Vulnerability of land cover and land use due to progress of climatic changes on temperate-continental plains of Eastern Europe: a case study of forests

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Abstract

Continental plains of SE Europe experience a rapid progress of climatic changes. Extreme droughts and decline of ecological services (decrease of groundwater and runoff resources) may jeopardise sustainability of forest cover and of life quality of rural population. Water availability dictates land use, however landcover change affects also albedo and evapotranspiration, which have a further feedback on climate. The problem is acute across the forest steppe belt which covers the plains of continental Southeast Europe and Central Asia, from Hungary to North China. Strategic planning requires the development of decision support systems.

Keywords: *drylands, xeric limits, ecohydrology, climate forcing, land use change, forestation, forest policy*

Introduction

The aim of this study is to present a range of views and arguments which should not only to underline the complexity of factors influencing the decisions about maintaining/increasing forest cover in the "forest steppe" zone, but also to emphasize the necessity to strengthen research in an ecological zone, which has received relatively moderate attention in the past. The forest steppe belt covers the plains of continental Southeast Europe, South Russia, Southern Siberia, and North China. It exists also on other continents, such as along the edge of the Prairies of North America, northward into Alberta (Canada). Generally, the forest steppe belt is a densely populated and an agriculturally important region which has been under human influence for centuries.

In Hungary, similar to other regions of the semiarid temperate-continental forest steppe zone, forestation has long been considered being crucial for rehabilitating degraded, over-exploited land, for improving water supply and quality, reducing soil erosion, and for moderating extreme weather events. However, the largely affirmative valuation of effects of forestation on climate and water resources is debated. Water consumption of man-made forests might contribute to water scarcity and aridification in the forest steppe zone, and may not achieve the expected goals of environmental protection and ecological restoration (Andréassian, 2004; Jackson et al., 2005; Brown et al., 2005; Sun et al., 2006; Wang, Y. et al., 2008; Mátyás & Sun 2014). Due to the limited understanding of interactions between physical processes and land cover, the dispute on forest-water relations is still ongoing, especially at a regional scale (Ellison et al. 2011, Gribovszki et al., 2006, 2014).

Projected changes in global climate generate a further challenge for dryland ecosystems. Water availability determines ecosystem structure and function, and relatively small changes in the soil moisture balance may lead to considerable ecological shifts (Ryan and Vose, 2012). On the other hand, enlarging forest cover may become a factor of increasing climate forcing at regional scale (Bonan, 2008; Mátyás et al., 2009; Drüszler et al., 2010; Gálos et al., 2011) and thus may affect regional water balances.

The climatic transition zone at the forest/grassland edge

Forest steppe (open woodland) is the grassland-forest transition zone (ecotone) where forest ecosystems largely depend on locally accessible water. Xeric forest limits[1] appear at the low latitude, low altitude end of distribution ranges of temperate-continental closed forests, where presence or absence is determined by climatically limited water supply during the growing season (Mátyás et al., 2009). At the xeric limit, the closed forest belt forms a transition ecotone toward the open woodland or forest steppe. The ecotone is dependent on a volatile minimum of rainfall and is therefore sensitive to prolonged droughts. In this special ecological zone, the biophysical characteristics of the land surface (e.g., albedo, evapotranspiration, roughness etc.), the carbon cycle, and ecological functions are strongly affected by land cover and its changes.

Forest ecologists in Eastern Europe identified a specific forest steppe climate type. In Hungary, the zone classified into this category is characterized by an average precipitation of 560 mm per year and a July mean of 21.5 °C (Mátyás & Czimber 2000). Scarce precipitation in the growing season (approximately 320 mm) and frequent summer droughts confine the spontaneous presence of closed forests to sites where supplementary ground water resources are available. Forest canopy and litter interception may further reduce water availability (Gribovszki et al. 2006). Native, deciduous species have generally interception rates under 30%, whereas conifer plantations intercept between 35 and 40% (Járó 1980). Natural forest cover remains therefore patchy in this zone, indicating mosaics where groundwater influence improves site conditions.

[1] Synonymous terms are “trailing limit” or “receding limit”. Both terms refer rather to the migration aspect of the postglacial or recent past, than to the critical availability of water

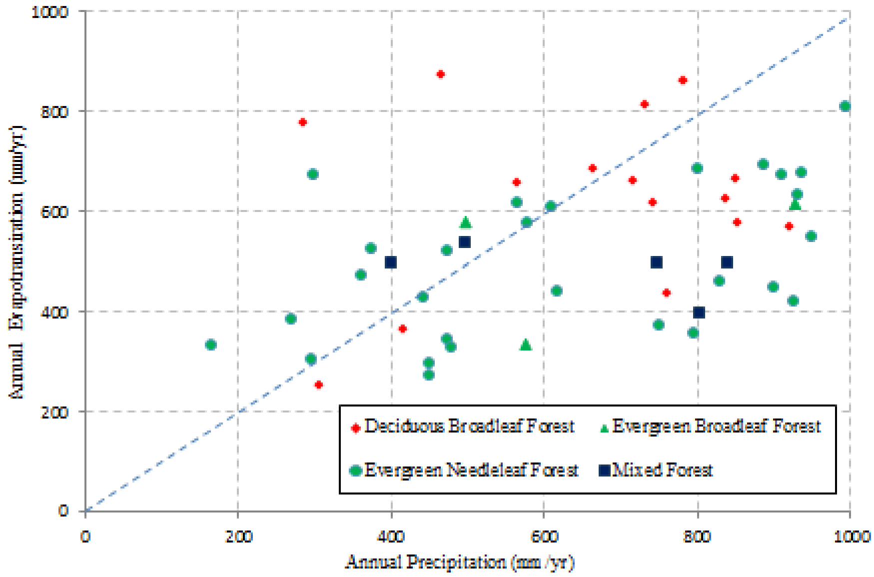

Figure 1. Mean annual precipitation vs. annual evapotranspiration in forests as measured at selected global eddy flux measurement sites (precipitation < 1000 mm/year). Explanation in the text (Mátyás & Sun, 2014)

Water use by forests

Globally, zonal (i.e. climate-dependent) forests are generally found in areas where annual precipitation exceeds evapotranspiration (*ET*). While water use by temperate forests is generally less than 700 mm, in the dry lands, ecosystem water use (tree transpiration + interception + soil evaporation) is limited by water availability (i.e. atmospheric precipitation). Water use by forests is difficult to quantify precisely, due to the dynamic character of forest evapotranspiration processes at tree, stand, and ecosystem levels. Global eddy flux measurement networks (*http://fluxnet.ornl.gov/*) presently provide the most reliable estimates of *ET* at the ecosystem scale. *ET* of forests is not strictly following precipitation amounts. On temperate and boreal sites with precipitation below 1000 mm/year, maximum forest water use seldom surpasses 750 mm (Figure 1). In regions where precipitation is around and below 600 mm/year, *ET* demand is seldom met by precipitation. *ET* exceeds precipitation at some forested temperate-climate sites where data points are above the 1:1 line. In such cases, forest water use is likely supported by groundwater or seeping water sources from surrounding areas. In Fig. 1, data from boreal sites with extreme low precipitation are also shown, where strong groundwater influence is likely, based on the *ET* values. The results are consistent with worldwide forest hydrology literature stating that *ET* of forests in temperate dry regions is relatively high in proportion to local precipitation, and their water yield is low.

Allocating water resources between forests and croplands

Compared to grasslands or short rotation crops, forests have large above-ground biomass and deeper roots and therefore use more water. Forests can capture larger amounts of carbon through photosynthesis as carbon and water cycles are highly coupled (Law et al., 2002). World-wide vegetation manipulation experiments show that forest removal reduces water use, i.e. evapotranspiration (*ET*), and thus increases watershed stream flow (Andréassian, 2004). On the other hand, afforestation or reforestation[2]on watersheds previously covered by grassland can reduce stream flow due to an increase in *ET* (Andréassian, 2004). Due to higher *ET* values, groundwater table levels are frequently lower under forests than under croplands (Major et al., 1991; see also Fig. 2 and Fig. 3).

Hydrologic studies on the consequences of forestation have emerged in the past decade (Sun et al., 2006; Wang, Y. et al., 2011). In particular, evaluation of worldwide forestation campaigns has shown that human interventions require a closer look at unexpected consequences. An emerging question is how forestation in different climatic regimes affects watershed functions such as water yield. The potential water yield reduction following forestation have drawn renewed attention to the relations between forests and water resources and carbon-water tradeoffs in watersheds (Calder, 2002; Jackson et al., 2005; Trabucco et al., 2008) and on a regional scale (Ellison et al., 2011). The hot debate on proper balancing of land cover management is especially relevant in regions with scarce water resources.

Effect of forestation on groundwater resources in Hungary

In the last century, large-scale forestation programs changed the land cover of the Hungarian Great Plain, with the aim to improve not only timber supply but also the regional climate and hydrology of a largely treeless landscape. For example, on the Danube-Tisza Sand Plateau, a forest steppe region of 828,000 ha, forest cover increased in four decades from 5 to 26%. A dispute between hydrologists and foresters about the effects of forest cover on water resources initiated numerous studies.

Measurements confirmed that in areas where deep rooting forests can tap the groundwater, the evapotranspiration (*ET*) rate surpasses the amount of precipitation. On the Sand Plateau, *ET* was estimated from *MODIS* daytime land surface temperature data. Average annual *ET* of forests was estimated at 620 mm/year, which was about 80 mm more than the local annual precipitation (Szilágyi et al. 2012). In a black pine (*Pinus nigra*) plantation, a mean annual *ET* rate of 712 mm/year was registered by Major (2002), out of which 130 mm originated from the groundwater. Consequently, forests often appear as groundwater discharge areas (see Figure 2).

[2] the distinction between the two terms, especially at the lowland "xeric limits", is often difficult as planting of forests on non-forest land (afforestation) means frequently the reestablishment (reforestation) of earlier eradicated forests – therefore the term forestation is mostly used

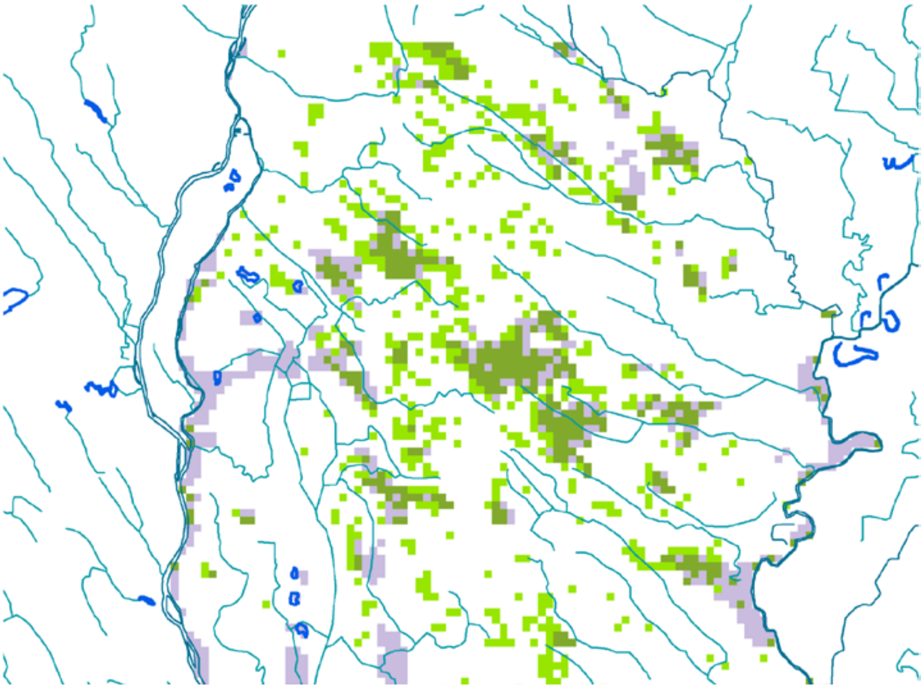

Figure 2. Distribution of areas of groundwater discharge (i.e. estimated negative recharge, in magenta) on the Sand Plateau in the Hungarian lowlands, estimated from MODIS daytime land surface temperature data. The map shows the frequent overlap of groundwater discharge areas and of forest cover. Forests are marked light green, overlapping areas in dark green. Rivers and ponds are marked dark blue (adapted from Szilágyi et al. 2012)

In another study (Móricz et al., 2012) the groundwater consumption by forest and by grassland was compared. On a site with 570 mm annual rainfall and a growing season precipitation of 360 mm, an oak forest had approximately 30% more annual evapotranspiration than the neighboring grassland (405 vs. 283 mm). The difference was however much higher in average groundwater use (oak: 243 mm, grassland: 85 mm). The groundwater consumption was close to 60% of the total transpiration of the oak forest and approximately 30% of the total transpiration for the grassland/fallow (see Figure 3).

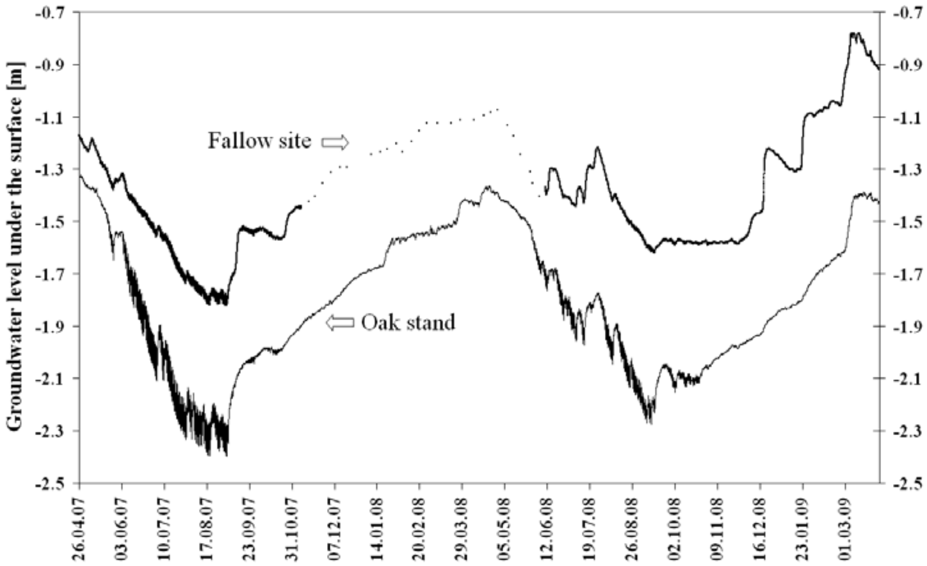

Figure 3. Water table fluctuation in the course of one year under an oak (Quercus robur) forest and on a neighboring grassland (fallow) site in the forest steppe zone of Hungary. Missing data are marked with dotted line (Móricz et al. 2012)

Various measurements have shown that forest vegetation may lower water table during the summer season by 0.5 to 1.1 m compared to the level below herbaceous vegetation in shallow groundwater areas on the Danube-Tisza Sand Plateau (Major, 2002). During an extreme dry period in midsummer, a lowland oak forest had a mean groundwater uptake of 7.59 mm/day vs. 3.29 mm/day in a nearby grassland plot, causing a continuous lowering of the water table (Gribovszki et al., 2014). The calculated well-watered short grass reference evapotranspiration for this period amounted to 6.58 mm/day (based on FAO methods).

Under natural conditions, if maximum groundwater level (in April) is deeper than -2.5 m, grassland predominates in forest steppe climate. Hydrologic observations revealed that in this climate zone, forest cover does not contribute to groundwater recharge or to runoff, and utilizes additional, near-surface groundwater resources. Due to lower groundwater levels under forests, local water table depressions develop, which may direct groundwater flow toward forest patches.

Climatic feedback of forests: ambiguous effects in the forest steppe zone

Theoretical analyses and climate model simulations in many parts of the world suggest that land cover, i.e. vegetation, has an important role in climate regulation. Due to their higher leaf area (LAI), deeper rooting and large above-ground biomass, forests maintain a relatively high photosynthetic activity and transpiration rates. LAI of deciduous forests exceed that of croplands by a factor of approximately 1.4 - 1.7 (Breuer et al., 2003). Forest cover change modifies the surface energy balance and, consequently, water balance through altering albedo and turbulent fluxes above land surface. The surface roughness of the forest canopy layer leads to changed aerodynamic conductance, which alters cloudiness and creates additional atmospheric feedback (Drüszler et al., 2010).

Although it is generally believed that planting forests may mitigate climate change impacts and slows down the aridification process, current views on the role of temperate forests are inconclusive and fragmented, and even contradictory. For example, some scientists state that, contrary to the tropics, forestation in the temperate zone may have climatically "little to no benefits" (Bala et al., 2007; Bonan, 2008). Forests have a lower albedo than crops (e.g. coniferous forests: 0.14 vs. crops: 0.24; Breuer et al., 2003). In addition, evergreen coniferous forest canopy masks highly reflective winter snow cover. Consequently, the lower albedo of forest cover may cause somewhat higher summer and winter temperatures. Thus, forests may have both direct and indirect contributions to natural and anthropogenic climate forcing (land use change, forest destruction or forestation).

The impact of energy balance on climate due to past land use changes in Hungary has been investigated by Drüszler et al. (2010). Lower albedo, as well as changed sensible/latent heat ratios resulted in a rise of summer temperature in afforested regions. In course of an intensive country-wide forestation campaign in Hungary, in the Eastern part of the country forest cover increased from 5 to 26 %, while in the Western half the increase was moderate, from 15 to 21 %. Applying the MM5 meso-scale weather forecasting model, the authors found that after four decades (1999 *vs.* 1959), forecasted summer daytime temperatures have increased. Forecasted temperature maxima at 2:00 P.M. increased in the West by 0.15 °C, but in the East, where afforestation drastically changed the land cover, the forecasted increase was 0.22-0.25 °C. In the same period of four decades, the recorded overall increase of average summer temperature was 0.45 °C. The climatic feedback of land cover change was verified also by landscape-scale analyses.

Contrary to the described results, investigations at the Canadian prairie-woodland border (Hogg and Price, 2000) indicate, that forest cover may also have a positive climatic effect. In a region where aspen forests were partly removed, summer temperatures were significantly higher than in areas where deciduous woodland cover remained. The deciduous forest mainly caused anomalies in summer; temperatures were cooler, mean precipitation was higher and length of growing season increased. It seems that the balance between albedo and actual evapotranspiration determines whether there is a cooling or warming effect. The calculated effect of forests on surface energy conditions and water budget may probably depend also on the selected time scale: in the short term, forests may contribute to the increase in temperature, but on longer time scales they may reduce the impact of extreme heat weaves (Teuling, 2010).

In another regional study, Gálos et al. (2011) studied the regional feedback effect of forestation on projected climatic scenarios in the forest steppe transition zone in Hungary. The climate of the recent past (1961-1990) with the forest cover of 20% was considered as standard. The mitigating effect of forestation on transpiration (*dTr*) and precipitation increase (*dP*) was investigated for the projected climate in 2070-2100, when precipitation is expected to decline by 24% (Gálos et al., 2007). To model the feedback of land cover change, two scenarios were simulated with the climate model REMO, assuming a realistic 7% forest cover increase and a hypothetical extreme scenario, where all available agricultural land was converted to forests, resulting in a forest cover of 92%.

Although the expansion of forest cover led to an increase in evapotranspiration and precipitation, the mitigating effect remained relatively modest. Afforestation may increase local precipitation, but even the unrealistic maximum forestation could only partially (by <6%) offset the projected precipitation decrease of 24%.

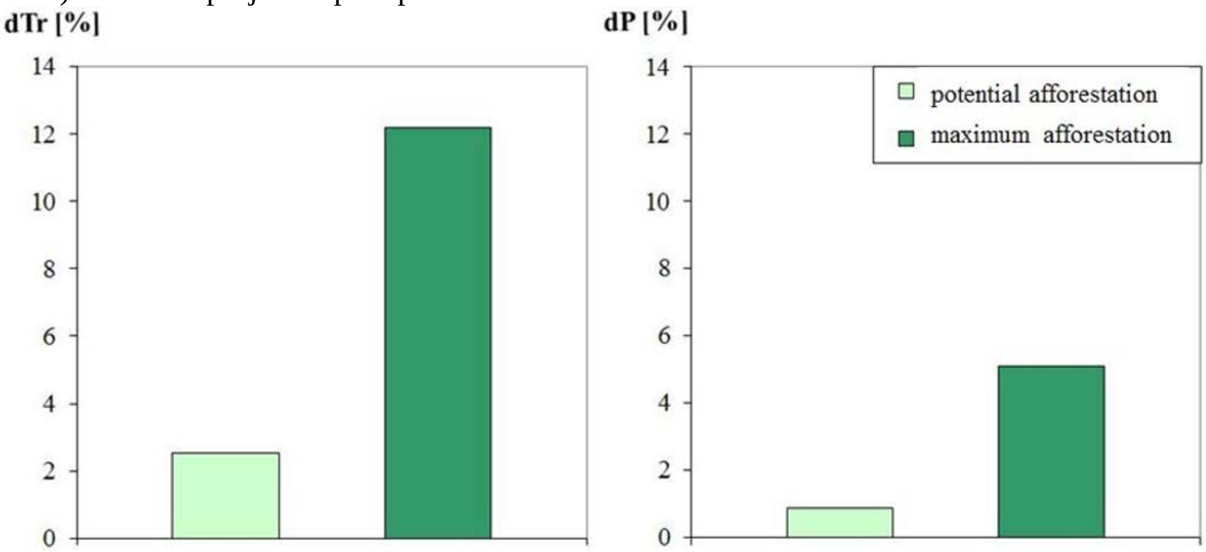

Figure 4. Modeled feedback of planned afforestation on future climate conditions in Hungary. Left: projected transpiration increase (dTr); right: projected precipitation increase (dP), for a realistic (7% forest cover increase - light columns) and for an extreme scenario (92% forest cover increase - dark columns). Explanation in the text (Gálos et al., 2011, Mátyás et al. 2013)

Forest management under climate change

Global climatic change may have a series of cascading effects on forest ecosystems. A change in climate triggers changes in soil water availability, biogeochemical cycling, forest disturbance patterns and thus leading to changes in forest species composition and in age distribution (Ryan and Vose, 2012). Recent drought episodes in dry regions call for a dramatic shift in forest management practices to adapt to climate change (Führer et al., 2013)

In most countries in the temperate zone, returning to close-to-nature forest management seems to be the general trend to adapt to expected environmental change, even at the xeric limits (e.g. Cao et al., 2011; McNulty et al., 2014). The concept is based on the hypothesis that stability and persistence of forest ecosystems is warranted by plant communities having evolved during the past millennia, and enhancing the naturalness of forests will enhance also their stability. The hypothesis is challenged at the xeric limits by numerous constraints, such as

- long-lasting human interference and land use have caused a partial or total loss of natural (woody) plant cover and spontaneous recovery of vegetation might be slow,
- functioning of close-to-natural systems is disturbed by direct and also by indirect human effects (e.g., uncontrolled grazing, game damage, pollution)
- projected climatic changes and extreme events may generate ecologically novel conditions,
- introduction of some intuitively beneficial interventions (e.g. creating multi-storey stands, plenterwald management) may not deliver the expected benefits.

These constraints necessitate a considerate revision of forest management practices, first of all in regions of high drought risk. A cost-effective, scientifically based forest policy in the forest steppe or open woodland zone requires particularly the consideration of local environmental conditions, of land use alternatives such as restoration of grasslands and scrublands, and the use of the proper technology. Decision support systems may greatly facilitate the choice of proper alternatives and measures on local scale. Carefully planned human interference is therefore essential, to achieve successful adaptation to the expected environmental changes.

Summary and conclusions

Current views and experiences about the effects of forestation at dryland margins are multifaceted. Although forests provide multiple ecological benefits, forestation on watersheds previously used by agriculture or covered by grassland can reduce stream flow due to higher water use and may have serious disadvantages for water management and sustainable development. In the forest steppe or open woodland climate zone, increase in forest cover does not necessarily contribute to groundwater recharge or to runoff. Instead, forests may utilize near-surface groundwater resources for biomass accumulation.

Forest cover influences atmospheric climate forcing at a large scale. Therefore it is believed that forests mitigate climate change effects such as warming and aridification. Simulation studies indicate however that in spite of increased evapotranspiration, precipitation changes only moderately even in extensively afforested regions. Regarding temperature conditions, the balance between actual evapotranspiration (cooling) and sensible heat increase (warming) determines the net cooling or warming effect at a particular site or region.

The stability of the forest steppe ecotone is limited by available rainfall and is therefore sensitive to climate change. Stability and growth of forests depend on humidity and soil water conditions of the future, especially in the grassland/forest transition zone. Projected summer precipitation decline and increase in drought frequency and subsequent wildfires may easily trigger the loss of forest cover, leading to the disruption of certain ecological services that forests provide. Because of the extreme long-term perspective of forest management, the consideration of projected future climate effects has to play a central role in management planning. In order to provide a sound foundation for long-term adaptive measures, hydrological and ecological research needs to be strengthened in the drylands.

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