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Forests in a water limited world under climate change

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Abstract

The debate on ecological and climatic benefits of planted forests at the sensitive dry edge of the closed forest belt (i.e. at the 'xeric limits') is still unresolved. Forests sequester atmospheric carbon dioxide, accumulate biomass, control water erosion and dust storms, reduce river sedimentation, and mitigate small floods. However, planting trees in areas previously dominated by grassland or cropland can dramatically alter the energy and water balances at multiple scales. The forest/grassland transition zone is especially vulnerable to projected drastic temperature and precipitation shifts and growing extremes due to its high ecohydrological sensitivity. We investigated some of the relevant aspects of the ecological and climatic role of forests and potential impacts of climate change at the dryland margins of the temperate-continental zone using case studies from China, the United States and SE Europe (Hungary). We found that, contrary to popular expectations, the effects of forest cover on regional climate might be limited and the influence of forestation on water resources might be negative. Planted forests generally reduce stream flow and lower groundwater table level because of higher water use than previous land cover types. Increased evaporation potential due to global warming and/or extreme drought events is likely to reduce areas that are appropriate for tree growth and forest establishment. Ecologically conscious forest management and forestation planning should be adjusted to the local, projected hydrologic and climatic conditions, and should also consider non-forest alternative land uses.

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

(Some figures may appear in colour only in the online journal)

1. Introduction

Forest steppe (open woodland) is the grassland-forest transition zone where forest ecosystems largely depend on locally accessible water. In the semiarid temperate-continental regions of the Eurasian and North American 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 desertification, and for moderating regional climate (Sun and Liu 2013). However, the largely affirmative valuation of effects of forestation on climate and water resources is debated. Studies suggest that 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 *et al* (2008)). Due to the limited understanding of interactions between physical processes and land cover, the dispute on forest-water relations is still unresolved, especially at a regional scale (Ellison

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et al 2011). Projected changes in global climate generate a further challenge for dryland ecosystems. Climate change is hydrological change, and this is especially true in the dry regions. Water availability determines forest 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 coverage 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 aim of this study is to present a range of views and arguments which should not only underline the complexity of factors influencing the decisions about maintaining/increasing forest cover in the 'forest steppe' zone, but also emphasize the necessity to strengthen research in an ecological zone, which has received relatively moderate attention in the past.

We examine two main thematic fields: (1) the hydrological significance of forest cover in the drylands, and (2) the vulnerability of these forests under climate change and their potential in mitigating projected effects. We present and discuss results and experiences from three selected regions with comparable ecological conditions, in China, in the United States, and in continental SE Europe (Hungary).

2. Effect of forests on the hydrological balance in dry regions

2.1. The climatic transition zone at the forest/grassland edge

Xeric forest limits 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). The term was introduced beside the widely used terms 'trailing limit' or 'receding limit'. Both terms have a similar meaning, but the latters do not specifically refer to water-limited conditions (e.g. competition or antagonists may cause a trailing limit as well). At the xeric limit, the closed forest belt forms a transition ecotone toward the open woodland or forest steppe, which dissolves into the true steppe or grassland with decreasing precipitation. The forest/grassland 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 (ET), roughness etc), the carbon cycle, and ecological functions are strongly affected by land cover and its changes.

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). In Southeast Europe, and also in China the forest steppe belt is a densely populated and an agriculturally important region which has been under human influence for millennia. On flat terrain, the transition from closed forests to grassland is difficult to trace, due to the variability of hydrological conditions and, first of all, due to strong human interference.

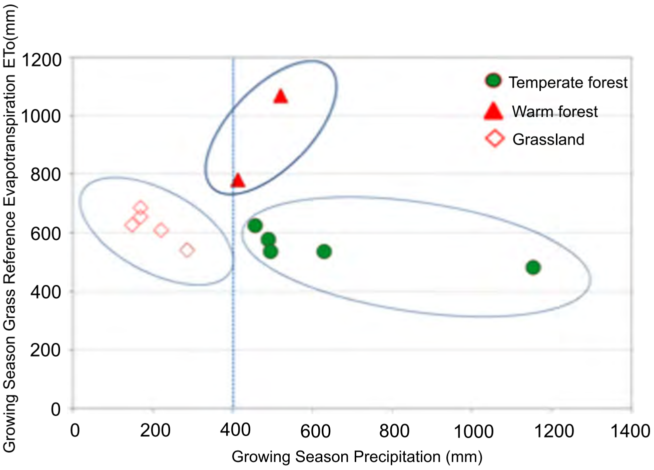

Figure 1. Growing season precipitation and potential evapotranspiration (grass reference evapotranspiration, i.e. ET was calculated based on meteo data) are major drivers for zonal vegetation distribution. Data are derived from an ecohydrological study with sites in the United States, China, and Australia. The figure shows grassland sites (cold steppes and milder-climate shrublands), poplar plantations where precipitation exceeds 400 mm (warm forests), respectively temperate forest sites. (Sun *et al* 2011a, Mátyás *et al* 2013).

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 yr^{-1} and a July mean of 21.5 °C (Mátyás and 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.

2.2. Water use by forests

Globally, zonal (i.e. climate-dependent) forests are generally found in areas where annual precipitation exceeds ET. For example, it is estimated that over 50% of US water supply comes from forest lands (about 30% of the surface; Brown *et al* 2008). Depending on local climate, but 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). Analyzing temperate grassland and forest sites, Sun *et al* (2011a) found that in the warm-temperate zone forests require at least 400 mm of precipitation in the growing season to sustain desired functions, and grassland and scrubland are found at sites where growing season precipitation is below 400 mm (figure 1).

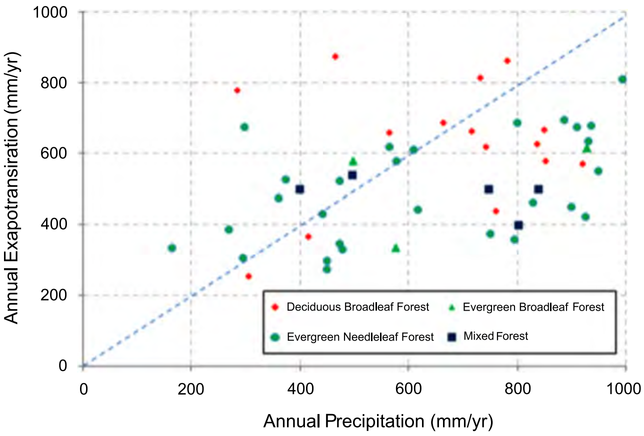

Figure 2. Mean annual precipitation versus annual evapotranspiration in forests as measured at selected global eddy flux measurement sites (precipitation <1000 mm yr^{-1}). Annual ET rates approach to precipitation rates in dry regions where additional water sources such as groundwater are needed to meet evapotranspiration demand. Data of boreal sites with extreme low levels of precipitation are also included. Further explanation in the text.

Water use by forests is difficult to quantify precisely, due to the dynamic character of forest ET 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 yr^{-1}, maximum forest water use seldom surpasses 750 mm (figure 2). In regions where precipitation is around and below 600 mm yr^{-1}, 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 figure 2, 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.

2.3. 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 (Wang *et al* 2011b). Forests can capture larger amounts of carbon through photosynthesis as carbon and water cycles are highly coupled (Law *et al* 2002, Sun *et al* 2011b). World-wide vegetation manipulation experiments show that forest removal reduces water use, i.e. ET, and thus increases watershed stream flow (Andréassian 2004). On the other hand, afforestation or reforestation[3] 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 (Sun *et al* 2000, Major 2002; see also figures 3 and 4).

Earlier long-term forest hydrologic studies focused on deforestation effects, floods and sedimentation (Alila *et al* 2009). Hydrologic studies on the consequences of forestation have emerged in the past decade (Scott *et al* 2005, Sun *et al* 2006, Wang *et al* 2011b). 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 (Sun *et al* 2006). The potential water yield reduction following forestation for timber production and ecological restoration for climate change mitigation and adaptation have drawn renewed attention to the relations between forests and water resources and carbon-water tradeoffs in watersheds (Calder 2002, Brown *et al* 2005, Jackson *et al* 2005, Trabucco *et al* 2008, Malmer *et al* 2009) and on a regional scale (Ellison *et al* 2011). The hot debate on ‘planting’ or ‘not planting’ policies is especially relevant in regions with scarce water resources. How to balance water regime of forest ecosystems between water for carbon sequestration and water available for human use, remains a research question (Grant *et al* 2013). In the following subchapters, effects of forest cover on surface- and groundwater resources and the balancing potential of land cover management are demonstrated on examples from three selected regions.

2.3.1. 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 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^{-1}, 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^{-1} was registered by Major (2002), out of which 130 mm originated from the groundwater. Consequently, forests often appear as groundwater discharge areas (figure 3).

In other studies 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 (i.e. still a potential grassland climate according to figure 1, an

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[3] 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.

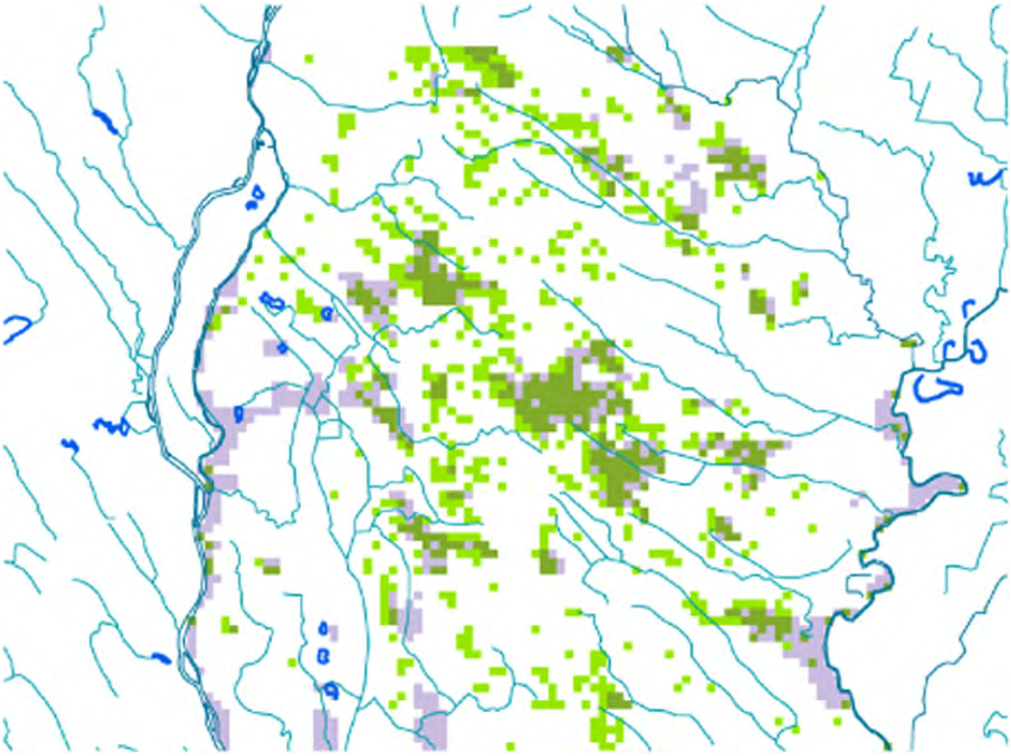

Figure 3. Distribution of areas of groundwater discharge (i.e. estimated negative recharge, in magenta) on the Sand Plateau in the Hungarian lowlands, estimated from *MODIS* daytime land surface temperature data. The map shows the frequent overlap of groundwater discharge areas and of forest cover. Forests are marked light green, overlapping areas in dark green. Rivers and ponds are marked dark blue (adapted from Szilágyi *et al* 2012).

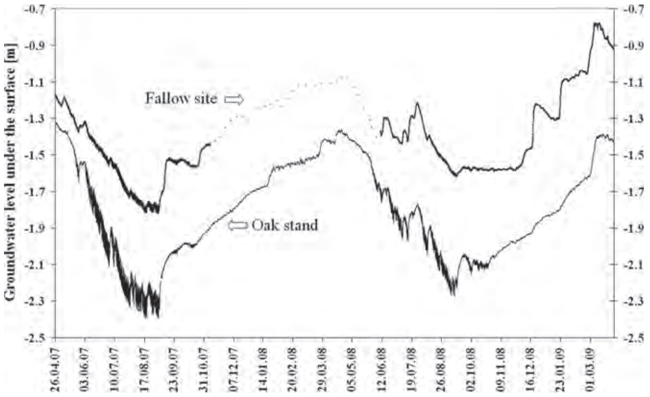

Figure 4. Water table fluctuation in the course of one year under an oak (*Quercus robur*) forest and on a neighboring grassland (fallow) site in the forest steppe zone of Hungary. Missing data are marked with dotted line (Móricz *et al* 2012).

oak forest had approximately 30% more annual ET than the neighboring grassland (405 versus 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 (figure 4, 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^{-1} versus 3.29 mm day^{-1} in a nearby grassland plot, causing a continuous lowering of the water table (Gribovszki *et al* 2014). The calculated well-watered short grass reference ET for this period amounted to 6.58 mm day^{-1} (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.

2.3.2. Effects of land cover changes on streamflow in China.

Comprehensive forest hydrological studies that address forest-water relations did not start until the 1990s in China. Hydrologic models, both empirical and theoretical, have been widely introduced as tools to understand the hydrologic effects of deforestation or reforestation (Wei *et al* 2008). The capacity and precision of models is often challenged by complex soil and vegetation management and conditions of previous land-use practices such as overgrazing or regular collection of forest litter from beneath the tree canopies for fuel—a practice common in the countryside in northern China. In spite of the uncertainties, models provide important insights into hydrologic processes and are used to answer 'what if' type management questions, as data are scarce in developing countries (Sun *et al* 2006).

In dry Northern China, such as the Loess Plateau, a region exposed to heavy soil erosion, empirical and modeling studies confirmed that forest vegetation and associated soil conservation engineering had a significant influence on watershed stream flow (Zhang *et al* 2008a, 2008b, Wang *et al* 2011a, 2011b, Feng *et al* 2012). Recent forest hydrology studies detected that land cover and land use changes played a substantial role in stream flow reduction. A water balance modeling study suggests that if 5.8% or 10.1% of the study area on the Loess Plateau is planted with trees, stream flow will decrease by 5.5% or 9.2%, respectively (Zhang *et al* 2008a). In another 40-year retrospective study (1959–1999), Zhang *et al* (2008b) examined stream flow and climate data from 11 catchments in the Loess Plateau to investigate the response of stream flow to land use/cover changes. They found that all catchments have shown a significant reduction in annual stream flow of −0.13 to −1.58 mm yr^{-1} between 1971 and 1985. Land use/cover changes accounted for over 50% of the reduction in mean annual stream flow in 8 out of the 11 catchments while in the remaining three watersheds precipitation and potential evaporation changes were more important drivers. The other half of stream flow reduction was caused by soil conservation measures, construction of sediment-trapping dams and reservoirs, and by water diversion for irrigation.

To understand the effects of vegetation on stream flow in the Loess Plateau region, Wang *et al* (2011b) constructed multi-annual water balances for 57 basins to estimate annual ET and runoff for forest lands and non-forest lands. Mean annual precipitation was 463 mm and the corresponding averages of annual ET and runoff were 447 and 16 mm for forest lands, and 424 and 39 mm for non-forest lands. Although the difference in annual runoff was only 23 mm, in relative terms this is equivalent to nearly 60% of the annual runoff from non-forest lands. The authors argue that large-scale forestation may have serious consequences for water management and sustainable development in dry regions because of runoff reduction. A recent regional modeling study by Feng *et al* (2012) suggested that forest restoration efforts in the past decade in the Loess Plateau might have increased ET, thus decreasing water yield especially in wetter years, while climatic variability may have partly masked the effects of land cover change.

2.3.3. Balancing effect of land cover management: experiences in the United States. Since the late 1930s, numerous 'paired watershed' studies have been conducted in the United States to examine forest management effects (harvesting with various intensities, species conversion, mountain farming as an alternative land use), on water quality and yield across various climatic and topographic conditions (Ice and Stednick 2004). The general conclusion was similar to the experiences in China: humid areas with high precipitation exhibit a higher hydrologic response in absolute terms, but dry areas with low water flow may have a higher relative response. For example, clear-cutting a deciduous forest in the humid south-eastern US, with an annual precipitation >1800 mm, can result in an increase in stream flow of 130–410 mm yr^{-1}, which is 15–40% of the runoff of undisturbed control watersheds, while the same management practice in the drier area of northern Arizona with an annual precipitation of 500–600 mm may result in a water yield increase of 60 mm which is >40% higher than in the undisturbed control watersheds.

Zou *et al* (2009) summarized century-long vegetation manipulation experimental studies in the Colorado River Basin that provide a bounty of knowledge about effects of change in forest vegetation on stream flow in water-deficit areas. The watersheds are situated in the headwaters of streams and rivers that supply much of the water to downstream users in the western United States. The authors found that vegetation can be managed to enhance annual water yields while still providing other ecological services. The effects of vegetation manipulation on stream flow are associated with the precipitation/elevation gradient and, therefore, with vegetation type. An annual water yield increase between 25 and 100 mm could be achieved by implementing vegetation manipulation in the high elevation subalpine and mixed conifer forests, and in lower ponderosa pine forests. The annual precipitation was generally above 500 mm in areas where a 100 mm increase in stream flow was achieved. Negligible or small increases in water yield were observed from treating sagebrush, piñon-juniper woodlands and desert scrubs, with an annual precipitation below 500 mm.

3. Dryland forests and the challenge of climatic change

3.1. Observed and expected climatic changes and the vulnerability of forest cover

Numerous studies and also the reports of the International Panel on Climate Change (IPCC) forecast a decline in growth and production of forests in dry regions. At the same time, large-scale analyses of impacts of climate change on forests at the xeric or trailing limits are still sporadic. For instance, global statistics of the Food and Agriculture Organization of the United Nations (FAO) do not yet calculate with the loss of forest cover due to aridification (FAO 2010). There are numerous reports about observed impacts from North America's West and Southwest (e.g. Hogg and Price 2000, Garfin *et al* 2013), from Western and South Europe (for review, see Lindner *et al* 2010) and also from other parts of the world (Allen *et al* 2010), while impacts on forest cover in the drylands of Eastern Europe, Central Asia and China are still less scrutinized (Zhang *et al* 2008b, Piao *et al* 2010, Mátyás 2010b, Mátyás *et al* 2013). Measurements of growth and yield at the margins of the closed forest belt confirm the

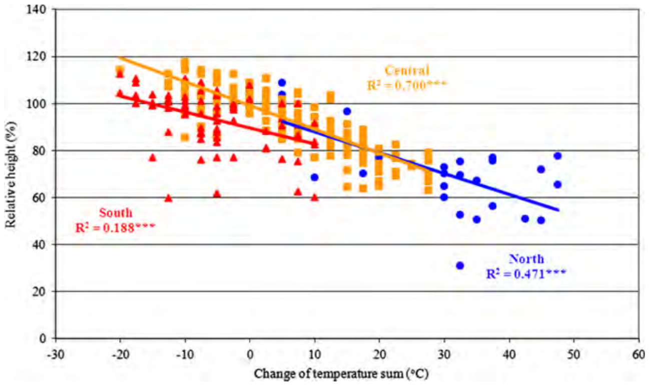

Figure 5. Growth response of geographically transferred Scots pine (*Pinus sylvestris*) populations (provenances) into warmer environments. The increase of annual temperature sum (in °C degree-days) resulted in a decline of relative height irrespective of origin (central, northern or southern populations). Re-analyzed data, measured in six Russian common garden experiments (Mátyás *et al* 2010, 2013).

Table 1. Frequency of recent and projected drought events for Hungary, according to IPCC's scenario A2 (further growing population, slower economic growth), calculated with MPI's REMO[4] climate model (Gálos in: Mátyás 2010a).

	Drought summers		
Period	Number of years (out of 50 years)	Mean of precipitation anomalies (%)	Mean of temperature anomalies (°C)
1951–2000	15	–28.02	+0.95
2001–2050	9	–29.21	+2.00
2051–2100	24	–34.98	+2.86

expected negative impact of rising temperatures, both on total dendromass (Führer *et al* 2013) and on growth and vitality, measured in common gardens (Mátyás *et al* 2010; figure 5).

Across the temperate zone, a relatively rapid increase of annual mean temperature has been observed in recent decades, and the continental dryland zones are no exceptions. In the last half century, both average temperatures and climatic extremes increased in Eastern Asia (Qi *et al* 2012). For instance, average temperatures in Mongolia increased by more than 2 °C since 1940 and nine out of the ten warmest years occurred after 1990 (Lu *et al* 2009). In North China, the frequency of droughts intensified during the past several decades, leading to an unprecedented increase in dry areas (Piao *et al* 2010). Growing season anomalies have been generally increasing in China in the 2000s: drought events got significantly stronger in North China and soil moisture declined (Zhao and Running 2010).

Garfin *et al* 2013 also concluded that the US Southwest has seen a warming trend in recent times. The past decade was the warmest of the period 1901–2010. The period since 1950 has been warmer than any other of comparable length in at least 600 years. Fewer cold waves and more heat waves occurred over the past decade compared to the long term climate records. Recent droughts have been unusually severe relative to the ones in the last century. Streamflow is declining in major river systems in the region. Climate change predictions suggest that warming in the southwest region will continue, with longer and hotter heat waves in summer. Simultaneously, average precipitation will decrease and may cause more severe and frequent droughts and forest fires.

In Europe, significant drying tendencies were observed in regions of Central and Eastern Europe. Year-to-year variability of precipitation and of summer temperature increased significantly, coupled with a general warming tendency in the recent 4–5 decades. In the Carpathian Basin, notably in Hungary, the years since the end of the last century were the hottest since the start of weather measurements. The frequency of extreme high temperatures increased, while summer precipitation declined. In general, precipitation occurred less frequently, however, the number of heavy or extreme precipitation days has risen (Bartholy Pongrácz 2007).

In Eurasia, projected temperature changes of the critical summer climate will be more drastic in the forest/grassland transition zone than in the boreal zone (Mátyás 2010a). The projected probability of recurrent severe summer droughts is increasing, particularly in the second half of the present century (Gálos *et al* 2007). Projected summer precipitation decline and shifts in drought frequency are of special significance at the xeric limits which are extremely sensitive to even minor humidity fluctuations. Mass mortality may appear in forests, especially on sites with an unfavorable water regime.

As an example, projected frequency changes of drought events are presented for the territory of Hungary. The future frequency of droughty summers (precipitation decline exceeding 15% of the seasonal mean) are shown in table 1. It is highly remarkable that from 2050 onward, the applied model defines every second summer as a drought event: 24 summers out of 50 years will be drought summers, with growing anomalies (Gálos *et al* 2007). The majority of other investigated models come to the same conclusion.

3.2. Balancing climate change impacts: the potential of forestation

3.2.1. Climatic feedback of forests: ambiguous effects. 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 (see review in Sun and Liu 2013). 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).

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[4] REMO is a climate model developed at the Max Planck Institute (MPI) for Meteorology, Hamburg, Germany.

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 even 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 versus 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 has also been investigated. Lower albedo, as well as changed sensible/latent heat ratios resulted in a rise of summer temperature in afforested regions. For instance, an intensive country-wide forestation campaign was carried out in Hungary, first of all in the Eastern part of the country, where forest cover increased from 5 to 26%, while in the Western half of the country the increase was moderate, from 15 to 21%. Applying the MM5 meso-scale weather forecasting model, Drüszler *et al* (2010) found that after four decades (1999 versus 1959), forecasted summer daytime temperatures have increased. The difference between land cover changes in the East and the West of the country is reflected by the results as well. 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 ET determines whether there is a cooling or warming effect. The dual role of forests is supported also by other research results. The effect of forests on surface energy conditions and water budget depend 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 (potential afforestation, see figure 6) and a hypothetical extreme scenario, where all available agricultural land was converted to forests, resulting in a forest cover of 92% (maximum afforestation, figure 6). Although the expansion of forest cover led to an increase in ET and precipitation, the mitigating effect remained relatively modest. Afforestation may increase local precipitation, but even the unrealistic maximum forestation could only partially offset the projected precipitation decrease ($dP < 6\%$, see figure 6, versus the mentioned decline projection of 24%).

3.3. 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 in the US have caused concerns about the traditional functions of forests, supplying water and sequestering carbon (Grant *et al* 2013). Scientists call for a dramatic shift in forest management practices to adapt to climate change.

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. Mátyás 2010a, Cao *et al* 2011, Xu 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,
- projected climatic changes and extreme events may generate ecologically novel conditions,
- functioning of close-to-natural systems is disturbed by direct and also by indirect human effects (e.g., uncontrolled grazing, game damage, pollution).

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. Experiences from the United States confirm that vegetation can be successfully managed to enhance water yields while still providing other ecological benefits. Carefully planned

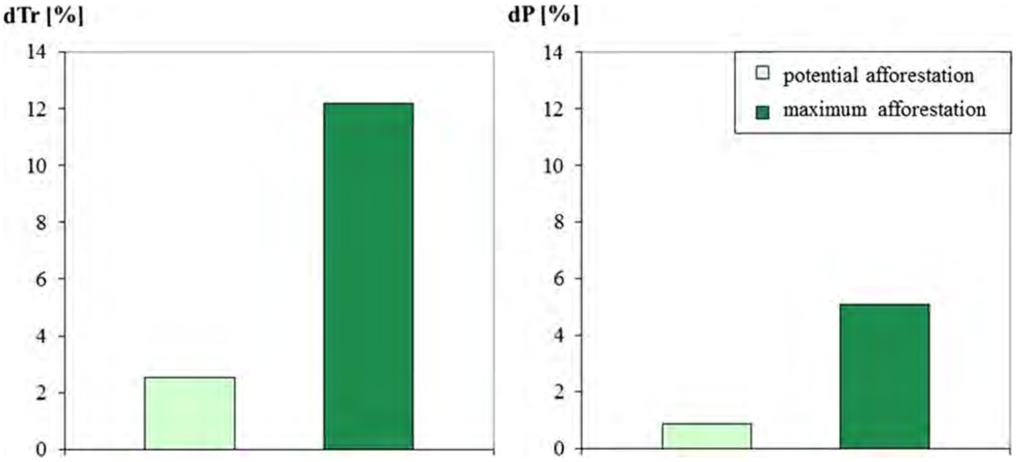

Figure 6. Modeled feedback of planned afforestation on future climate conditions in Hungary. Left: projected transpiration increase (*dTr*); right: projected precipitation increase (*dP*), for a realistic (7% forest cover increase—light columns) and for an extreme scenario (92% forest cover increase—dark columns). Explanation is in the text (Gálos *et al* 2011, Mátyás *et al* 2013).

human interference is therefore essential, to achieve successful adaptation to the expected environmental changes.

4. 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 carbon sequestration and 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 that in spite of increased ET, precipitation changes only moderately even in extensively afforested regions. Regarding temperature conditions, the balance between actual ET (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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