Adaptation of dryland vegetation to climate

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Abstract: Dryland ecosystems of Sub-Saharan Africa are particularly vulnerable to climate variability, of which rainfall is the most important component. Shortage of water is one of the greatest threats facing dryland. Since water is the major determinant of many ecosystem characteristics and processes in these dryland ecosystems, slight shifts in seasonal rainfall intensity and frequency can potentially lead to major ecological and biogeochemical impacts. In such cases, phenological and physiological plasticity of plants determines their response to the rainfall fluctuation and water stress. Areas of forest appear to have contracted due to climatic factors, especially rainfall variability (drought) and not merely due to human influence.

Introduction

Much has been written about land degradation especially in the dryland. There has been a continuous debate on the general nature and especially the reversibility or irreversibility of land degradation. In order for us to predict how dryland vegetation may respond to future climate change and other disturbances we must have a quantitative understanding of the exchange mechanisms and linkages between the atmosphere-plant-soil continuum that governs and regulates water fluxes and the potential ability of the vegetation to respond to these changes. At this end acclimatisation and adaptation of the vegetation to the climate as well as what species to plant and where to plant are questions open for discussion.

Over the past century the planet has seen an exponential increase in the human population. This drastic increase in population has been accompanied by an increased demand for resources, mainly food. As demand for resources increases there is an intensification of exploitation of the environment and therefore, without sustainable land use practices, these resources are depleted. More than half of the world's population resides in developing countries in tropical regions where there is a shortage of necessary resources such as food, fodder and fuelwood due to the intense demand. Land degradation is a direct result of this increased population pressure. Such degradation can be defined as a change in the physical, chemical and biological properties of the land that lead to a reduction in the area's productivity (Elevitch and Wilkinson, 1999). A number of different factors such as soil erosion, leaching, soil compaction, decreased soil fertility, decreased amount of soil nutrients, waterlogging, salinisation, or the establishment of weeds can initiate this reduction. It has been estimated that 2 billion hectares of the earth's soil is degraded, which is equivalent to 70% of land currently cultivated (Parham, 2001). In order to curb this dangerous cycle of land degradation, sustainable management strategies must be researched and employed in tropical regions. Almost all of this change has resulted from human action (Matthews et al. 2000)

According to the 1990 FAO assessment of tropical forest resources, 19% of the global annual loss in biomass due to deforestation is occurring in Africa. This means that the total annual decrease in forest cover in Africa is 4.1 million ha (0.78%), which is equivalent to a loss of 479 million tons (0.68%) of forest biomass. It has been suggested that this rate equals a two per cent loss in the total number of species in Africa per decade (FAO 1993).

The Sahel is characterised by a dry season of about nine months, and a short, erratic rainy season. This is over an area of sandy, infertile soils which are very deficient in nitrogen and phosphorus. Other obstacles include increasing land pressures due to population growth, unfavourable socio-economic relations, changing social perceptions and new land-use options. The complexities of these factors and their interactions have led to the deterioration of the existing traditional systems. Overcoming these obstacles (in biophysical and socio-economic terms) will lead to poverty alleviation and rural welfare. The notion that desertification is gradually advancing towards the south in the Sudan has been proved controversial. In fact, surveys have shown that the movement of the agronomic dry limit (the boundary between the desert and the Sahelian zone) southwards or northwards is determined by the yearly divergence of precipitation from the long-term annual mean.

Under dryland conditions, the successful establishment of trees is dependent on fast root growth. However, this characteristic is not desirable for trees prescribed for integration with agricultural crops. Different options exist to reduce the lateral extension of the tree root system so as to reduce competition. Shoot pruning has become a management practice in agroforestry for reducing both above and below-ground competition with associated crops (Fownes & Anderson, 1991; Sinclair et al., 1998), supplying organic materials to the soil (Mafongoya & Nair, 1997) and providing mulch during the cropping season (Kadiata et al., 1998). However, as the functional balance of the tree is altered through pruning, it reacts both morphologically and physiologically in response to the changes and consequently the growth and development of shoots and foliage may be altered (Singh & Thompson, 1995). In the dryland the abundance of plant species increases with water availability.

Maley (2002) concludes that 2500 years ago a climatic deterioration lasting several centuries led to a catastrophic destruction of central-West African forests, almost halving their current range. The same author hypothesises that the climatically induced break (3,500-4000 years ago) in the Dahomey gap forest may have been much wider than it is now. Based on previous studies conducted in Cameroon, Maley (1999) concluded that more than one million ha of savannah have become forest in that region over a period of about fifty years.

The effectiveness of each climatic factor on species performance depends on the stage of development of the vegetation cover, both within one annual period and within the stand succession time scale, and on the geographical location that normally reflects the species adaptation to prevailing climatic patterns. In many parts of the tropics, unusual droughts and variation in rainfall are recognised as the most important factors.

Implications of climate for vegetation adaptation

The main impact of climate change derives from the positive response of photosynthesis to enhanced CO_2 levels resulting in increased biomass production and crop yield. In the dryland however, the major variables are the amount and temporal distribution of the rainfall, the composition and evolution of the vegetation and the soil water availability. In case of C3 species, the temperature dependency of growth rates, related to higher photorespiration rates at higher temperatures as well as decreased assimilation rate or its complete inhibition at raised CO_2 levels has to be accounted for. In this respect, the net CO_2 assimilation decreases progressively with the depletion of the soil water availability in the root zone of the dryland vegetation especially in the savannah area. However, the response to the climate and/or the disturbance depends on the plasticity of the plants that can be reflected in their growth rates, size and age at maturity, architecture, seed size and seed bank, dispersal syndrome, resprouting ability and leaf palatability. In this paper responses to climate rather than to disturbance will be discussed.

There are broad mechanisms for drought tolerance or avoidance, and within each there are considerable variations. Therefore it is possible that species exposed to the same environment can have very different physiology, regeneration and growth dynamics and morphology and can be equally successful in the long term. With respect to seeding and fruiting a number of adaptation mechanisms have been documented which include seed dormancy, seed mass germination, longevity and germination type.

In general, the acquisition of knowledge of the physiological and morphological characteristics of the species and the understanding of the factors affecting their growth dynamics and regeneration are obligatory objectives of any vegetation adaptation approach.

Seeds

The morphology and physiology of a seed are important factors in determining the success of germination, seed viability and establishment. Dormancy, seed size and mass, germination longevity and germination types are the main traits affected by climate. Seed traits include, for example, the seed size and the hard seed coat or fruit covering which has a resistance to desiccation or fire. Generally seeds are classified as either recalcitrant or orthodox. Recalcitrant seeds are species with only brief viability in forest soils which germinate quickly when water for imbibition is available, otherwise they die (recalcitrant seeds in the terminology of seed technologists, meaning seeds which lose viability quickly when stored and typically have high water content and are killed by drying). Neem (*Azadirachta indica*) is a typical example of this type.

Orthodox (ephemeral) seeds are of species which have extended viability in soil (often several to many years). These are the seeds which can be stored for long periods and which have low moisture content and are tolerant of drying. By a ‘soil seed bank species’, people usually mean the orthodox (persistent) type, typical of many, but not all, pioneers. Many of the dryland tree species are of this type of which the genera *Acacia* and *Prosopis* are widely distributed. Their seeds are likely to be present in soil at all times (whenever sampled), in relatively high abundance (they accumulate over time), and distributed to greater depths (more time for percolation with water movement, and transfer by invertebrates to greater depths). The difference between ephemeral and persistent species is probably a continuum, despite the dichotomy implied by the recalcitrant-orthodox terminology. However, a large intermediate group exists.

Seedlings, saplings and mature trees

The seed will germinate once the germination requirements are met; seedling growth depends on the food reserves in the seed. The further seedling growth will be determined by the growing conditions, which reflect the adaptability of the seedlings. Species vary in their response to these conditions. Most of the morphological traits associated with the size of the plant parts and the timing of growth may vary according to environmental conditions. These include leaf longevity and seasonality, leaf duration, bud dormancy patterns, leaf colour, texture and dimension, leaf thickness expressed as specific leaf area, SLA, wood density, relative sapwood width, leaf area to sapwood area, leaf area index, LAI, crown area/breast height diameter (dbh) index, stem height allometry, and branching architecture. Here it is important to mention that the distinction between morphological, physiological and reproductive traits is often blurred.

Plants respond differently to water stress. In the natural dryland environment, trees are frequently subjected to seasonal water stress, which limit their growth and development. Trees differ remarkably in their ability to withstand water-deficit periods and they have developed mechanisms for adaptation to drought. The term *drought resistant* has often been used to describe trees growing in the arid and semi-arid regions of the world. The avoidance strategy and the tolerance strategy for adaptation to drought has been extensively studied (Levitt 1972, Grime 1977, Turner and Jones 1980, Correia et al. 2001). Some species avoid drought through maximisation of water uptake through development of deep root system or minimisation of water loss through sensitive stomatal control, leaf movement, small leaves and shedding of leaves (Kozlowski et al. 1991) and this strategy is more desirable in situations where survival is more important than growth. Species possessing tolerance strategy exhibit osmotic and elastic adjustment (Arndt et al. 2000) and is more desirable in the context of production forestry (Honeysett et al. 1996).

The importance of nitrogen fixing trees (NFT), in the tropics cannot be overemphasised. They provide firewood, charcoal, timber, forage and organic fertilisers. They are important in the re-vegetation of hill slopes, stabilising sand dunes, providing windbreaks, firebreaks, shade and ornamentation. Furthermore, they are important in improvement of soils of the arid and semiarid tropics, by improving soil fertility through nitrogen fixation. *Acacia* trees are grown in different parts of the world for various types of afforestation programs for providing different benefits. Members of this genus have the ability to grow well in a variety of soils and under different kinds of environmental conditions. In Africa, they are an important component of agroforestry systems. For quite a long time leguminous woody plants, which utilise atmospheric nitrogen, have played a major role in sustainable management of the arid areas.

Because water availability is the main factor regulating the productivity of dryland ecosystems, extensive research has focused on structural and physiological adaptations to drought. Excess light and high temperatures have been reported to inhibit photosynthesis and may lead to destruction of photosynthetic apparatus.

Agroforestry

Traditionally, farmers in the drylands of Africa developed a wide range of agroforestry and soil conservation strategies to adapt their crop and livestock production systems to the marginal conditions of their lands and to minimise climatic risk to household and food supply. The strategies include the deliberate preservation of selected valuable trees and shrubs in cropped fields or the use of tree/shrub biomass (leaves and twigs) as mulch on crusted and/or compacted soils to improve organic matter input and soil structure.

Agroforestry involves management systems that incorporate a tree or shrub component in an agricultural landscape and can increase carbon storage and biodiversity in areas with annual crops. Agroforestry is one land use method that has shown promising results in the rehabilitation of degraded land. With its low level of inputs and multipurpose species focus, agroforestry as a land restoration strategy possibly holds significant potential for small-scale subsistence farmers in developing regions. The presence of trees in an agriculture system can have a significant influence on increasing soil fertility and ecosystem health as a whole. Although agroforestry systems have recently been seen as a solution for the reclamation of degraded land, it is important to note that success depends on increasing the current knowledge base and ultimately acceptance by local communities.

There are many benefits associated with the incorporation of trees into a degraded agriculture system. Increases in soil fertility/conservation and higher levels of biodiversity aid in the restoration of unproductive ecosystems. Although the basic process of restoration through agroforestry can be outlined, it is of utmost importance to understand that each system must be tailored to the specific ecological and socio-economic needs of the region. The rehabilitation effort must cater to the ecological factors of the ecosystem, but in order to for the strategy to be successful it is of more importance that the subsistence and economic needs of the communities and individual farmers are accounted for. Without the motivation of local people to take the risk and change to a more sustainable system, land management strategies will remain the same. Although it is ultimately a decision of the local communities whether or not to adopt agroforestry practices in land rehabilitation, the government plays a key role in providing support through financial aid and policy. Research also has a significant role in the success of a restoration effort. Although promising steps have been made in the area of land rehabilitation through agroforestry it is necessary to remember the infancy of the practice and continue to improve upon current knowledge.

In the Sudan, research on nitrogen fixing trees (NFT) is very limited. Emphasis has been placed on grains and legume crops while NFT research was mainly a shade house activity and mainly focussed on the seedling stage. Nodules in *Acacia* trees are found in relatively deep layers, contrary to the common concept that most nodules are found near the soil surface. Several authors have reported that inoculation and supplementary nutrition had no significant effect on nodulation, and addition of peat to the soil increased the number of nodules in *A. mellifera*, *A. senegal* and *A. seyal* seedlings. Until now, is not known whether nodulation is a seedling phenomenon that takes place at the nursery stage. This is especially true for the dry land where it has been found that soil water availability is more limiting than soil nutrients. Trees growing in the dry land have extensive root systems through which they are able to collect nutrients as much as they need. Nitrogen fixation is a very expensive process in terms of carbon assimilation, which implies that extensive amounts of CO_2 assimilation are needed in association with N fixation.

The leguminous trees nodulate well under drought stress conditions. Plants of the genus *Acacia* are pioneer plants, which play an important role in preservation and fertility of poor and eroded soils in Africa. Deficiency in mineral nitrogen often limits plant growth and hence symbiotic relationships have evolved between plants and a variety of N_2-fixing organisms. These plants produce extensive, deep root systems in addition to their potential to fix atmospheric N_2. For example, *Acacia* and *Prosopis* are widespread in the dry lands and have proven to form effective (N_2-fixing) nodules. Some leguminous trees fix as much as 43-581 kg of N per ha compared to 15-210 kg per ha for grain legumes.

Pruning of leguminous trees with a high N_2-fixing potential is a very important component in the sustainability of agroforestry systems. In the dry lands where low soil fertility and soil moisture often limit crop yields, research on neglected symbiotic native leguminous trees with N-fixing and drought tolerant traits would constitute a sound basis for increased sustainable production. Despite the fact that numerous studies have been done on isolation and characterisation of rhizobia aided with new technologies in biochemistry and genetic engineering, significant differences were observed among the isolates.

The geographical origin appears to have some effect on the heterogeneity of rhizobia which nodulate wild tree legumes. Many microsymbionts associate with many partners while a few are more selective and have a narrow host range. Specificity of the rhizobia in soil could be attributed to soil, plant species, temperature, moisture, organic matter, or humidity. Also, it is known that rhizobia species often change with natural tree succession. In this context, it may be right to speculate that spatial and temporal variability in habitats may result in temporal or spatial variation in rhizobia.

Several environmental conditions are limiting factors to the growth and activity of nitrogen-fixing legumes. Salinity and drought are the two main factors, which threaten agriculture in arid and semi-arid regions. In the Sudan, drought stress has the greater impact on agricultural productivity and yield. Nearly 40% of the Sudan’s surface land can be categorised as having drought stress problems. Even in areas of high rainfall, there are spells of drought, and many of them coincide with either establishment or grain filling stages, and both stages are very critical to productivity. Very few plants are capable of establishing and growing under these harsh conditions. Trees can form a natural resource base for agriculture in such areas; providing shelter and ameliorative microclimatic conditions and at the same time providing inputs from BNF.

The legume-rhizobium symbioses and nodule formation in legumes are more sensitive to salt stress or osmotic stress than the rhizobia. However, the degree of tolerance to drought stress is not yet known. Identification of the mechanisms of rhizobial tolerance to drought is required in order to select rhizobial strains with superior performance in arid environments. Drought tolerant rhizobia had been used as inoculants for legume production in arid and semi-arid regions.

High soil temperatures and lack of soil moisture may limit the growth and nodulation ability of legume-rhizobium symbioses, and many rhizobial strains surviving under heat stress may lose their effectiveness due to plasmid curing or to alterations in cellular polysaccharides necessary for infection. It has been often reported that high soil temperatures (35-40 C^0) usually result in formation of ineffective nodules, however, some strains of rhizobia e.g. *R. leguminosarum* were reported to be heat tolerant and to form effective symbioses with their hosts.

References

Arndt, S. K., Wanek, W., Clifford, S.C. and Popp, M. (2000). Contrasting adaptations to drought stress in field-grown *Ziziphus mauritiana* and *Prunus* *persica* trees: water relations, osmotic adjustment and carbon isotope composition. Aust. J. Plant Physiol. 27: 985-996.

Correia, M.J., Coelho, D. and David, M.M. (2001). Response to seasonal drought in three cultivars of *Ceratonia siliqua*: leaf growth and water relations. Tree Physiology 21, 645-653.

Elevitch, C. & Wikinson, K. (1999). Overstory # 78. United States Office of technology Assessment. http://www.agroforester.com/overstory/overstory78.html.

Fownes, J.H. & Anderson, D. (1991). Changes in nodules and root biomass of *Sesbania sesban* and *Leucaena leucocephala* following coppicing. *Plant and Soil*, 138: 9-16.

Grime, J.P. (1977). Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. American Naturalist, 111: 1169-1194.

Honeysett, J.L., White, D.A., Worledge, D. and Beadle, C.L. (1996). Growth and water use of *Eucalyptus globulus* and *E. nitens* in irrigated and rainfed plantations. Australian Forestry 59: 2, 64-73.

Kadiata, B.D., Mulongoy, K. & Mambani, B. (1998). Pruning effect on nitrogen nutrient release in the root zone of *Albizia lebbeck* and *Leccaena leucocephala*. Biology and Fertility of Soils, 26: 187-193.

Kozlowski, T.T., Kramer, P.J. and Pallardy, S.G. (1991). The Physiological Ecology of Woody Plants. Academic Press Inc., San Diego, 657p.

Parham, W. (2001). Degraded lands of China.: Problems and opportunities. China Tropical Lands Research. http://www.fas.org./china_lands/sketch.htm

?????? J. (1972). Responses of Plants to Environmental Stresses. Academic Press Inc., NY, 697 p.

Maley, J. (2002). A catastrophic destruction of forests about 2,500 years ago still exerts a major influence on present vegetation formations. IDS Bulletin 33:13- 30.

Mafongoya, P.L., Nair, P.K.R. & Dzowela, B.H. (1998). Mineralization of nitrogen from decomposing leaves of multipurpose trees as affected by their chemical composition. *Biology and Fertility of Soils*, 27: 143-148.

Matthews, E., Payne, R., Rohweder, M., and Murray, S. (2000). Pilot analysis of global ecosystems. Forest ecosystems. WRI, Washington.

Parham, W. (2001). Degraded lands of China.: Problems and opportunities. China Tropical Lands Research. http://www.fas.org./china_lands/sketch.htm

Sinclair, T.R., Luther, C.H., and Harrison, J. (1998). Extractable soil water and transpiration rate of soybean on sandy soils. *Agronomy Journal*, 90: 363-368.

Turner, N.C. and Jones, M.M. (1980). Turger maintenance by osmotic adjustment: a review and evaluation. In: Adaptations of Plants to Water and High Temperature Stress. Eds. N.C.Turner and P.J. Kramer. John Wiley and Sons, NY, pp 87-103