Chapter 1

ECOHYDROLOGY OF ARID AND SEMIARID ECOSYSTEMS: AN INTRODUCTION

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1. Ecohydrology: Objectives and Challenges

Ecohydrology has been recently defined as "*the science, which seeks to describe the hydrologic mechanisms that underlie ecologic patterns and processes*" (Rodriguez-Iturbe, 2000; p. 1). This type of inquiry is fundamental to the understanding of the coupling existing between ecosystem dynamics and the water cycle, in particular in arid and semiarid environments, where water is an important limiting resource not only for its scarcity but also for its intermittency and unpredictable presence (Porporato and Rodriguez-Iturbe, 2002; Rodriguez-Iturbe and Porporato, 2005). The biogeoscience community has been recently trying to establish stronger connections between research in the physical and the natural sciences to provide a process-based understanding of the interactions existing between the hydrosphere and the biosphere. Thus, the research area at the border between hydrology and ecology is recently receiving a considerable attention. The term "Ecohydrology" itself, is becoming increasingly popular in the scientific literature. Nuttle (2002) provides a thorough analysis of this new and combined approach to hydrological and ecological studies: "*Eco-hydrology emerges as an engaging topic with multiple facets and deep roots in the history of hydrologic science*". It is "*the subdiscipline shared by the ecological and hydrological sciences that is concerned with the effects of hydrological processes on the distribution, structure, and function of ecosystems, and on the effects of the biotic processes on the elements of the water cycle.*" The same author notices that in this new context "*previously unrelated areas of scientific inquiry are now coming together.*" This approach is fundamental to the analysis of ecosystem dynamics, of their response to different hydrologic and climatic regimes as well as of their impact on regional and global climate. This book represents an effort exactly in this direction, in that it provides a background for a synthesis of new research approaches and recent results in the study of ecological and hydrological processes characteristic of arid environments.

The focus on drylands is motivated by their high sensitivity to daily, seasonal, and decadal perturbations in water availability. The analysis of how arid ecosystems respond to such perturbations is receiving increasing attention also due to the ecologic, climatic, and economic significance of most of the drylands around the world. This book addresses the impact of different hydrologic regimes on soil properties and processes, landforms, and spatial patterns of soil moisture. It shows what is the effect of these hydrologic conditions on the biosphere, in particular on plant physiology, nutrient cycles, plant competition, fire regime, and spatial patterns of vegetation. At the same time it is shown how changes in the biotic components of dryland ecosystems can affect the soil properties, the landscape, as well as the regional hydrology and climate. The book includes chapters on field studies, data analysis, interpretation of hydrologic and ecologic dynamics, and process-based modeling of ecosystem dynamics. In this chapter we briefly review some of the main eco-physiographic characteristics of dryland ecosystems.

2.   Dryland Climates

Drylands are drought-prone areas of the world in which rainfall is less than the potential evapotranspiration for the whole year or for part of it, and conditions of either permanent or seasonal soil water deficit occur. The obvious features of the rainfall regime are the low precipitation amounts and the high variability and unpredictability of precipitation, which occurs in a discrete number of relatively infrequent events. Thus, dryland ecosystems are in general water-controlled "*with infrequent, discrete, and largely unpredictable water inputs*" (Noy-Meir, 1973, p. 26).

More than 40% of the continents is covered by drylands (e.g., Slaymaker and Spencer, 1998). These regions are mostly located (Figure 1) (1) in continental areas, away from marine sources of moisture; (2) in regions of persistent high pressure cells (i.e. between 20° and 40° latitude); (3) in rain shadow areas; (4) or along the western continental margins, where, due to the upwelling of deep oceanic water, low sea surface temperature causes high atmospheric stability (Slaymaker and Spencer, 1998).
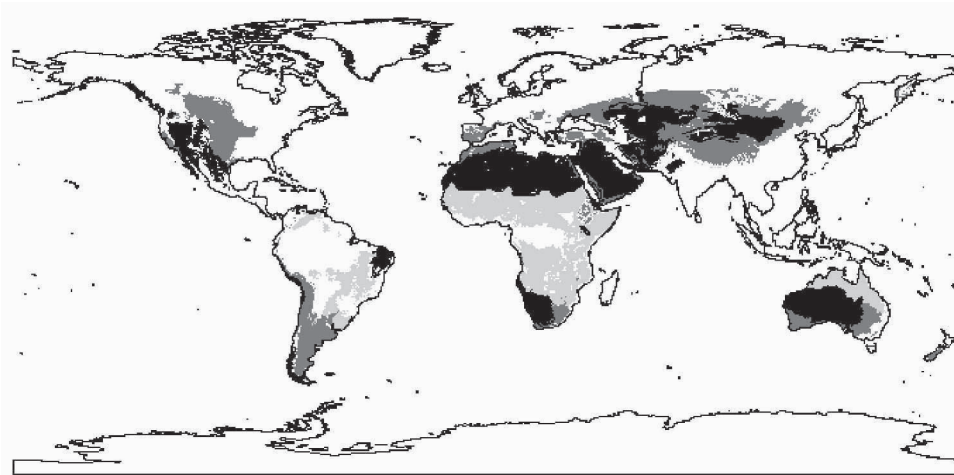

Figure 1. Map of the major drylands of the world classified as deserts (black), Mediterranean shrublands and mesic grasslands (in dark gray), and tropical savannas (light gray).

Annual precipitation is generally used to define four main dryland zones (e.g., Noy-Meir, 1973; Mainguet, 1994):

Extremely arid zones, with average annual rainfall below 60-100 mm, which is insufficient for dryland farming or livestock grazing;
Arid zones, with average annual rainfall between 100 mm and 150-250 mm and possible livestock grazing;
Semiarid zones, with average annual rainfall between 250 mm and 500-600 mm and possible cultivation of drought-resistant crops;
Dry sub-humid zones, with precipitation in the range from 600 mm to 1200 mm concentrated in one (or more) rainy seasons. Water deficit can be either seasonal or intermittent (Mainguet, 1994).

Other criteria for dryland classification are based on annual temperature or on the seasonality of precipitation. Mean annual temperature is used to distinguish *warm drylands*, which occur at low latitudes and altitudes (e.g., Northern Australia, Sahara, Sahel, Kalahari, and southwestern U.S.),

from *cold drylands* (e.g. Central Asia and Central Chile). Drylands can be also divided into summer-rainfall and winter-rainfall regions. The timing of the rainy season is of foremost importance to the phenology of ephemeral and annual vegetation in the desert margins (see Section 4). In summer-rainfall drylands (e.g., the Sahel or the Kalahari) plant phenology is strongly dependent on precipitation (e.g., Larcher, 1995); both onset and length of the growing season are controlled by soil water availability (e.g., Noy-Meir, 1973). Vegetation resumes growth a few days or weeks after the beginning of the rainy season, while senescence occurs soon after the last storms of the season; ephemerals maintain no photosynthetic activity during the dry season, while perennials reduce photosynthetically active biomass by shedding leaves and rootlets in the surface soil layers. In winter-rainfall drylands (e.g. drylands with rainfall occurring in the cold season or cold deserts) bud burst and greening of vegetation is generally inhibited at low temperatures, despite the availability of soil moisture. Due to low evaporative losses, cold-season precipitation is stored in the ground and taken up by vegetation during the subsequent (dry) growing season. Thus, greening does not occur concurrently with moist surface conditions. Mediterranean regions, where the winters are cool, represent a particular case of winter-rainfall dryland in which growth is not completely inhibited by winter temperatures (Noy-Meir, 1973). Other types of dryland climates are characterized by two distinct rainy seasons (e.g. west Texas) and two associated germinations (Mott, 1972).

2.1 DROUGHT CONDITIONS

The classification of drylands on the basis of the rainfall regime provides a useful indication of their level of permanent or seasonal *aridity* through long-term average climatic variables. The concept of *drought* is instead used to characterize deviations from "normal" (i.e. long-term average) conditions. Droughts are generally defined as prolonged periods of below-normal water availability (Mainguet, 1994), which persist long enough to cause stress on water bodies, ecosystems, and societies. Thus droughts need to be studied with respect to their climatic, hydrologic, ecologic and human implications, including the feedbacks between climate and changes in land cover and use (Mainguet, 1994). To this end, four different types of droughts have been defined (American Meteorological Society, 1997): the meteorological, hydrological, agricultural, and societal droughts.

A number of indices have been developed and applied to quantify the severity and magnitude of aridity and drought conditions. Aridity indices are generally based on long-term average precipitation, available water, mean annual net radiation, or evapotranspiration. For example, the difference between precipitation and evapotranspiration, the ratio between potential and actual evapotranspiration (e.g., Thorntwaite, 1948), or between mean annual net radiation and the energy required to evaporate the total annual precipitation (Budyko, 1958; Lettau, 1969) can be used to characterize aridity. On the other hand drought indices should measure the departure from the long-term mean conditions. To this end, other indices are commonly used to characterize the meteorological, hydrological and agricultural droughts (Heim, 2002). The most common ones are the Palmer's indices (Palmer, 1965), i.e. the PDSI (Palmer Drought Severity Index) and the PHDI (Palmer Hydrological Drought Index) indices, which are calculated on the basis of a simplified soil water balance. However, neither these nor other drought indices can be considered as universal indicators, able to characterize completely drought occurrences and all their implications at any spatial and temporal scale (Heim, 2002).

2.1.1 Meteorological Drought
Droughts are often associated with anomalies in the regional and global climate, though they can be enhanced by changes in land cover and resource management. Meteorological droughts are periods in which precipitation is significantly below the long-term average at a certain location and time of the year. This definition is based only on rainfall statistics. Depending on the spatial

extent of the region affected, droughts are usually classified as local, regional, and subcontinental (Mainguet, 1994).

The occurrence of meteorological droughts (i.e. departures from mean rainfall conditions) is usually strongly related to aridity (i.e. to mean rainfall conditions), in that the interannual rainfall variability is generally higher in the more arid regions, which are also the most sensitive to droughts. This fact is illustrated for example by the data in Table 1 (Nicholson, 1980; Porporato et al., 2003), showing changes in rainfall variability along two rainfall gradients in Northern and in Southern Africa: the stronger variability is associated with the most arid zones, suggesting a more frequent drought occurrence at the low end of these rainfall gradients.

In the case of Sahel, it has been reported (Lebarbe and Lebel, 1997) that most of the interannual variability of rainfall is due to changes in the number of rainstorms affecting a certain location in the course of the rainy season, more than to changes in the amount of rain yielded by each storm (or "storm depth"). Different results were found for savannas in southern Texas (D'Odorico et al., 2000) and in the Kalahari (Table 1, data from Porporato et al., 2003), where a strong variability was observed also in storm depth.

Table 1: Mean annual rainfall and coefficient of variation (CV) along two rainfall gradients (data from Nicholson, 1980 and Porporato et al., 2003). In the case of the Kalahari coefficients of variation are separately provided for the interannual variability of storm depth and storm frequency.

Zone	Mean Annual Rainfall (mm)	CV (%)	
Guinea-Sahel Transect			
Sahelo-Saharan	50-100	>50	
Sahelian	100-400	30-50	
Sudanian	400-1200	20-30	
Sudano-Guinean	1200-1600	15-20	
Kalahari Transect		*CV (%) (Storm Depth)*	*CV (%) (Storm Frequency)*
Vastrap	305	31	32
Sesheke	715	20	18
Mongu	942	17	16

2.1.2 Hydrological Drought

Hydrological droughts occur when the water level in lakes or rivers falls significantly below "normal" conditions for a certain location and time of the year. Thus, the hydrological drought is defined only on the basis of anomalies in storage or flow (generally base-flow) conditions in water bodies (e.g., Heim, 2002). Because these conditions depend also on water usage, evapotranspiration and infiltration, hydrological droughts are not necessarily a consequence only of meteorological conditions. Moreover, even when hydrological droughts are caused by below-average precipitation, there can be a significant delay in the response of water bodies to the climatic anomaly. In fact, fluctuations in lakes and rivers are indicators of changes in the rainfall regime integrated over the watershed area. Thus, the two types of drought (meteorological and hydrological), though related, are not necessarily concurrent. Mainguet (1994) discusses a number of cases of hydrological droughts through the analysis of multi-decadal records from Lake Victoria, Lake Chad and the Nile River. These hydrological droughts are shown to be associated with changes in weather patterns, soil type, land use and plant physiological characteristics (see Chapters 2-4).

Hydrological droughts are usually characterized (Yevjevich, 1967; Dracup et al., 1980) in terms of their duration, magnitude, severity, frequency, and spatial extent. With the exception of short-term seasonal events, droughts are defined as periods with below-average mean annual

flow. Thus, drought duration is the number of consecutive years in which drought conditions persist, drought severity is the cumulative streamflow deficit observed throughout the event, while drought magnitude is the average streamflow deficit for the event duration (Heim, 2002).

2.1.3 Agricultural Drought

The agricultural drought is associated with the occurrence of low levels of plant available water, and the consequent reduction in agricultural production (Heim, 2002). This concept can be extended from agro- to natural ecosystems. In this case drought would be due to low levels of soil moisture and to the emergence of conditions of water stress in vegetation. In North America, Palmer's indices (1965) are generally used to characterize the severity of drought conditions. Ridolfi et al. (2000) and Porporato et al. (2001) have pointed out the importance of a probabilistic approach to plant water stress based on a statistical characterization (intensity, frequency and duration) of periods when plant activity is impaired by soil water deficit (see also Chapter 3). These types of drought are by definition associated only with soil moisture conditions occurring in the course of the growing season; thus, average root-zone seasonal soil moisture, as well as the duration and frequency of periods in which transpiration is limited by soil water availability can be taken as useful indicators of agricultural and ecosystem stress.

2.1.4 Societal Drought

This concept is closely related to the notion of agricultural drought: it occurs when the soil water deficit affects crop production to the point that there are significant economical losses with disruptive effects on the rural societies (e.g., Heim, 2002). This type of drought causes social and economical stress, which, in turn, is associated with famine and migratory fluxes. Societal drought is not necessarily just an effect of extreme agricultural droughts, in that it depends also on demographic changes, expansions of farming areas, and grazing pressure. The analysis of societal stress and of its interactions and feedbacks to dryland ecohydrology is beyond the scope of this book.

3. Dryland Soils

Soils of arid and semiarid regions are generally characterized by low soil water contents, high potential evapotranspiration and consequently relatively low rates of percolation and leaching, depending on the soil texture (e.g., Brady and Weil, 1996). Thus, water and nutrients partly remain available to vegetation in the root zone. The soil profile generally lacks of an E-horizon, while the processes of calcification and salinization accumulate within the soil column calcium carbonate, sodium chloride and other salts (e.g., Aber and Melillo, 1991). The typical soils (*Aridisol*) have a deep A-horizon and sustain tropical and temperate shrublands. Soils underlying grasslands and savannas have an A-horizon that is fairly well-mixed by animal activity and have a darker color, due to the more abundant organic material (melanization). This type of soil is classified as *Mollisol* and can be found both in tropical and temperate grasslands. It is not always clear what controls the predominance of either grasses or shrubs in arid and semiarid environments (see Section 4), though an important role seems to be played by rainfall regime, soil texture (Sala et al., 1997) and disturbances, such as climate fluctuations, grazing and fires (e.g., Aber and Melillo, 1991). Both Aridisols and Mollisols are characterized by very limited leaching and slow soil-forming processes. In areas with limited vegetation density these pedogenetic processes are mainly due to the physical weathering of the parent material by wind and water, while in grasslands and savannas soil formation is significantly contributed by biological processes.

Vegetation plays an important role in limiting water and wind erosion (Chapter 9); vegetation removal due to anthropogenic or natural disturbances is known for being one of the major causes of desertification (Chapter 18), i.e. of complex dynamics able to turn - even irreversibly - arid grasslands into deserts.

The seasonally dry tropics and subtropics are characterized by different soils, which are dry only in the course of the dry season. Thus, these soils (*Ultisols*) are significantly more humid than the Aridisols and Mollisols, and are consequently affected by severe weathering, leaching of iron and aluminum oxides and clays, which accumulate in the E horizon. Due to the higher moisture contents, soil formation and nutrient cycling are relatively fast, soils are nutrient-poor, and plant transpiration is limited by soil water availability only during the dry season (see Chapter 13).

4. Dryland Vegetation

The vegetation of arid and semiarid environments is in general well-adapted to conditions of water stress. Phenological and morphological adaptation to drought conditions, plant water relations and drought tolerance are among the attributes that are frequently used to group species into a few classes on the basis of their different access and use of the main limiting resource: water. This approach differs from more traditional classifications based only on morphology, evolutionary relationships, or plant genetics (Meanut et al., 1988).

Thus, dryland vegetation has been divided into a few major plant functional types - such as grasses, shrubs, forbs and succulents (Sala et al., 1997; Dodd and Lauenroth, 1997) - on the basis of their different water relations. According to this model the dominant vegetation type would result from its relative advantage in using available soil water stores (Noy-Meir, 1973): for example, grasses take up water from the surface soil layer and rely on relatively frequent and short pulses of soil moisture, while shrubs utilize water from deeper layers and rely on moisture that is available in infrequent and long-lived pulses. This classification would explain the dominance of a particular vegetation type on the basis of soil texture and seasonality of precipitation. In fact, these two environmental factors affect the amount and timing of water available at different depths (Sala et al., 1997). Grasses dominate drylands with continental climates, i.e. with rainy seasons occurring concurrently to the warm season. In these regions soil moisture is readily available to grasses during the growing season and grasses are in competitive advantage with respect to shrubs and trees. Deep-rooted perennials (e.g., shrubs and trees) dominate regions with a more Mediterranean climate, where the rainy season occurs in wintertime and, due to the low evaporative demand, rainfall is able to percolate to relatively deep layers. Thus, the overlapping between warm and wet seasons partly explains the dominance of different plant functional types. This analysis can be partly modified by the effect of soil texture, which affects the regime of soil moisture at different depths. For example, the presence of coarse-textured soils in continental regions allows for a relatively deep percolation of water in the course of the growing season, reducing the competitive advantage of grasses with respect to trees (Sala et al, 1997; Figure 2). This framework (Sala et al., 1997), which is based on the interplay of competitive advantages/disadvantages resulting from spatial and temporal niches of water availability, is coherent with Walter's observation (1971) that in tropical regions with summer rains and sandy soils, trees and grasses are found in ecological equilibrium (savannas). In these conditions the co-dominance of trees and grasses would be explained by the two-layer hypothesis (Walter, 1971) that grasses and trees compete for water at the surface, while woody plants have exclusive access to deep water. Even though the climate pattern would tend to favor grasses at the surface, the soil texture would allow trees to have a competitive advantage in the deeper layers, explaining the co-dominance of these two functional types.

Alternative theories have been recently formulated (Rodriguez-Iturbe et al., 1999), which explain the tree-grass coexistence on the basis of an optimality principle: for a given climate and soil texture, the most likely proportion of herbaceous and woody vegetation would be associated with the conditions of minimum ecosystem water stress. This and other theories (e.g., Schlesinger et al., 1990; Scholes and Archer, 1997) recognize the importance of the horizontal redistribution of of water and nutrients in the presence of heterogeneous vegetation cover. This concept has been recently incorporated in a more general framework (Breshears and Barnes, 1999) explaining

the dominance and codominance of trees and grasses in semiarid landscapes on the basis of horizontal (e.g., Schelsinger et al., 1990) and vertical (e.g., Walter, 1971) heterogeneities in the distribution of soil moisture.
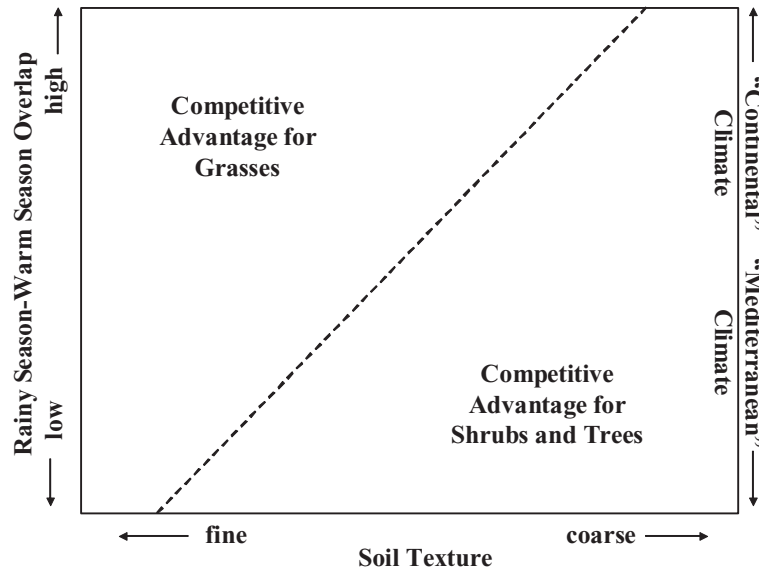

Figure 2. Conceptual model of the effect of climate and soil texture on dominant plant functional type (modified after Sala et al., 1997).

Southern African savannas are an example of how the soil geology may affect vegetation composition, nutrient cycling, and disturbance regime. By contrasting the ecohydrologic processes taking place on granitic and basaltic soils in Kruger National Park (S. Africa), Venter et al. (2003) showed how the clayey basaltic soils support a higher grass biomass than the granitic sandy soils. Due to the high water-holding capacity and the lower infiltration and leaching rates, the basaltic clayey soils retain moisture and nutrients at the surface, offering a competitive advantage to grasses (Figure 2). The typical vegetation in these nutrient-rich soils is an open savanna dominated by high-productivity C_4 perennial bunchgrasses (often exceeding 50 cm in height) and fine-leaf trees (*Acacias*). The high grass biomass characteristic of these soils results in high-intensity fires, which, in turn, prevent the establishment of denser woody vegetation (Venter et al., 2003). The nutrient-poor, granitic, sandy soils at Kruger are in general well-drained and with high rates of nutrient leaching (Scholes et al., 2003). Due to the low water retention, the soil surface is generally dry, and grasses are in competitive disadvantage with respect to woody vegetation (see Figure 2). As a consequence, these sites are dominated by short annual grasses (seldom taller than 50 cm) mixed with a dense vegetation of broad leaf woody plants (*Combretum* and *Terminalia*). The low grass productivity, combined with consequently low fuel loads and fire intensities explain the presence of dense bush savannas at these sites. Moving on the same granitic soils along a rainfall gradient (from 530 mm at Skukuza to 720 mm at Pretoriuskop) grass biomass and fire intensity are observed to increase (Venter et al., 2003). A similar combination of fine-leaved (*Acacia tortilis*) and broad-leaved (*Burkea africana*) vegetation sites can be found at the Nylsvley Nature Reserve (S. Africa), with the fine-leaved savanna having lower tree cover than the broad-leaved vegetation (Scholes and Walker, 1993). The different type of vegetation is associated with the soil nutrient content, with nutrient-rich soils supporting the fine-leaved savanna.

While Sala's model (1997) explains the dominance and co-dominance of different plant functional types on the basis of water relations, a more general analysis would account for the existence of other environmental controls able to determine vegetation types and structure. For example, south American savannas - also known as "*cerrados*" (e.g., Sarmiento, 1984) – generally grow on weathered infertile soils and in seasonally-dry sub-humid to humid climates. In this case tree-grass coexistence seems to be associated with nutrient rather than water limitations, as evidenced by the positive correlation found between soil fertility and tree cover across different types of cerrados (Kauffman et al., 1994). Nevertheless, climate exerts an important control on the vegetation structure through its influence on the fire regime. Thus, when water is not the only limiting resource, soil chemistry (in particular nutrients) and disturbances may explain the dominance of different vegetation types. This view supports other classifications of savanna ecosystems. For example, the Johnson-Tothill classification presented by Adams (1996) recognizes the existence of savannas in humid and sub-humid climates (Figure 3). While the existence of tropical savannas on sandy soils would be explained by water limitations, the occurrence of tropical savannas on fine-textured soils in floodplains and valley bottoms could be associated with nutrient limitations and disturbances.
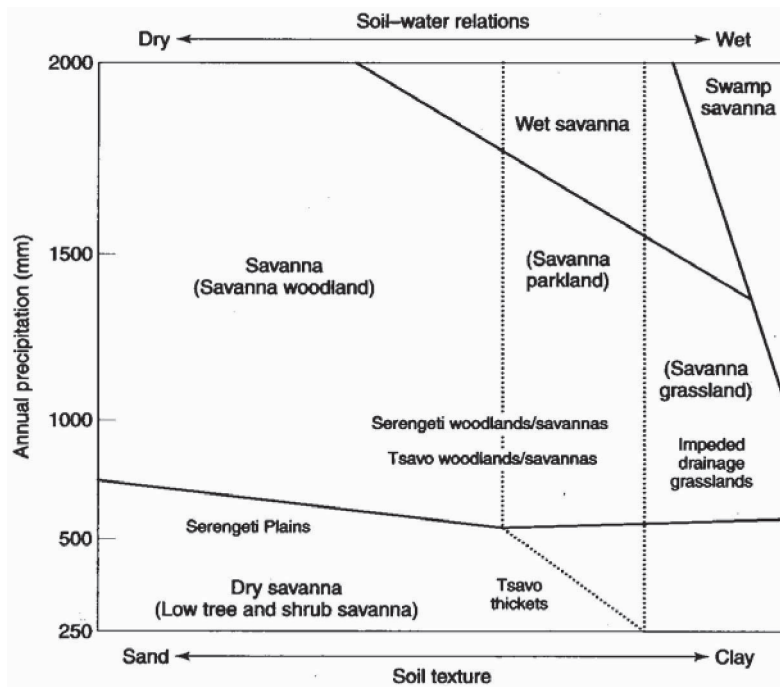

Figure 3. The Johnson-Tothill (1985) classification of tropical savannas (taken from Adams, 1996).

5. Multifaceted response of arid and semi-arid ecosystems

In summary, the dynamics of dryland ecosystems are complex and involve processes acting at different scales both in time and in space. These scales are dictated by a hierarchy of forcings and responses, from after-storm nutrient flushes, to plant competition, and community succession (e.g., Schwinning and Sala 2004; Austin et al. 2004). The unpredictable and pulsing nature of resource availability propagates through the complex ecosystem structure with many interactions and feedbacks and finally translates into a hierarchy of scales of ecosystem responses. The

following chapters will describe the various interactions among the biotic and abiotic processes of dryland ecosystems (Figure 4), starting from basic processes in the soil-vegetation-climate system (Part I), to landscape-scale hydrologic and geomorphic processes (Part II), ecohydrologic controls on soil nutrient dynamics (Part III), and multiscale analyses of disturbances and patterns (Part IV).
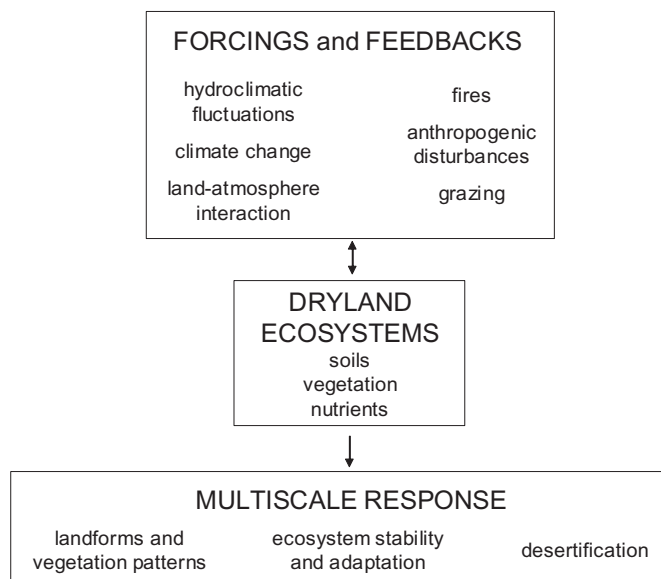

Figure 4. Interactions between biotic and abiotic processes in dryland ecosystems addressed in the following chapters of this book.

6.   Acknowledgements

7.   References

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