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Forest and water relations in miombo woodlands: need for understanding of complex stand management

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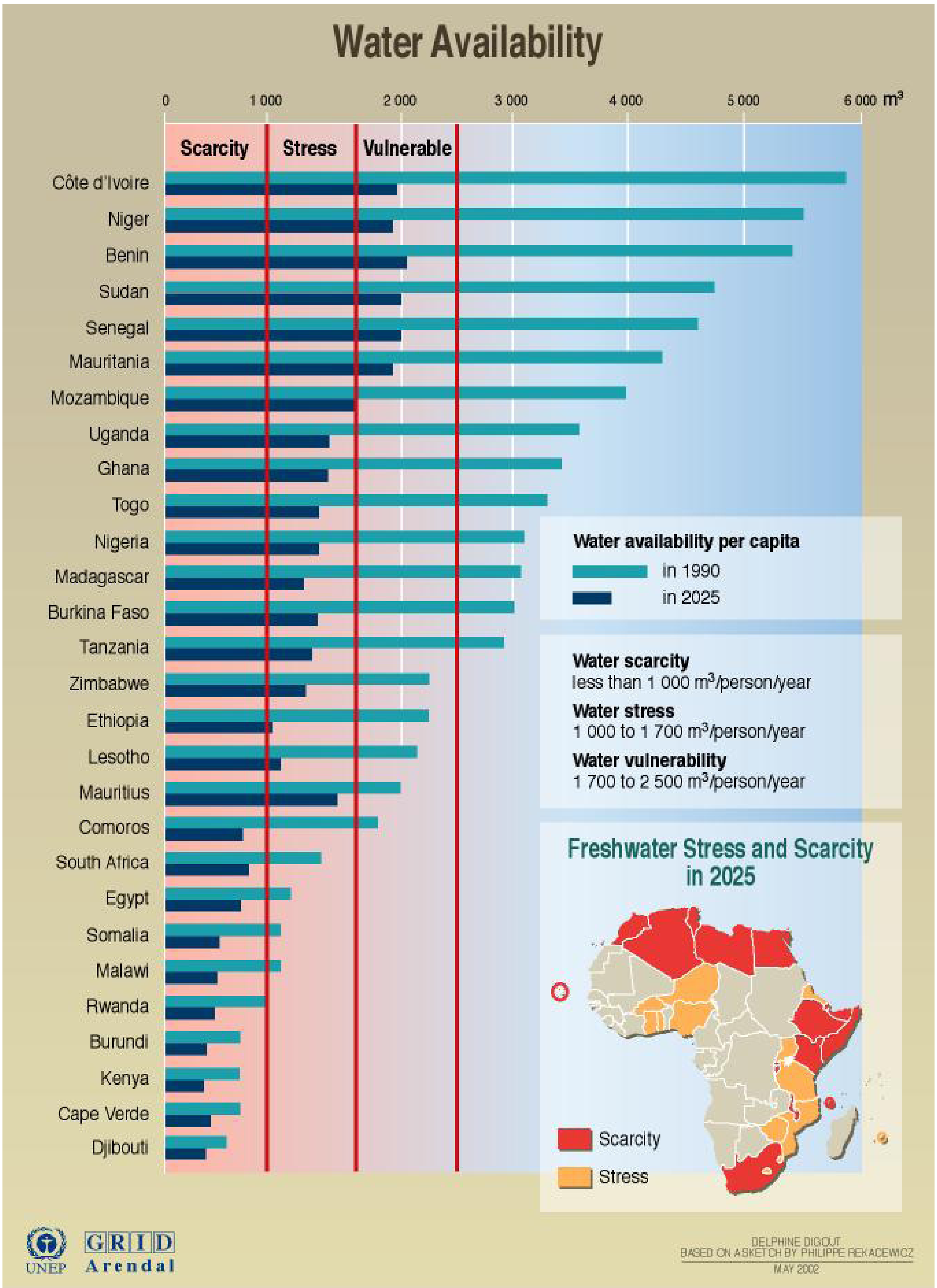
Miombo is a significant biome covering about 10% of the African landmass. Climate semi-aridity is the main edaphic determinant. Range of annual rainfall and dry season length is high, but the unimodal rainfall distribution is common for all miombo. Water is increasingly an issue of trade-off between different land uses and increasing demand on biomass production. This review gives a basic description of major components in the relations between tree cover and water in semi-arid landscapes. From this, in lack of relevant research within miombo landscapes, a scientifically based discussion is given on how future uses and management of these complex woodlands could serve in better management of scarce water resources and in what ways more research in these aspects could enlighten this discussion. It is concluded that, like for other semi-arid landscapes, there is need for understanding and developing more complex stand management to optimize biomass production and water use efficiency. At the same time climate change adaptation will add to this need of deepened biophysical process understanding.

Keywords: water soil, management, organic matter, vegetation, woodlands

1 Background

The understanding and wise management of miombo woodlands is crucial to a large part of Africa. It supports the livelihood of 100 million people in the area or outside, relying on products from this distinct and unique biome (Campbell et al. 2007). Under dynamic societal change (Falkenmark and Molden 2008) and for climate change adaptation there is need for a deeper and higher resolution of ecologically and land-use based understanding of the system (Malmer 2007, Milly et al. 2008). Projected water demand and supply for Africa is problematic (Fig. 1), not least for countries in the miombo region. This review aims to give a basic description of major components in the relations between tree cover and water in semi-arid landscapes. From this, in lack of relevant research within miombo landscapes, a scientifically based discussion is given on future uses and management of these complex woodlands and in what ways more research in these aspects could enlighten this discussion. The discussion is also mainly directed towards the positive relation or trade off between plant (forest) production and water available for other uses. It does not cover more established effects of deforestation on degrading water quality and risks for flooding.



Source: United Nations Economic Commission for Africa (UNECA), Addis Ababa ; Global Environment Outlook 2000 (GEO), UNEP, Earthscan, London, 1999.

Figure 1. Predicted water availability in African countries.

2 Defining the miombo landscape

Miombo woodland is a significant biome covering about 10% of the African landmass (c:a 2.5 – 4 million km^2 depending on definition, White 1983, Millington et al. 1994). Miombo can be found in most countries of Southern and Central Africa and it is the dominant forest component of Angola, Zambia, Tanzania, Malawi, Mozambique and Zimbabwe (Fig. 2). Miombo ranges of physiognomic and functional properties as well as within landscape spatial variation is high which makes definitions broad and overlapping with deciduous forests and open savannas. Frost (1986) gave a useful definition; ”Those tropical and some near tropical ecosystems characterised by continuous herbaceous cover consisting mostly of heliophilous C_4 grasses and sedges that show clear seasonality related to water stress. Woody species (shrubs, trees, palms) occur but seldom form a continuous cover paralleling that of the grassy layer.” However, there are many definitions and in common language terminology varies with terms like; woodland, bushland, thicket, wooded grassland and savanna.

Miombo trees are dominated by generas *Brachystegia, Julbernardia* and *Isoberlina* (*Fabaceae, subfamily Caesalpinioideae)*. Miombo is also related to Sudano-Sahelian parklands which have the abundant genera *Isoberlina* in common. These later eco-systems for long time have had zones of strong human influence on structure of vegetation. While small-scale shifting cultivation is dominant in miombo (Campbell et al. 1996), the parkland of West Africa is dominantly under more permanent traditional agroforestry systems (Pullan 1974).

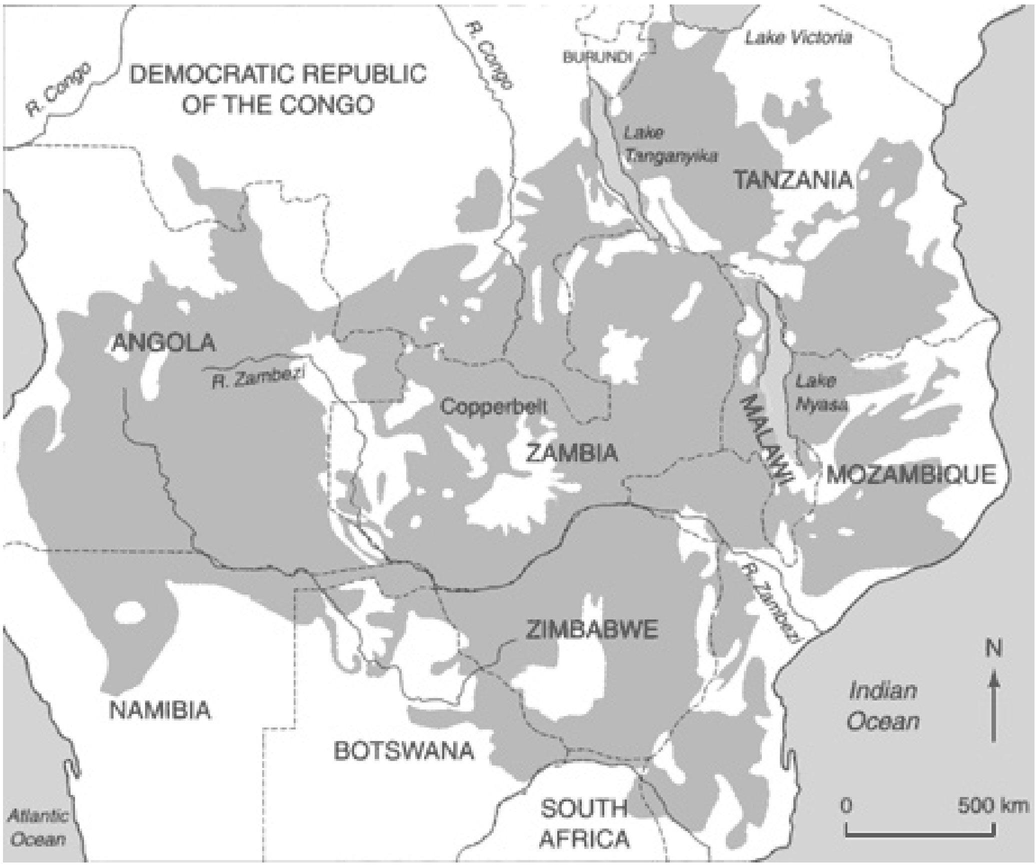


Figure 2. Distribution of Miombo woodlands. (White 1983)

2.1 Semi-natural miombo and planted forests in miombo landscapes

Deforestation is an old and ongoing process in miombo (FAO 2007), but large areas are still covered by miombo in various states. Long-term human impact is often profound on forest structure and species composition in many areas (Campbell et al. 2007). Forest management and tree planting has mostly been focussed on exotic species in plantations and woodlots (Gerhart and Nemarundwe 2006), even if, more recently, there are increasing numbers of interesting examples of natural forest management in Zimbabwe (Gerhart and Nemarundwe 2006) and elsewhere (Campbell et al. 2007).

Tanzania and Zimbabwe are the concerned central miombo countries that have the most forest plantations. Total areas are still moderate and about half of them are industrial (Varmola and Del Lungo 2002). Looking ahead, with increasing demands of energy, industrial wood and carbon credits there is a growing interest for plantation forestry in the relatively low populated miombo region, not least in Tanzania (e.g. Stave 2000).

So, the miombo landscape hosts a very varied structure and net primary productivity of the continuum from degraded miombo over well managed miombo to even-aged forest plantations. This has large bearing on impact on water management, both trough water use by the trees as well as by the impact on soils and potential groundwater recharge as will be described below.

2.2 Dambos – wetlands in the miombo landscape

Dambos are wetlands attributed to flatter lower laying parts of the miombo landscape (Mapaure and McCartney 2001). Mainly covered with grass, these wetlands can make up up to one third of the landscape (Whitlow 1985). They are shallow and often dry out seasonally (Campbell et al. 1996), but have often been positively perceived to delay downstream streamflows into the dry season (Balek and Perry 1973).

2.3 Isolated high mountains draw rainfall and host other forest types

In Tanzania rainfall in the highland is much related to relief (Jackson 1972a, TNRIC 2008). Isolated mountain massifs in the eastern part of Tanzanian miombo, like Uluguru and Rubeho mountains, receive more than 2000 mm annually and have higher rainfall intensities (Jackson 1972b). These mountains display various wetter montane forests (Burgess et al. 2007) and play an important role for water distribution into the surrounding miombo. Here and globally, for tropical moist cloud forest (TMCF) the effect of forest conservation in such mountains have been discussed as a prerequisite for the high moisture input, and distribution to surrounding regions, by the ability of tree crowns to catch horizontal rain and to “strip clouds” (Bruijnzeel 2005). However, as there are very few empirical studies both globally and in Tanzania (Uebel 1997), this specific effect remains unproven.

3 Edaphic determinants for miombo

3.1 Climate

Climatic semi-aridity is the main edaphic determinant. Precipitation is typically unimodally distributed (Fig. 3). However, high ranges (annual rainfall 550–1200 mm; length of dry season 3–7 months; mean annual temperature range 15–25 °C, Frost 1996) give way to division into dry and wet miombo woodlands with wide floristic and functional differences (White 1983). The dry miombo is found in areas of less than 1000 mm annual rainfall. Wet miombo has higher tree height (typically > 15 m) and has higher floristic diversity. Wet miombo mainly occurs in the northern part of miombo distribution; eastern Angola, northern Zambia, south-western Tanzania and central Malawi.

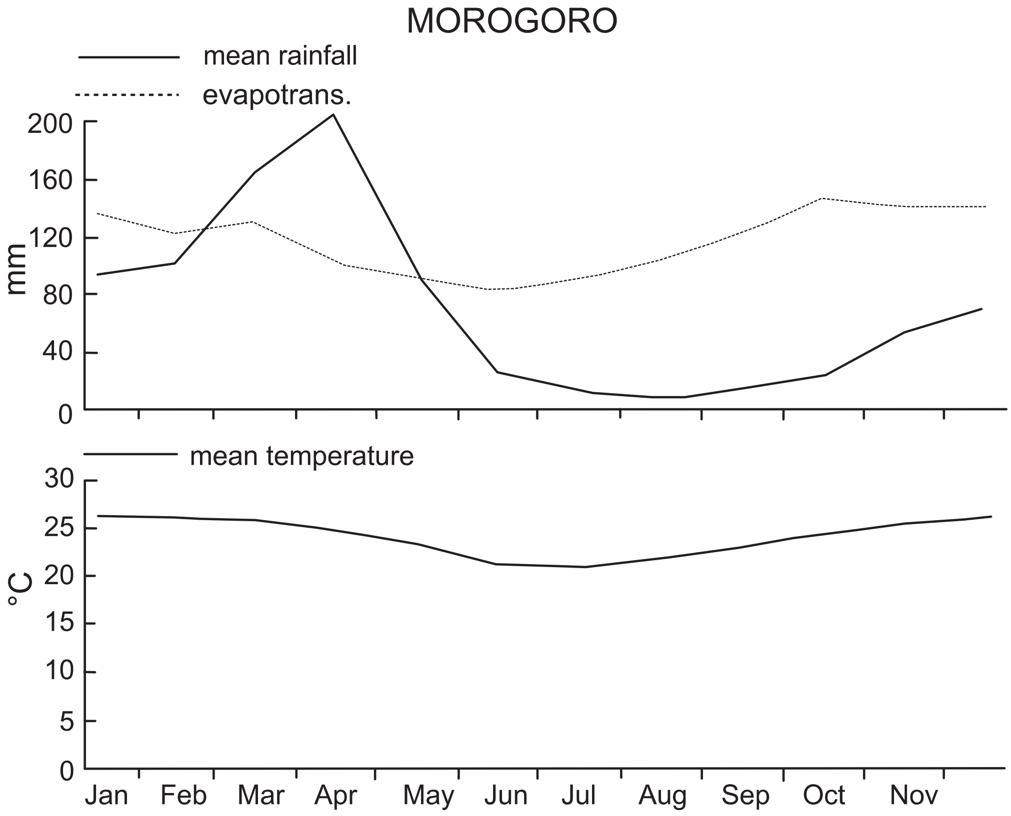


Figure 3. Typical intermediate miombo monthly rainfall, potential evapotranspiration and temperature with unimodal rainfall distribution (Morogoro, Tanzania, source FAO 1984).

3.2 Geology, carbon, soils and root symbiosis

Apart from sections of inselbergs or enscarpments miombo geomorphology is dominated by old surfaces of low relief. In these areas the balance of weathering and erosion over long time has produced relatively deep soils (typically > 3 m, FAO 1974). Soils have a wide range in mineral properties but means of pH, cation exchange capacity and total exchangeable bases are low (Frost 1996). In general it has been argued that richer geology and mineral soils support more open *Acacia* savannas (Frost et al. 1986, Campbell et al. 1996), but miombo do occur on as wide soil groups as Ferralsols, Acrisols, Luvisols and Nitisols (FAO 1974, Frost 1996).

Top soil organic content is typically low (Frost 1996, Walker and Desanker 2004). On average, agricultural soils contain 40% less soil carbon than the natural miombo woodlands. Soil carbon declines logarithmically with depth within all land use types. Clay content is typically positively correlated with soil carbon in the top 40 cm and therefore areas of higher clay content contained elevated carbon levels (Walker and Desanker 2004). In a nutrient poor system, soil organic matter (SOM) can play an important role in the stability, quality, and fertility of the soil. Farmers and land use planners are therefore interested in land use management that will enhance soil carbon levels. Also important for climate/carbon management, as is common in drier systems (Woomer et al. 1997), in the miombo woodlands ecosystem of South-Central Africa roughly 60% the total carbon stock is found belowground (Campbell et al. 1998) (Table 1). Nitrogen availability is low as a result of the frequent fires and relatively slow decomposition from high acidity.

The strong dominance by *Caesalpinioideae* in miombo has not been fully understood, but the main reason is surely the widespread associations with ectomycorrhizae (Högberg and Nylund 1981). Poor soils and the loss of N (and P) by regular fire makes the mycorrhizal association an important advantage. Nitrogen fixing species are also important for replacing N lost. Like in other ecosystems N concentrations are considerably higher in leaves from N-fixing miombo species (Högberg 1996).

Table 1. Carbon content in different biomes. Biome C densities from Houghton et al. 1983 (except for miombo from Chidamayo 1994 and Cambell et al. 1998).

Biome	Veg. C density ton/ha	Soil C density ton/ha	Total ton/ha
Tropical moist forest	200	120	320
Tropical seasonal forest	160	120	280
Miombo	30–70	100	~150
Tropical woodland and schrubland	30	70	100
Tropical grassland	20	40	60
Temperature grassland	10	190	200
Cultivated land	5	60	65
Pasture land	10	190	200

3.3 Fire a principal disturbance

About 1.3 million km^2 of fire adapted savanna and grassland burn annually in Africa (FAO, 2001). Dry season fire is a main determinant for succession of vegetation and soils in a stand-age time perspective. Principal fuel for fires is the dry herbaceous layer and dry components of litter and top soil humus. Most mature trees and woody plants are fire resistant. This makes fire swift and relative C and N atmospheric losses moderate. Various amounts of fuel make fire contribute to the high spatial structural variability of miombo. Estimates of fire return intervals for miombo lies between 1.6 – 3 years (Frost 1996). Reliable studies of fire frequencies are scarce and it can be debated what is "natural". Human use of fire (to improve grazing and/or for hunting) has probably been part of the miombo fire regime for millennia (Clark and van Zinderen Bakker 1964).

In general, for many tropical forest ecosystems, the increasing human impact today and changing vegetations (and fuel) make any estimate of what is "true" fire patterns very difficult (Malmer et al. 2005).

4 Perceptions and empirics on water dynamics in semi-arid forests

4.1 General implication of forest management on water budgets

Falkenmark (1997) introduced a useful terminology with "green and blue water". Green water is the return of water to the atmosphere as evapotranspiration (ET, including transpiration by vegetation, evaporation from soil, lakes, and water intercepted and evaporated from (mainly tree) canopy surfaces), i.e. to a large part water that is used to produce food and environmental services by forests and agricultural crops. Blue water is on the other hand what is left for deeper groundwater and stream runoff, ie. water available for animal and human consumption for example in downstream urban areas. Critical processes are the partitioning of rainfall between green and blue water, which is 1) infiltration of water into the soil or surface runoff and 2) uptake of soil water by plants or recharge of groundwater.

It is an empirically and theoretically well established general scientific paradigm that forests use more water than lower vegetation and rain-fed agriculture. This could also be expressed as a positive relationship between biomass production and water use (Rockström 2003). Consequently, empiric evidence is strong that cutting forest results in increased streamflows (Bosch and Hewlett,1982). Typically, also regenerating forests and afforestation is shown to partition more of the rainfall to green water, reducing availability of blue water (Farley et al. 2005, Scott et al. 2005).

4.2 In contrast: Old forests in semi-arid areas may work as "sponges" to better recharge groundwater and retain higher dry season flows

The role of forests for partitioning between green and blue water in tropical semi-arid regions is under long term scientific and policy debate (Bruijnzeel 2004). In the first partitioning step described above, forests have been shown to maintain high infiltrability by superior litterfall and soil protection (eg. Bruijnzeel 1990). Increasing surface runoff after deforestation and possible soil deterioration leads to more "blue water" in streams momentarily. In the semi-arid situation this means that less water during the wet season in the second partitioning to contribute to long term ground water recharge and subsequently to maintain dry season streamflows. This is often observed by rural people, but physically this is elaborate and time consuming (expensive) to investigate in environments of low infrastructure. Consequently only a few studies have reported the expected long term decline in dry season flows (Bruijnzeel 1989, Sandström 1998). So in these aspects we have some evidence that a "sponge effect" can be lost by deforestation and subsequent soil degradation, but the conclusion can hardly be made general for all semi-arid forest ecosystems.

Upon massive evidence on how tree litterfall and soil protection can improve soil quality and reduce surface runoff and erosion (eg. Hurni and Tato 1992), the restoration of a "forest sponge effect” have generally been taken for granted (Kaimowitz 2005). This has been the paradigm behind numerous forest/tree planting projects and one of several drivers for positive development in agroforestry. However, in this case there are many local witnesses to tell that new forests often make wells and streams drier. As for scientific studies also in this case long term studies are scarce. In contrast to the “lost sponge effect” the few studies made in semi-arid environments all confirm that new forests use more green water than they may contribute to blue water in terms of groundwater recharge. This effect of “not enough ground water recharge effect” is manifested in these studies as generally declining streamflows (Scott et al. 2005).

4.3 Physical interpretation to why new forests use more water

The new forests established are most often planted exotic species like Eucalypts and Pines. They are chosen for high productivity. Many of the species used are pioneer species in their respective original ecosystems, and increasingly they are genetically improved for fast wood production. Furthermore, these new forests are monocultures of vigorously growing young trees in contrast to old growth forest, which are mixes of species and old trees, young trees and treeless gaps.

Studies of sap flow in plantation trees also confirm high water use (eg. Cienciala et al. 2001), but notably also indigenous tree species in secondary “bush vegetation” may use as much water as the exotics (Fritzsche et al. 2006). Deep rooted Eucalypts are often given as the “bad example” of the highly water consuming exotics. However, other trees pecies may be as “bad” (or effective biomass producers) if used in the concept of highly productive, landscape-covering, mono-culture plantations.

4.4 Lack of semi-arid field research is a global problem

The few studies mentioned above to verify the higher water use by semi arid plantations are made in areas where dry season streamflow have been very seriously affected, and in some cases approached closed water basins (meaning no streamwater outflow from the watershed, Falkenmark and Molden 2008). These are regions in South Africa and India, where former non-forested grasslands and savannas have been afforested. In contrast there is no designated long-term study on the effect of streamflow where forestation is made on degraded soil. For this case the partitioning by improved infiltration, relevant to typical rain intensities, is securely established (Ilstedt et al. 2007). In the cases in India and South Africa the natural grasslands probably already had reasonable infiltrability, so the effect of the afforestation was possibly only on increased water use (Bruijnzeel 2004).

Long-term studies of forest water use are typically catchment studies where the treatment covers all or a large part of the studied area (the whole landscape). With many industrial plantations this is often also the case. However, to be able to make recommendations on how large, or in what part of the landscape, forest would be recommendable, is then not possible from the “black box approach” of the catchment study. In lack of ecologically based studies including soil water partitioning, sometimes models only looking at forest water use are applied (eg. Calder et al. 2004). This mostly results in negative recommendations towards forestation, possibly underestimating water benefits of forested areas.

On the global scale, under the challenges of meeting demands of biomass production for the Millenium Development Goals (and adding recent increasing demand on biofules), specifically the more efficient partitioning of rainfall is key and limiting for success (Rockström et al. 2007). This is increasingly stressed for Sub-Saharan Africa (Falkenmark and Rockström 2008), while data resolution for these regions remain too poor to verify current landscape based ecosystem models (Ilstedt et al. 2007).

5 Empirics about miombo specifically and what can be hypothesised?

5.1 Few studies confirm decreasing dry season flows for various reasons

In an early study in Sao Hill, Tanzania, *Eucalyptus saligna* planted in miombo landscape showed to result in much lower annual and dry season streamflows than from nearby grassland, while the streamflow reduction by *Pinus patula* was much less (Mhando 1991, Fig. 4). This study did not have a reference period to study how different the catchments were before treatments, which makes the results insecure, but it is another indication of high water use by Eucalypts, also form the miombo region. This may be due to deeper roots, higher productivity, etc. in comparison with

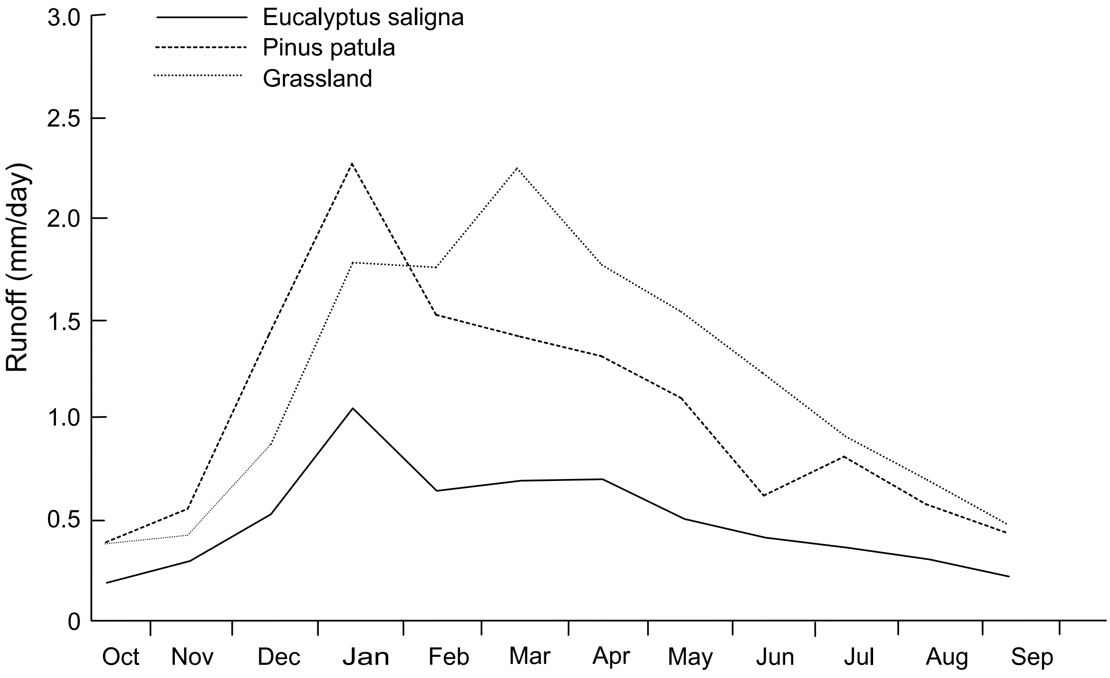
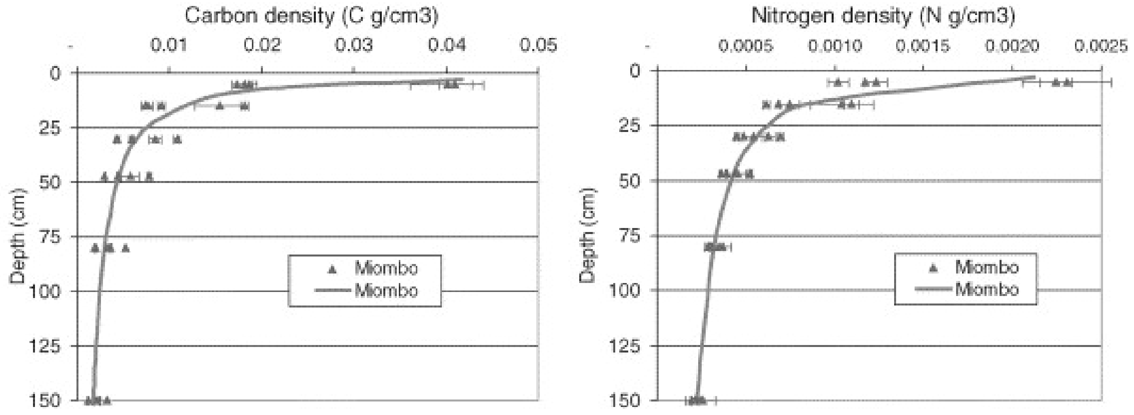
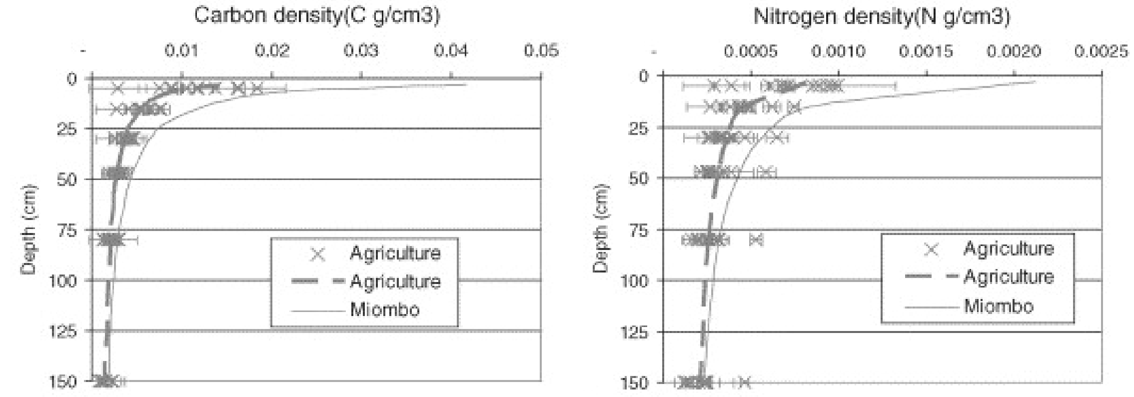


Figure 4. Monthly mean daily runoff of eucalypt plantation and pine plantation and grassland in Sao Hill, Tanzania 1981–1989 (Mhando 1991).



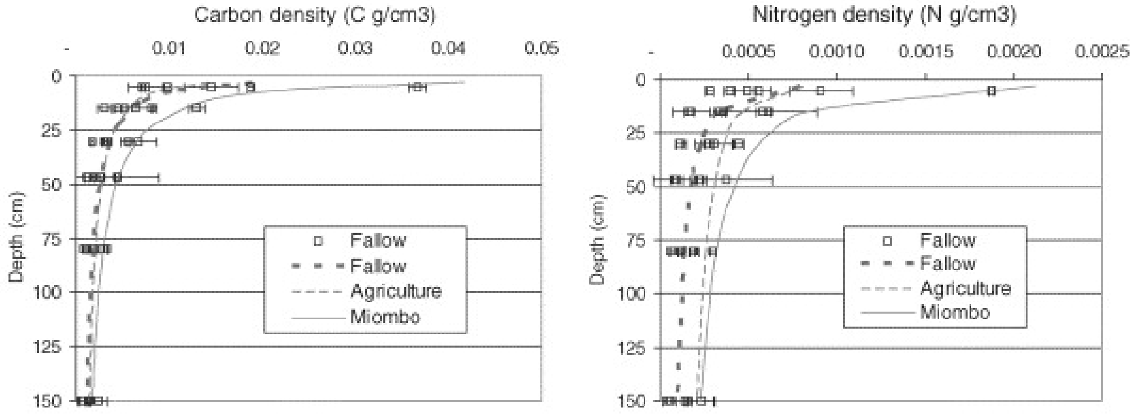
Miombo
log C density = -0.995+(-0.807*log cm) $R^2 = 0.83$

Miombo
log N density = -2.4+(-0.58*log cm) $R^2 = 0.84$



Agriculture
log C density = -1.56+(-0.595*log cm) $R^2 = 0.66$

Agriculture
log N density = -2.93+(-0.35*log cm) $R^2 = 0.465$



Fallow
log C density = -1.379+(-0.719*log cm) $R^2 = 0.62$

Fallow
log N density = -2.85+(-0.54*log cm) $R^2 = 0.32$

Figure 5. Regression of carbon and nitrogen density with depth by land use type (Bars denote SE, after Walker and Desanker 2004).

the pine plantation, and certainly in comparison with the grass.
In another study using long term data, Kashaigili et al. (2006) show dramatically decreasing dry season flows (60–70%) between 1958 to 2004, downstream the Usangu wetlands in Tanzania. In the upstream areas woodlands have decreased strongly on behalf of cultivated land and bare land. In this case it may be tempting to hypothesise on "lost sponge effect", but Kashaigili et al. (2006) use modelling to show that the major reason for declining dry season flows are due to reverting of blue water into green water in a strong increase of irrigation in the same period.

In the above study of the Usangu wetland, the wetland itself is called a "scarcity enhancer", even if possibly delaying flows into the dry season, the evapotranspiration from the wetland is considerable. In another study of dambo hydrology in Zambia, von der Heyden and New (2003) showed that the dambo studied dried out in the dry season. In that case the downstream baseflow was maintained by deeper groundwater, i.e. stemming from infiltration upstream.

5.2 In miombo or planted forest – soil organic matter and soil fauna are important

Management of organic material in soils is crucial for soil quality and fertility. Harvesting, grazing and fire add to decomposition in reducing soil organic matter by reduced litterfall and oxidation. In miombo already low topsoil organic contents are typically reduced up to 50 % by agriculture (Fig. 5). Soil organic matter also determines top soil physical properties. The soil structure (soil aggregates increasing amount of large pores) determines to a large extent the partitioning between surface runoff, erosion and soil infiltrability (Bruijnzeel 1990, Malmer et al. 2005). In various land use in Zambia, the structural stability of the soil was shown to be direct positively related to soil organic carbon (King and Campbell 1993)

Soil crusting is a common reason for reduced infiltrability in semi-arid areas. Perrolf and Sandström (1995) described various processes for crust formation in Tanzania and Botswana and concluded vegetation cover to be determinant apart from soil texture. Similarly, Casenave and Valentin (1992) from 87 sites in semi arid West Africa found also intensity of surface sealing, vegetative cover and soil faunal activity to be determinant for infiltrability.

From data in meta-analysis by Ilstedt et al. (2007) it is clear that soil infiltrability is restored with much different success under different trees (Fig. 6). In Zambia also King and Campbell (1993) could show rather different size distributions of soil aggregates, more larger aggregates under *Pinus patula* than under closed miombo and *Eucalyptus grandis*. In Sao Hill, Tanzania, Ngegba et al. (2001) also had highest soil organic matter in top soils under *Pinus patula* plantation compared with *Eucalyptus saligna* and poorly stocked miombo, but in this study differences were small compared to those observed in the Zambian study.

As already mentioned in the general section above, the heterogeneity of miombo stands have to be stressed. Nord (2008) measured infiltrability in miombo with various stocking and in *Albizia vesicolor* plantation. Her major finding was the very high variability of infiltrability in these stands making statistical differences show only between extremes, with the *Albizia* having highest mean infiltrability and the most degraded miombo the lowest.

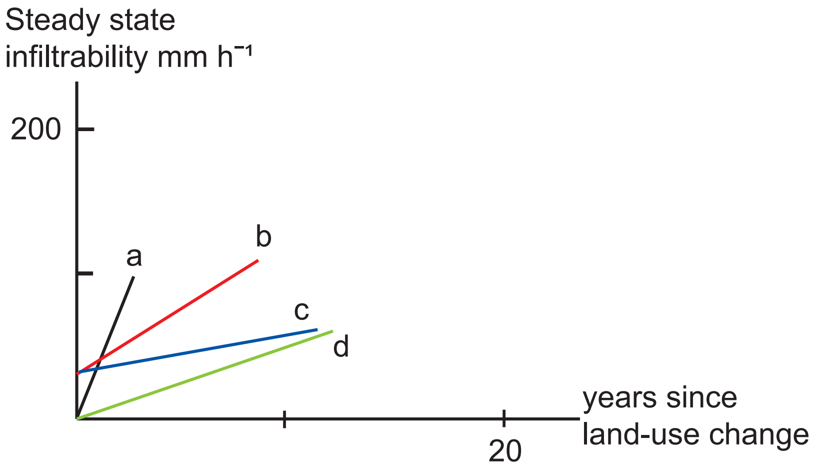


Figure 6. Rehabilitation of infiltrability after planting trees of different species and in different situations. a) open land to *Sesbania*, b) open land to *Leucena* agroforestry, c) grassland to *Tectona* (teak) and d) tractor track rehabilitation under rainforest (after Ilstedt et al. 2007).

5.3 Forest and water management in miombo landscapes based on current knowledge

Already Hough (1986) identified the major problems for semiarid areas described above; 1) increasing dry season flows, 2) trees preserve infiltrability and reduce surface runoff and erosion, but 3) trees/forests use more water than other vegetation. Not much research to resolve "conflicts" and underlying process explanations between these three points have happened since Hough (1986) where he elaborated on miombo management options to reduce evapotranspiration while at the same time retaining good soil quality. The following management options and their effects given below in this section are from Hough (1986), unless otherwise cited.

5.3.1 Conversion to grassland

Grasses may have considerable biomass production potential but they have less deep roots than trees. Hence, miombo conversion to grass consume less water and increase streamflow. In contrast, grassland after deforestation often shows lower infiltrability and thereby may increase surface runoff, erosion and stormflows. Furthermore, the conflicting results on unaffected or reduced groundwater recharge/dry season streamflows should be kept in mind (c.f. section 4 above). Also, not suppressed grasses build up very flammable fuels for severe dry season fires.

5.3.2 Forest structure modifications

Thinning and crown pruning have lowering effect on evapotranspiration, but the stand adapts soon to make the change very temporary. Alternatively, maintaining stands with dominantly young trees might mean fewer deep roots to reduce water acess/transpiration. However, even if deep-root studies still are scarce, for example studies on *Acacia mangium* have showed full rooting depth (2–3 m to the bedrock) within two years (Boström 2000). Hough also discussed reduction of woody understory to, again, reduce more relatively deep rooted individuals.

5.3.3 Species selection within moimbo

If differences in rooting depth and water use would be better known, species with lower water consumption could be chosen. The problem is then that this would most probably mean a trade off with productivity.

5.3.4 Grazing

Intensive grazing in miombo keeps grass short and reduces regeneration of young woody plants. This may reduce transpiration, but again, induces risks for soil compaction by trampling and thereby reduced infiltrability.

5.3.5 Phreatophytes eradication

Phreatophytes is a tree form that is adapted to the riparian zone along streams. The removal of these trees would reduce transpiration at large (practiced in South Africa), as they reach water all year around. Tree removal might jeopardize stream bank stability, but exchange with deciduous trees might reduce water use in the dry season.

5.3.6 Dambo management

Hough put emphasis on the evapotranspiration from the wetlands and discussed how drainage would decrease water use and increase base flows. On the other hand, in the longer run drainage would lead to forest establishment and increased water use in the concerned area. Drainage might also dramatically negatively affect possibilities for dry season grazing in these areas.

6 Urgent research needs

From above it would be clear that there is an unsatisfactory scientific clarity in biophysical process knowledge and lack of empirical data on basic links between trees and water budgets for miombo as well as for semi arid ecosystems as a whole. This especially concerns the possible trade off or mutual benefit between forest production and groundwater recharge/dry season flows (green and blue water partitioning of rainfall). Scott et al. (2005) express that possibly in most cases productive forests might use more water than they contribute to groundwater recharge. On the other hand, with increasing demand on high production of both wood and food, the alternative with continued deforestation and continued deterioration of miombo stands is hardly a viable alternative.

6.1 Forestry must develop with understanding of use and conservation of water

In agriculture, much of expected increase in food production is expected from semi-arid areas and rain fed agriculture. Falkenmark and Rockström (2008) stress the importance of increasing efficiency in cultivation systems to shift losses in evaporation to productive transpiration, Makurira et al. (2007) giving a good example from Tanzania. In the same manner there is need for fundamental process knowledge about rainfall partitioning in forest ecosystems to be able to elaborate on effects of forestry applications like the ones discussed above. Specific fields of study include 1) study of not only infiltrability but actual groundwater recharge, 2) links between groundwater recharge and macropore flow, top soil carbon and aggregation and (miombo) tree species, 3) tree root development and symbiosis, deep roots and water uptake by (miombo) trees, 4) (miombo) tree species transpiration in relation to productivity, 5) interception (evaporation from tree canopies) by various forest structures and species.

For better efficiency of biomass productivity also forestry itself needs to develop in the understanding of multispecies systems like miombo or intensively managed miombo. Multi-species plantations in general are shown by meta-analysis to be more productive than monospecies plantations (Piotto 2008).

6.2 Long term environmental monitoring valuable

Long term monitoring programs and qualified analysis have been behind much of the success in development of northern forestry. In this sense there is also an urgent need for such monitoring programs and trials (eg. long term stream and rainfall monitoring and long term forestry trials) and academic capacity building in the miombo region. This base for research is not least important for understanding of climate change, its effect on forest production and water management and possibilities for adaptations to climate change.

7 Conclusions

In general it can be concluded that descriptive data for key ecological variables are lacking to apply process based modelling of soil development and water in complex miombo landscapes. Not least is this a problem for the understanding of miombo land use under climate change and the proper representation of the biome in regional and global modelling and policy formation.

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