape to attempt to model their behaviour with any confidence. Likewise, too little is known of the response of chenopod shrubs to rainfall pulses of contrasting properties to attempt to build a more process-oriented model. For these reasons, the modelling performed here is significantly abstracted and can only be used to explore the generalised influences of soil and climate on the vegetation mosaics.

12.4.1 Representing the Time Series of Annual Rainfalls in Western NSW

The frequency distribution of dryland annual rainfall depths is often positively skewed (e.g. Tilahun 2006). The longest rainfall records from western NSW span about 130 years, and show that the driest years receive 40–50 mm of rainfall. Some very dry periods have been recorded, including the 6-month period December 2004–May 2005 inclusive when the total rainfall at the Fowlers Gap Arid Zone Research Station was just 7.4 mm. Conditions for plants would be severe under such conditions, with summer daytime temperatures commonly exceeding 35 °C. Modelling with annual totals fails to capture the possible influence of such intensely dry periods. Similarly, there are often months in which the total rainfall exceeds the median annual total, and these maxima are commonly recorded from late summer or early autumn in western NSW. Some details of the frequency distributions of annual rainfall depth for five stations in western NSW are presented in Tables 12.2 and 12.3, and Fig. 12.7. These show means of about 200 mm/a and slight positive skewness. However, it cannot confidently be said that a single statistical distribution can be used to characterise these time series data. Rather, it seems equally reasonable to suggest that the distribution can be characterised by an essentially normally distributed series of totals, with outliers that are both very dry and very wet, reflecting the wide swings away from the mean rainfall that arise from the ENSO phenomena mentioned earlier. High rainfall years often constitute only one or a few percent of years, and the distributions (Fig. 12.7) are commonly discontinuous and longer rainfall time series will be needed to explore the distributions more fully.

The cellular model was run for 50–100 year sequences. Annual rainfall depths were derived from a series of normally distributed random numbers, using routines derived from Press et al. (1986). The series was truncated at an annual rainfall of

Table 12.2 Statistical measures of the distribution of annual rainfalls for five stations in western New South Wales

Meteorological station location	Years of record	Mean annual rainfall (mm)	Standard deviation of annual rainfalls (mm)	Skewness of the distribution of annual rainfalls
Broken Hill	118	251.2	114.8	1.52
Corona	130	207.1	101.6	1.35
Sturt's Meadows	57	154.7	76.5	1.28
Milparinka	127	191.7	121.7	2.43
Tibooburra	125	221.3	130.9	1.39

Source: data extracted from records of the Bureau of Meteorology, Australia

50 mm, to correspond with the data of Table 12.3. The mean was set to 200 mm/a and the standard deviation to 100 mm/a, again to correspond with typical rainfall records from western NSW (Table 12.2). To explore the influence of rainfall climate, in some model runs the random number series was modified purposively by including short runs of 3–5 dry years, to represent La Niña drought conditions, and in others, by including single very wet 'outlier' years, to represent the kind of widespread rains that were recorded across much of western NSW (and other parts of Australia) in 1974, and presumably at other times during the development of the mosaic communities, but prior to the commencement of record keeping (see Table 12.3).

12.4.2 Water Retention Rules in the Model

As is usual with CA models, a small 'neighbourhood' of cells was used as the basis for the application of the model rules, in this case a modified von Neumann neighbourhood. An initial set of randomly-selected cells covering 10 % of the tesselation was vegetated. In the operating rule set of the model, vegetated cells have a trap efficiency for rainfall that is dependent on the depth of rainfall received each year. This is intended to reflect the loss (or gain) of foliage and surface litter that occurs in dry (and wet) years. In drought conditions, when litter is scarce, the soil surface becomes increasingly bare, and it is reasoned that infiltrability is reduced owing to increasingly open and connected flow paths across the soil surface, diminished bioporosity created by soil fauna, and increasing exposure to rain, with formation of surface seals.

Given that the mean annual rainfall was defined as 200 mm, the dimensionless trap efficiency (Et; the fraction of the incident rainfall absorbed by a vegetated cell) was specified as: $Et = R/200$ mm for $R \leq 200$ mm and $Et = 1$, otherwise, in which R is the rainfall of any model year, varying through the model run.

This results in complete trapping of rainfall by vegetated cells in 'normal' years ($R \sim 200$ mm), declining to only 25 % absorption in the driest years ($R \sim 50$ mm).

Table 12.3 Distribution of annual rainfalls for five stations in western New South Wales

Meteorological station	Broken Hill (Patton Street)	Corona station homestead	Sturt's Meadows station homestead	Milparinka hotel	Tibooburra Post Office
Australian Bureau of Meteorology station number	47007	46003	46033	46018	46037
Years of record	1889–2010	1882–2010	1895–2010 (incomplete record)	1882–2009	1886–2010
Minimum rainfall (mm)	57.4	46.4	43.7	43.0	47.9
Mean rainfall (mm)	255.2	212.3	170.6	199.6	225.3
5th percentile	115.7	84.7	70.5	58.4	68.1
10th percentile	136.5	101.6	90.3	90.2	95.5
Median	241.6	202.6	156.3	174.3	196.0
90th percentile	396.7	335.4	291.0	322.5	396.9
95th percentile	449.9	379.9	329.4	427.9	442.1
Maximum recorded annual rainfall	838.0 (1974)	685.2 (1974)	396.0	916.4 (1974)	755.4 (1974)
Rainfall of wettest month	258.8 (March 1989)	241.4 (April 1974)	175.1 (March 1949; NB data for 1974 not available)	416.8 (January 1974)	398.4 (March 1949)

Source: data extracted from records of the Bureau of Meteorology, Australia

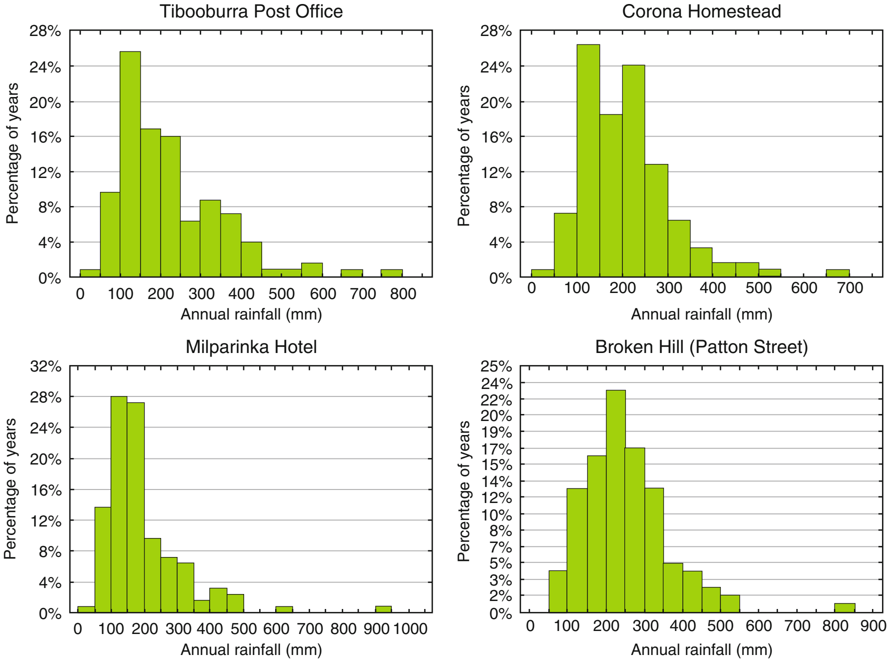

Fig. 12.7 Frequency distributions of the annual rainfall at Tibooburra, Milparinka hotel, Corona Homestead, and Broken Hill, in western New South Wales, Australia. The data are grouped into classes of width 50 mm (Source: data provided by the Bureau of Meteorology, Australia)

Vegetated cells also absorb any runon from upslope, while in contrast unvegetated cells absorb 20 % of the incident rainfall and pass the remainder downslope. Water absorbed into any cell is shared by seepage and percolation from ephemeral surface ponding among the lateral and downslope cells of the neighbourhood according to the scheme of Dunkerley (1997a). Rain was added, and other water balance calculations made, on each row of cells in turn, beginning with the farthest upslope row and working to the bottom of the slope. Water was allowed to escape from the edges and bottom of the tessellation. There are minor edge effects in the model because of this, but the behaviour of most of the tessellation is unaffected. The upslope edge (top, in the figures) also exhibits edge effects owing to the absence of runon water.

The primary model rules concern the controls on plant distribution. In the dryland being modelled, rainfall alone is insufficient to support vegetation groves, which clearly depend on the arrival of runon water from upslope. In recognition of this situation, the minimum depth of absorbed water for a cell to remain vegetated was set at 220 mm (i.e., 10 % larger than the annual mean open-field rainfall). At the end of each model ‘year’, cells with less accumulated water became unvegetated. Correspondingly, for an unvegetated cell to become vegetated, crabhole trapping and/or lateral seepage from adjoining vegetated cells were required to yield a total of 240 mm (i.e., 20 % larger than the annual mean open-field rainfall). The geometry of runoff sources and runon sinks required to yield these depths of water with the time-varying annual rainfall resulted in constant shifting of many vegetation grove boundaries, especially the lateral and downslope margins, as the model was run.

In order to account for the formation and re-healing of crabholes through subsoil contraction and expansion, a modified version of the model incorporated an increased trapping efficiency of 100 % for runon water in vegetated cells in years when the annual rainfall lay at or below the 10th percentile of the historical range of annual rainfalls (taken as 100 mm to accord with the data in Table 12.3), and the trap efficiency was returned to normal (governed by the rainfall as just described) once the rainfall returned to values above this threshold. Increasing trap efficiency under drought conditions is perhaps one of the strikingly distinctive features of the mosaic vegetation of western NSW, and appears not to have been described previously. It can be hypothesised that the mechanism of runoff trapping in crabholes, which only functions during drought conditions, would act to reduce the loss of plant cover that would otherwise occur at these times.

12.4.3 Exploring Model Operation

Given the inadequate knowledge of the ecological requirements of the vegetation in the drylands of western NSW, the sensitivity of the model to changes in the moisture threshold for vegetation to colonise or remain growing in a cell was varied from 220 mm as mentioned above, to 400 mm, in a series of steps, and the model run with an identical 50 year rainfall time series. Results show (Fig. 12.8) that as the threshold is raised, the groves become less continuous laterally, and also narrower in the direction of overland flow (top to bottom of the figure, plotted at year 21 of a 50 year simulation).

Nonetheless, contour-aligned grove structures emerge in all cases. The sensitivity of the model to a change in the moisture threshold for vegetation growth or persistence is not great. Lifting the parameter by 60 % from 220 to 400 mm resulted in a decline of only 32 % in the vegetation cover fraction, from a mean of 16.4 % to a mean of 11.2 %, averaged through all 50 years of the model run.

12.4.4 The Impact of Individual Years of Exceptionally High Rainfall

The impact of ‘outlier’ wet years was explored by modifying the 50 year runs of randomly generated annual rainfalls by inserting a single year of 800 mm (i.e., four times the mean annual rainfall, and approximately corresponding to the average of the wettest years on record at the NSW rainfall stations reported in Table 12.3, which was 798.5 mm, excluding the Sturt’s Meadows homestead record, which lacks data

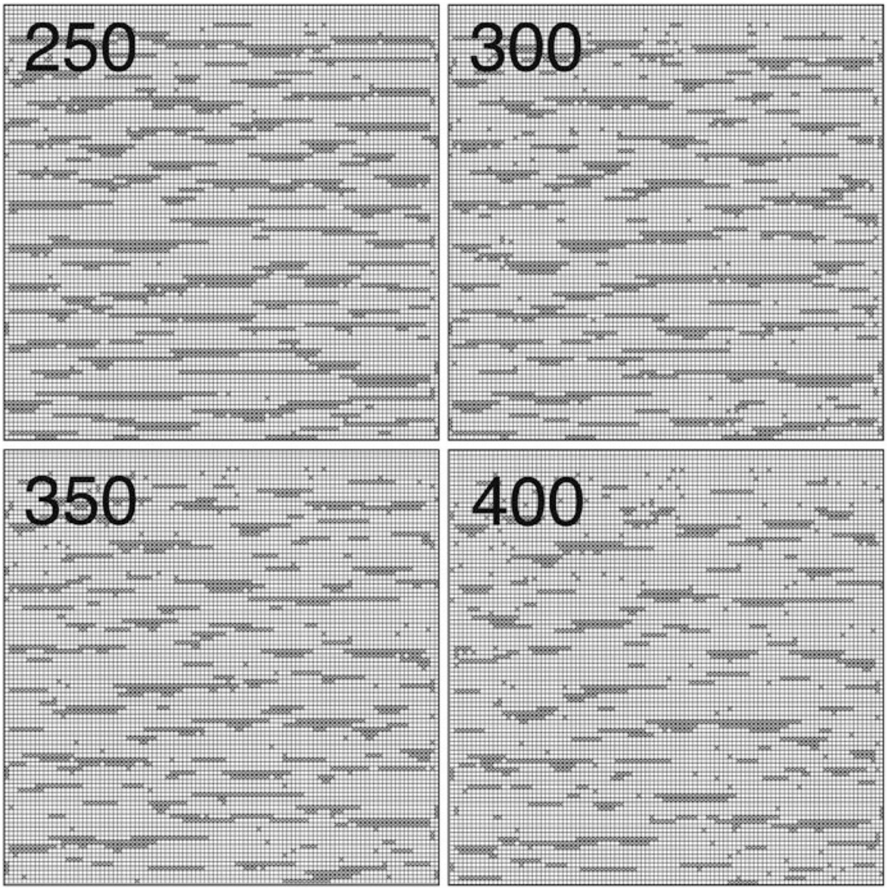

Fig. 12.8 Plotted vegetation cover across the model tessellation at year 21 of a 50 year run. The threshold accumulated infiltration depth (in mm) for a cell to become or remain vegetated is indicated in the *top left* of each plot. Effects on the grove and intergrove structure can be seen (see text for details) (Note: downslope is toward the bottom of each 100 × 100 tessellation)

for the 1974 record wet year). The wet year was inserted as year 20 of a 50 year simulation. Results showed that the vegetation groves widened considerably in the flow direction in the wet year (Fig. 12.9).

Across the 10,000 cells of the model tessellation, the plant cover jumped from 15.8 % in the preceding year (rainfall 193 mm) to 45.9 % in the wet year (rainfall 800 mm). Interestingly, owing to the persistence of the plant cover, there was a further increase in plant cover in the year following the wet year, to 47.0 % plant cover, even though the rainfall was only 290 mm. In the next year, plant cover had declined to 11.3 % with a rainfall of 141 mm. No persistent effect of the wet year on plant cover or on grove form and dimensions could be seen in the model.

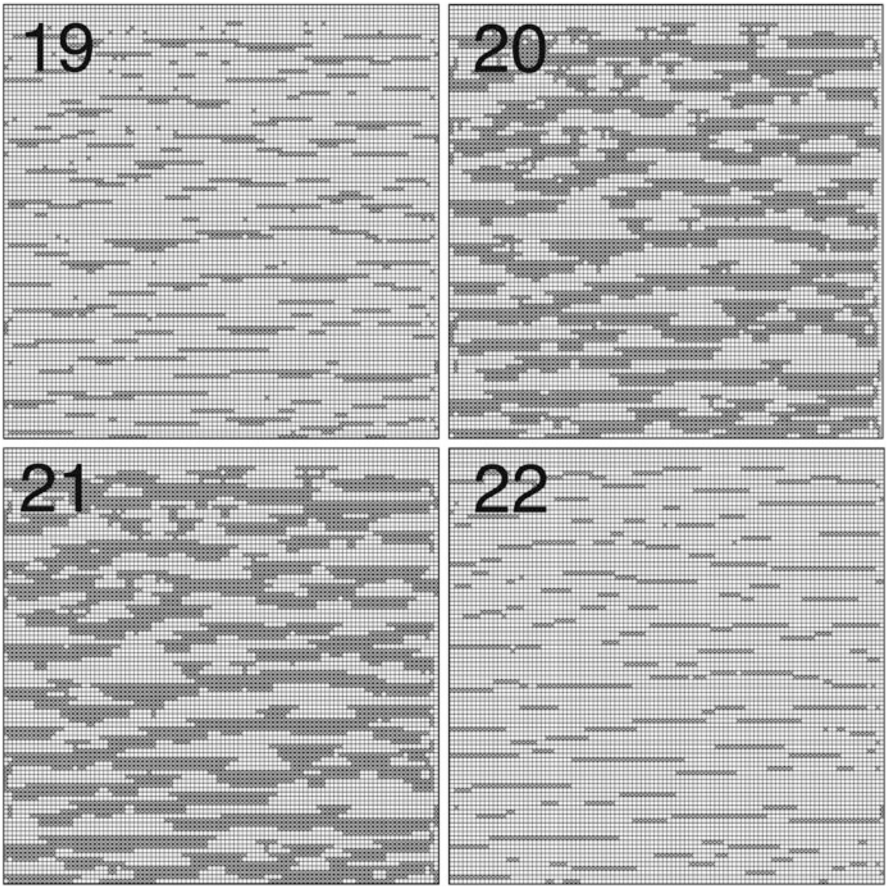

Fig. 12.9 Plotted vegetation cover across the model tessellation at years 19, 20, 21 and 22 of a 50 year simulation. Year 20 was a year of exceptionally high rainfall (800 mm). Considerable deepening of the groves can be seen in year 20 but this is rapidly lost when rainfall returns to more usual levels. See text for details (Note: downslope is toward the bottom of each 100 × 100 tessellation)

12.4.5 The Impact of Droughts and the Formation of Soil Crabholes

As noted earlier, the rainfall climate of western NSW involves very dry spells in which annual rainfalls can fall to about 50 mm, as well as rare wet years of 800 mm or more, lying at the extremes of the distribution of annual values.

In order to explore the significance of dry spells, the time series of random annual rainfalls was modified by including short runs of 3–5 years in which the rainfall was in the range 50–80 mm, i.e., lying in the lowest 5–10 % of recorded annual rainfalls (Table 12.3). Under these conditions, the model rule set incorporates the effect of subsoil contraction and crabhole formation. This is not invoked in wetter years when the subsoil clays expand and the crabholes are eliminated from the landscape. The model was run with this option and without it, in order to discern the consequences of crabhole formation for plant cover and grove and intergrove structure.

Figure 12.10 presents plots of the tessellation of cells for two versions of the cellular model, operated with and without the presence of the enhanced runon trap efficiency arising from crabhole collapse. Even though the crabholes form only intermittently in the model, and are subsequently removed, it is clear that the continuity of the vegetation banding is considerably enhanced when these are incorporated in the model than when they are not. Observation of the tessellation in successive iterations of the model also showed greater stability and persistence of the vegetation patterning when the effects of crabhole were incorporated. During year 30 of a 50 year simulation (plotted in Fig. 12.10) the vegetation cover declined to 10.4 % in the case where crabhole development was included in the model. In the same year and under the same rainfall but without crabhole formation, the plant cover declined to 5.4 %, and the vegetation groves were considerably smaller and less well connected. Significant numbers of gaps in the vegetation bands appear in this case, and in the absence of crabholes, would allow more connected overland flow paths and an increased leakiness of the landscape for water and other resources. In this situation, there is some likelihood that small flow concentrations could arise during convective storms, with associated rill or channel cutting possibly contributing to a decline in the integrity of the banded vegetation community. Interestingly, in the following year, the grove structure of the ecosystem modelled without the influence of crabhole formation shows fewer, and more widely spaced groves, than with crabholes present (Fig. 12.10f versus c). As noted earlier, this fluctuation in the spacing of groves is not seen in the field behaviour of these landscapes. Instead, groves narrow and widen in dry or wet periods, but remain in place rather than disappearing, albeit with diminished vegetation cover. This conservative behaviour can be seen successfully captured in Fig. 12.10a–c. There is a striking contrast between this behaviour and the loss of many groves between the years represented in Fig. 12.10d and e, a phenomenon that is not seen in the actual landscape.

Vegetation cover data summed over the entire tessellation (Fig. 12.11) show that in 60 year model runs with and without the incorporation of crabhole formation, there are no apparent differences in total plant cover in years with reasonable rainfall (years 1–29). A drought in years 30–32 (rainfalls 80, 84 and 88 mm respectively), vegetation cover in the absence of the crabhole effect drops to about 5 %, whilst in the presence of crabholes the cover declines only to about 12 %. For some time in years 33 and afterward, the plant cover in the non-crabhole scenario remains below that of the model with active crabholes, only recovering after about 10 years. Similar responses are seen in the second drought period (years 47–55).

Crabhole formation during very dry years and runs of years thus appears to be a very important aspect of the mechanisms that create and sustain the banded mosaic vegetation communities of the study area. The formation of crabholes within the groves during drought conditions appears to be capable of maintaining a high trap efficiency for rainfall and runon water within the groves. Without the crabholes, the

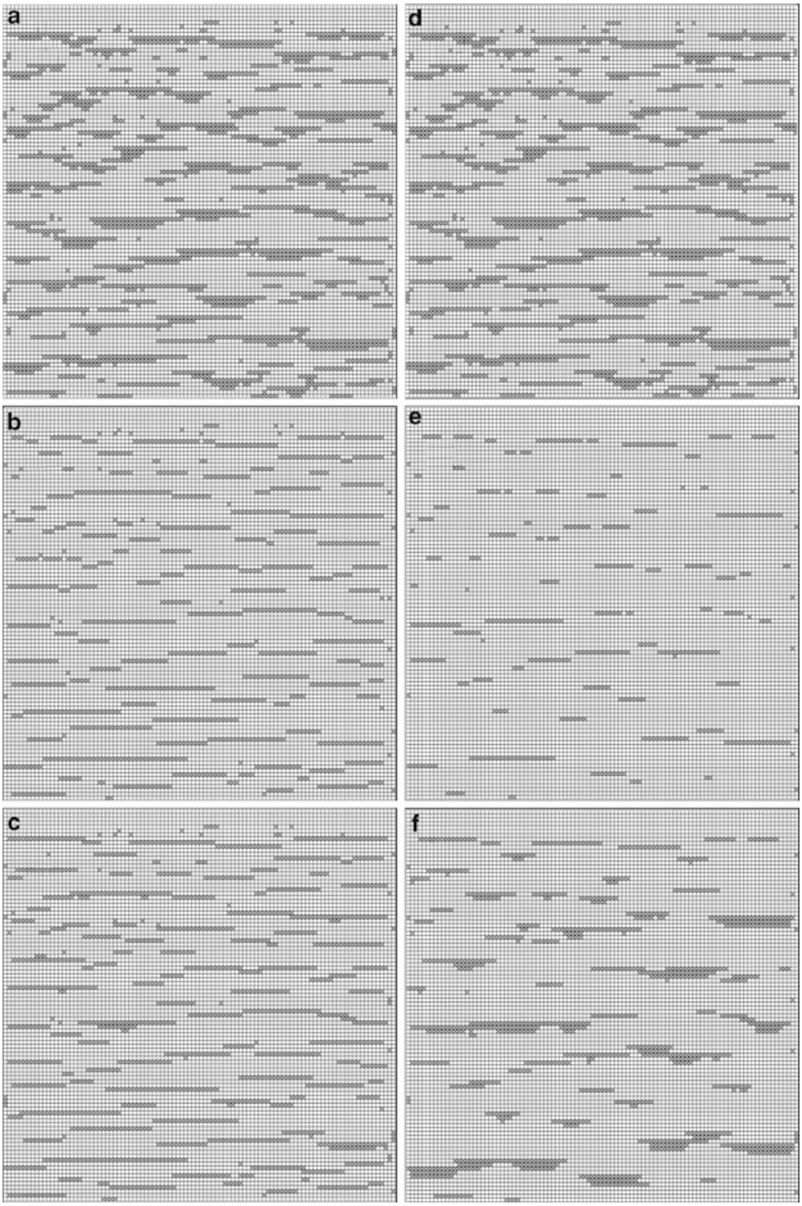

Fig. 12.10 Plotted vegetation cover across the model tessellation at years 22, 30 (drought), and 36 of a 50 year simulation. Parts (**a**–**c**) are for the model with crabhole formation included; Parts (**d**–**f**) show the model results when crabhole development was excluded. The input rainfall timeseries was the same for both model runs. Note that the pre-drought vegetation cover (Parts **a**, **d**) is the same in both models, since the crabhole development routine had not yet been invoked by years of very low rainfall. See text for details (Note: downslope is toward the bottom of each 100 × 100 tessellation)

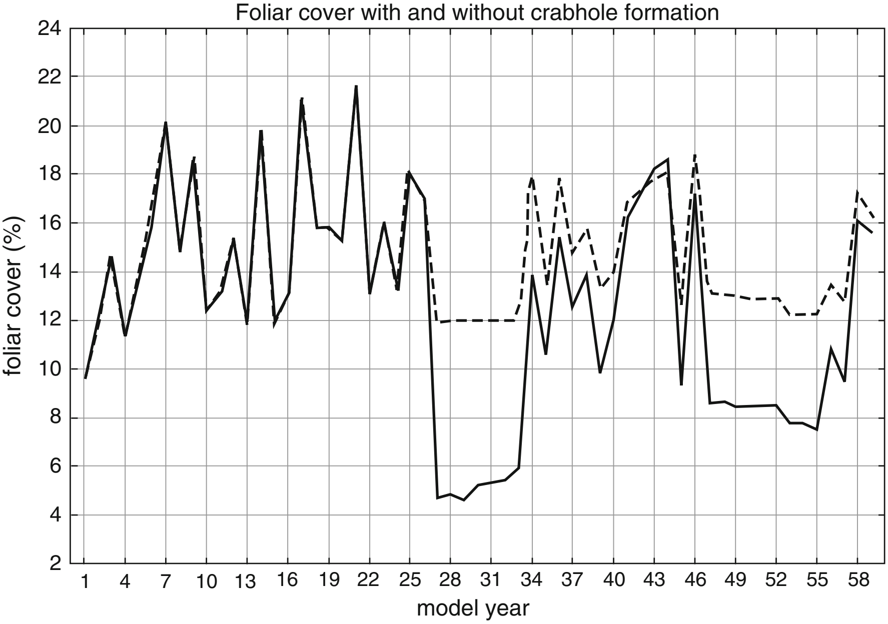

Fig. 12.11 Plotted vegetation cover summed across the model tessellation at year 30 of a 50 year simulation using a rainfall timeseries with two drought periods. The *solid line* is the vegetation cover modeled without incorporating the formation of crabholes, and the *dashed line* shows the vegetation cover with crabhole formation included. See text for details (Note: downslope is toward the bottom of each 100 × 100 tessellation)

smooth and bare soil surface, lacking organic litter and litter dams to slow runoff, and with reduced sheltering by plant canopies, would shed a larger fraction of the rainfall downslope as overland flow. This would represent a key resource loss for the ecosystem, and via positive feedback, further reduce the vegetation cover. Given that through the course of the past 160 years, grazing pressure has been added to severe, multi-year droughts, it is in some senses surprising that spectacular mosaic vegetation communities are still well represented in western NSW. However, it appears that the shrink-swell behaviour of the subsoil clays may provide at least one clue to this, resulting as they do in a critical change in the soil surface configuration during dry years that allows the ecosystem to be better supported by enhanced retention of the scarce rainwater resource.

12.5 Discussion and Conclusions

Soils and their influence on surface and subsurface hydrologic processes appear to be pivotal in the vegetation mosaics of western NSW. Many of these landscapes include exogenous dusts containing clay minerals that exhibit marked shrink-swell behaviour. This dust acts in concert with the marked interannual rainfall variability of the ENSO-dominated eastern Australian rainfall regime. One outcome is the quasi-periodic appearance of dense networks of crabholes and other closed depressions. These constitute traps for runon water that are largely unrelated to the role of the vascular plants. They may well be more important hydrologically than plants, especially after very dry years, when in their absence plant cover might be more vulnerable to collapse owing to the bare surface and high connectivity of overland flow paths across the intergroves and groves. The absence of crabholes would allow much increased loss of water from the hillslopes. Scant plant cover under such conditions would result in greatly diminished differentiation of intergrove and grove, in terms of foliar and litter cover; however, the soil-based processes may result in maximal differentiation under the same conditions.

A question not resolved here is the relative roles and importance of soil and vascular plant behaviour in the initial development of the vegetation patterning. However, a simple cellular automaton model suggests that soil collapse processes may well be able to act independently of the plant cover, and so this provides a potential mechanism for the progressive spatial organization of the soils into areas prone to repeated crabhole formation (and perhaps consequent plant colonisation) and areas that remain too dry for these processes to operate. Thus, it may be that soil pattern development is the leading process, and the emergence of patterned vegetation is an effect consequent upon the soil behaviour. It is likely, of course, that the vegetation patterning establishes a feedback process to further strengthen the hydrologic compartmentalisation resulting from the soil collapse processes. It is widely known that gilgai mechanisms operating in expansive soils can produce a wide range of vegetation patterns in association with surface pits and undulations. For instance, Maxwell (1994, Fig. 1) presented an aerial photograph of spotty vegetation in Texas, USA, that is related to soil gilgai phenomena. The pattern arising at that location from soil shrink-swell is very similar to other examples claimed to be self-organised vegetation patterns (e.g. see case study in Chap. 13). The extent to which the vegetation patterns are in fact self-emergent or are consequent upon, or interlinked with, the soil processes appears to remain unresolved, and appears to be an important but neglected aspect of the emergence of mosaic plant communities.

Consequently, further research is needed to examine these ideas in more depth. Models have successfully reproduced the kinds of emergent patterns seen in areas affected by soil freeze and thaw cycles (e.g. Kessler and Werner 2003). According to these models, bands or stripes resulting from freeze-thaw are oriented normal to the contour, reflecting differential downslope-upslope effects of gravitational loading. It has also emerged from these models that the patterns that emerge vary with the steepness of the hillslope, as for many forms of dryland vegetation patterning. Interestingly, in some environments, patterned ground and vegetation exhibit alignments that are intermediate between the common contour-aligned form described from dryland vegetation and the contour-normal form seen in cold climates (e.g. Haantjens 1965; Dunkerley and Brown 2002). It seems possible that these intermediate, oblique forms reflect a competition or interaction between hydrologic and pedologic processes. Oblique vegetation banding of the kind reported by Dunkerley and Brown (2002) remains an unresolved challenge, and the option of a hybrid origin is worthy of further examination.

The banded vegetation of western NSW has not been eliminated by drought or pastoral grazing pressure, despite being located in a region whose rainfall variability is extreme. Some of these landscapes are indeed known for their resilience and value as pasture, rather than their fragility. Ongoing field observation has drawn attention to the importance of soil processes in the development and maintenance of these systems. This includes the particular clay mineralogy that gives rise to shrink-swell behaviour in the soils, and the role of climatically-driven subsoil wetting and drying, that lead to crabhole formation and to efficient water trapping during periods when the vegetation cover is greatly diminished. Even though grove soils are much more permeable than intergrove soils, their point matrix properties (e.g. infiltrability) provide insufficient information for understanding the hydrology of the vegetation mosaics. This points to the need for more attention to be paid to physical and hydrological processes in patterned vegetation, a knowledge gap recently highlighted by von Hardenerg et al. (2010). The banded vegetation mosaics of western NSW have exhibited no upslope motion in 15 years of monitoring. Again, though many modellers assert that banded systems migrate upslope, clearly at least some actual instances do not. This suggests that either the models are incorrect, or that there are different sets of mechanisms working in different field locations. This clearly needs to be resolved by careful examination of mosaic stability in other sites, and this provides a potentially useful way to advance our understanding of these systems. The role of subsoil shrinkage and crabhole formation as explored here for the case of arid western New South Wales, Australia, provides a new mechanism that appears to be involved in the maintenance of mosaic plant communities in this area. Given that crabhole formation and disappearance in this region span multi-year to decadal timescales, linked to imperfectly understood aspects of the global climate system, the development and maintenance of the mosaic communities must be addressed using temporal scales that capture processes occurring at these timescales. In the context of these landscapes, key explanatory power lies not in a knowledge of the mean annual rainfall, but rather in an understanding of the multi-year variability of rainfall, and of the consequent changes in the soils and trap efficiency of the vegetation groves.

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