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Regional characteristics of climate change altering effects of afforestation

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Abstract
Climatic effects of forest cover change have been investigated for Hungary. For the time period 2071–100 we have analyzed whether the climate change signal for summer precipitation and the probability of droughts can be reduced assuming maximal afforestation for the entire country (forests covering all vegetated areas). The biogeophysical effects of land cover change have been assessed using the results of an A1B IPCC-SRES emission scenario from REMO (regional climate model at the Max Planck Institute for Meteorology, Hamburg). The simulation results indicate that afforestation may reduce the projected climate change through higher evapotranspiration and precipitation as well as lower surface temperature for the entire summer period. The magnitude of the feedback of the forest cover increase on precipitation differs among regions. The strongest effects are visible in the northeastern part of the country. Here, half of the projected precipitation decrease can be relieved and the total number of drought events can be reduced, assuming maximal afforestation. Afforestation brings about the smallest climatic effect in the southwestern region, in the area that shows the strongest climate change. The results can help to identify areas where forest cover increase should most effectively support the alleviation of climate change effects.

Keywords: climate change, drought probability, land cover change, afforestation

1. Background and objectives

Temperature and precipitation play an important role in determining the distribution of the terrestrial ecosystems that in turn interact with the atmosphere through biogeophysical and biogeochemical processes. Vegetation is a dynamical component of the climate system and affects the physical characteristics of the land surface, which controls the surface energy fluxes and the hydrological cycle (Pielke *et al* 1998, Brovkin 2002, Pitman 2003, Betts 2007). Forests have larger leaf area and roughness length, lower albedo and deeper roots compared to other vegetated surfaces.

Changes of the land cover due to climatic conditions and human influence feed back to the atmosphere, alter climate and hence can lead to the enhancement or reduction of the projected climate change signals (Feddema *et al* 2005, Bonan 2008). Long term studies (Betts 2007, Göttel *et al* 2008, Wramneby *et al* 2010) show that land use and land cover changes have a much weaker influence on the atmospheric circulation than changes in greenhouse gas emissions. However, for shorter time periods, in smaller areas or for regions with strong land–atmosphere interactions, the feedback processes can regionally affect and modify the weather and climate conditions, and the temperature and precipitation variability in various ways (e.g. Georgescu *et al* 2011, Seneviratne *et al* 2006, 2010, Weaver and Avissar 2001). For instance, changes of vegetation cover under future climate conditions enhance the warming trend in the Scandinavian Mountains as well as the drying trend in southern Europe, but mitigate the projected increase of temperature in central Europe (Wramneby *et al* 2010).

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Several studies have addressed the climatic effects of the northwards shift of the upper tree line in the boreal region (Bonan *et al* 1992, Brovkin 2002). The darker coniferous forest masks the snow cover resulting in lower surface albedo compared to tundra vegetation or bare ground. Consequently, the change of vegetation from tundra to taiga under future climate conditions amplifies global warming, especially in winter and spring (Göttel *et al* 2008). Tropical forests maintain high rates of evapotranspiration. The evaporative cooling effect is a negative feedback to climate change, which is much stronger in this region than warming due to the low albedo of forests (Bonan 2008). Several climate model studies confirm that large-scale replacement of the Amazon forest to pasture results in a warmer and drier climate (Shukla *et al* 1990, Dickinson and Kennedy 1992).

Results of model simulations agree quite well in the clear biogeophysical effects of boreal and tropical forests, whereas the magnitude of the net climate forcing and benefit of temperate forests and their role in the climate change mitigation are considered marginal (Bala *et al* 2007, Bonan 2008, Jackson *et al* 2008), however opinions and model results are conflicting. Climate model studies for the temperate regions showed that replacing forests with agriculture or grasslands reduces the surface air temperatures (Bonan 1997, Bounoua *et al* 2002, Oleson *et al* 2004) and the number of summer hot days (Anav *et al* 2010). Consequently, trees may contribute to the warming due to their lower albedo relative to crops. Other studies show opposite results: temperate forests cool the air compared to grasslands and croplands and contribute to higher precipitation rates in the growing season (Copeland *et al* 1996, Hogg *et al* 2000, Sánchez *et al* 2007). In the Mediterranean, recovery of the potential vegetation cover (mainly forests) led to an increase in evapotranspiration, which caused cooler and moister conditions in the period from April until mid-July (Heck *et al* 2001). In mid-July, soil moisture dropped below the critical value and transpiration was almost completely inhibited, which resulted in drier and warmer summers accelerating the projected climate change. Teuling *et al* (2010) pointed out the dual role of forests in surface energy conditions and water budget depending on the selected time scale: in the short term, forests contribute to the increase in temperature, but on longer time scales they may reduce the impact of extreme heat weaves.

These studies indicate that forests can cool or warm the surface air temperature depending on various contrasting feedbacks. Furthermore the variability of the climatic, soil and vegetation characteristics of a region, as well as the representation of land surface processes in the applied climate model, also have an influence on the simulated vegetation–atmosphere interactions.

In Europe, there is a lack of information about the effects of land cover and land use changes under future climate conditions on a country scale. Hungary has been selected as a study region, where regional climate model simulations project a significant increase in the summer mean temperature and a decrease in the summer precipitation sum for the 21st century (Bartholy *et al* 2007, Jacob *et al* 2008, Szépszó 2008, Radvánszky and Jacob 2009). For the time period 2051–100, the probability and severity of dry events can be significantly higher compared to 1961–90 (Gálos *et al* 2007). The projected change of the spatial and temporal distribution of precipitation can lead not only to economical and social impacts but also to severe consequences in vitality and distribution of the natural ecosystems. Hungary has a special ecological position on the border zone of closed forests and forest steppe. Here, many of the zonal tree species have their lower limit of distribution, which is primarily determined by climatic aridity (Mátyás 2009). Threats at the lower (xeric) limits of forest cover are seldom addressed in the literature (Jump *et al* 2009, Mátyás 2010), although this zone is especially sensitive and vulnerable to the increase of the frequency of climatic extremes.

In the last 50 years, large-scale afforestation was carried out in Hungary, which is planned to continue also in the near future. Results of mesoscale model studies showed that land use change in the 20th century had already altered weather and climate (Drüszler *et al* 2010). So far, however, climatic effects of forest cover change in Hungary have not been investigated for longer future time periods on a regional scale. Information about the forest–climate interaction is essential both for the assessment of mitigating effects, and for the development of future adaptation strategies.

In this case study, climate change simulations have been carried out for Hungary with the objective to address:

- How does the increase in forest cover affect the future climate in Hungary?
- Are there any regional differences in the climatic effects of forests within the country?
- Could the effect of maximal afforestation on summer precipitation alleviate the climate change signal?
- Can the probability of droughts be reduced by the increase in forest cover?

In order to answer these scientific questions, the paper is organized as follows: in section 2 the applied model and experimental setup and the main steps of the analyses are described. Results are presented in section 3: in 3.1 the projected climate change and drought tendencies are introduced and the most climate change affected region is selected. Effects of the forest cover increase on the regional climate are analyzed in 3.2. In section 3.3 the magnitude of the climatic feedbacks of afforestation is compared to the magnitude of the climate change signal for precipitation, with a special focus on the probability of droughts. Results are discussed, conclusions are drawn and the possibilities for practical applications are stressed in section 4.

2. Model and methods

2.1. *The regional climate model REMO—general characteristics and land surface parameterization*

To study long term climatic feedbacks of land cover change on a regional scale, climate modeling with fine horizontal resolution is essential. REMO (Jacob 2001, Jacob *et al* 2001, 2007) is a regional three-dimensional numerical model of the atmosphere. It is based on the ‘Europamodell’, the former numerical weather prediction model of the German

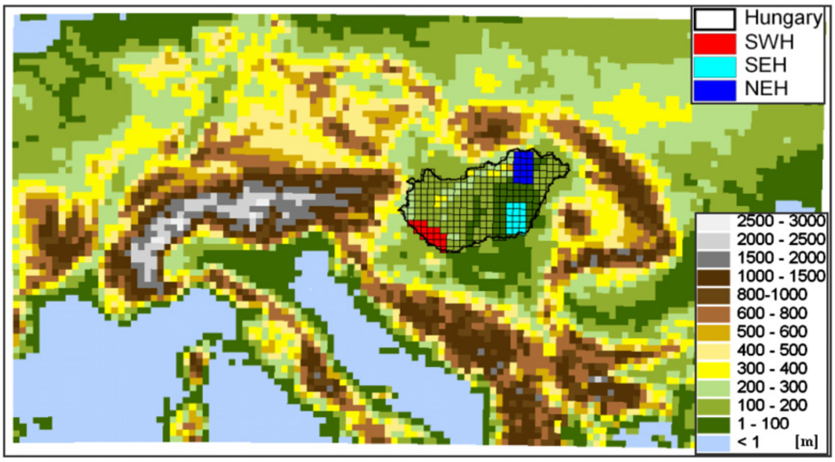

Figure 1. Simulation domain. Land cover has been changed only in Hungary. Regions selected for detailed analyses are: Southwest Hungary (SWH), Southeast Hungary (SEH), Northeast Hungary (NEH).

Weather Service (Majewski 1991). The calculation of the prognostic variables is based on hydrostatic approximation. The physical parameterizations from the global climate model ECHAM4 have been implemented at the Max Planck Institute for Meteorology in Hamburg (Roeckner *et al* 1996) in the regional model. REMO can be applied to forecasts as well as in climate mode. In climate mode the model runs continuously for long time periods with updates of the lateral boundaries every 6 h (Jacob 2001). It is possible to simulate statistical characteristics of meteorological quantities.

Regarding vegetated land cover, surface processes are controlled by physical vegetation properties in REMO. The parameter values of leaf area index and fractional vegetation cover for the growing and dormancy season, background albedo, surface roughness length due to vegetation, forest ratio, plant available soil water holding capacity and volumetric wilting point are allocated for each land cover type in the global dataset of land surface parameters (Hagemann *et al* 1999, Hagemann 2002). These datasets include the major ecosystem types according to the classification list of Olson (1994a, 1994b). Their global distributions were derived from AVHRR[4] data at 1 km resolution supplied by the International Geosphere–Biosphere Program (Eidenshink and Faundeen 1994) and constructed by the US Geological Survey (1997, 2002). The global dataset of land surface parameters has been validated for application in regional (Hagemann *et al* 2001, Rechid and Jacob 2006, Rechid *et al* 2008b) as well as in global climate models (Hagemann *et al* 2000).

The leaf area index in the model influences evapotranspiration through stomatal conductance and defines the size of the precipitation storage capacity. The fractional vegetation cover determines the fraction of grid area where vegetation properties take effect on surface exchange processes. In REMO the background albedo is the albedo of a snow-free surface. Influencing the net radiation budget, this parameter has an impact on the simulated vertical energy exchange and modifies the surface heat fluxes and temperatures. The turbulent exchange of momentum, energy and moisture between the surface and the atmosphere is calculated as a function of roughness length. The forest ratio is used to account for the different behavior of snow albedo in forested and non-forested areas. The soil water content is influenced by the soil water holding capacity. The plant available water holding capacity is the maximum amount of water that plants may extract from the soil before they start to wilt (Hagemann *et al* 1999). The construction of this parameter is based on the optimized rooting depths (Kleidon and Heimann 1998). The partitioning of the total amount of water into surface runoff and infiltration follows the Arno-scheme (Dümenil and Todini 1992), in which surface runoff is computed as infiltration excess from a bucket type reservoir. Soil temperatures are calculated for five discrete layers until 10 m depth according to the scheme of Warrilow *et al* (1986).

During the model integration, each surface fraction is characterized by its own land surface parameters, which are aggregated over the model grid box in the given horizontal resolution (Mason 1988, Feddes *et al* 1998). In the current model version, vegetation phenology is represented by monthly varying values of the leaf area index and vegetation ratio. The mean climatology of the annual cycle of background albedo is also implemented (Rechid and Jacob 2006, Rechid *et al* 2008a, 2008b). The other land surface parameters remain constant throughout the year. Land cover change in REMO can be implemented by modification of the characteristic land surface parameters.

2.2. Experimental setup

The simulation domain covers Central Europe (figure 1). The horizontal grid resolution is 0.176°, with 121 × 65 grid boxes and 27 vertical levels. The model has been initialized and driven by REMO 0.44° simulations, applying a double nesting procedure.

The following simulations have been performed and analyzed (table 1):

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[4] Advanced Very High Resolution Radiometer.

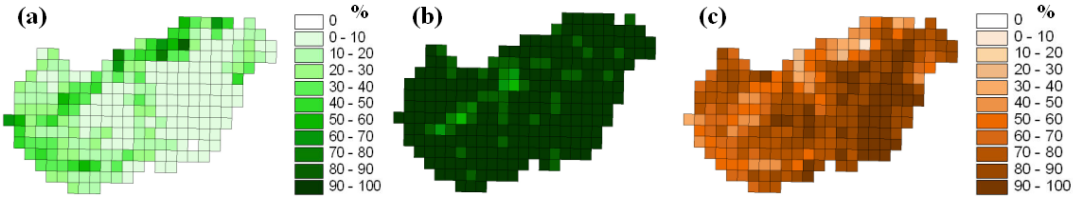

Figure 2. Forest cover in the reference (a) and in the maximal afforestation simulation (b) and the increase compared to the reference (c).

Table 1. Analyzed data and time periods.

	Experiment		
	Reference		Maximal afforestation
Characteristics	Present forest cover unchanged		Forests covering all vegetated areas
Time period	1961–90	2071–100	2071–100
Greenhouse gas forcing		A1B IPCC-SRES[a] emission scenario	
Horizontal resolution (deg)	0.176	0.176	0.176
Lateral boundaries (deg)	REMO[b] 0.44	REMO[b] 0.44	REMO[b] 0.44

[a] IPCC-SRES: Intergovernmental Panel on Climate Change—Special Report on Emission Scenarios.

[b] REgional climate MOdel (Jacob 2001, Jacob *et al* 2001, 2007).

- *Reference simulation* for the past (1961–90) with present forest cover based on the CORINE Land Cover vector database[5] for Hungary (figure 2).
- *Emission scenario simulation* for the future (2071–100) with present forest cover applying the A1B IPCC-SRES emission scenario[6], serving as reference simulation for the land cover change study.
- *Maximal afforestation simulation* for 2071–100 with the assumption that the whole vegetated area of Hungary is forest (figure 2) and the new afforestations are all deciduous forests. Across the simulation domain, forest cover has been changed only in Hungary. Compared to the reference the afforestation rate is the highest in the southeastern region (figure 2).

In accordance with the forest cover increase in all grid boxes, the new distribution of the land cover categories has been determined and a new land surface parameter set has been calculated. Figure 3 shows the change of three selected land surface parameters, which have the largest influence on the simulated climate in REMO for the mean of May, June, July and August. Afforestation resulted in the increase of surface roughness length and leaf area index and the decrease of albedo compared to the reference land cover (figure 3).

2.3. The main steps of the analyses

Simulation results for May, June, July and August have been selected for the analyses and considered ‘summer’ with respect to the special focus of the paper on dry summers. In these months water availability is especially important for the forest growth (Czúcz *et al* 2011). The leaf area index reaches its maximum, which has a strong control on the land–atmosphere interactions.

Climate change due to emission change has been investigated analyzing monthly precipitation sums and 2 m temperature means for 2071–100 (without any land cover changes) compared to 1961–90. The region, which is affected mostly by warming and drying has been determined. Here, probability and severity of droughts have been studied in more detail. The model has been successfully validated against observations for temperature and precipitation (Jacob *et al* 2008, Szépszó and Horányi 2008) as well as for the occurrence and severity of droughts in Hungary (Gálos *et al* 2007). To eliminate the uncertainty related to the model bias the ‘delta change approach’ has been used, i.e. changes in climatic variables were analyzed rather than absolute values calculated by the model. This approach is based on the assumption that model bias does not change under climate change conditions (Jacob *et al* 2008). Meteorological droughts have been defined and classified based on Gálos *et al* (2007): for each investigated year the relative precipitation anomaly has been calculated from the mean summer precipitation sum in the period 1961–90. Weather conditions were considered as drought if the relative precipitation decrease was larger than 15% of the mean. Considering relative precipitation anomalies, further severity classes have been determined. The applied thresholds are based on the precipitation and temperature anomalies of extreme/moderate dry summers in Hungary in the past, which characterize the Hungarian circumstances quite well.

Climate change due to maximal afforestation has been studied comparing the simulated evapotranspiration, surface temperature and precipitation with and without forest cover increase for the time period 2071–100.

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[5] http://dataservice.eea.eu.int/.

[6] A1: very rapid economic growth, global population peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system; A1B means a balance across all sources (IPCC 2007).

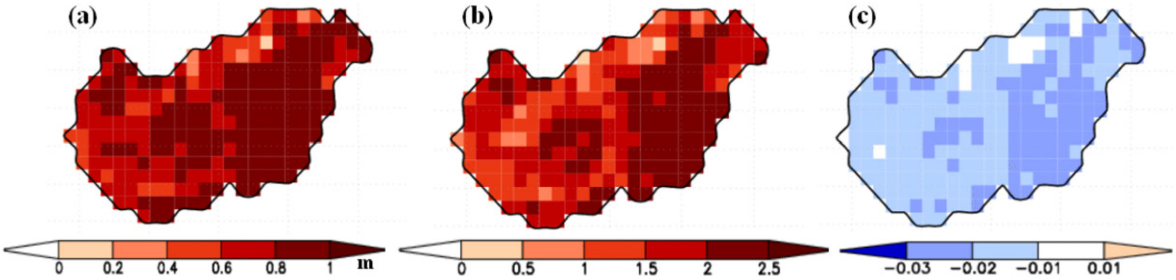

Figure 3. Change of the surface roughness length (a), leaf area index (b) and albedo (c) in the maximal afforestation simulation compared to the reference.

Climate change due to emission change and maximal afforestation has been determined comparing the results of the maximal afforestation experiment (2071–100) with the reference study of the past (1961–90). For precipitation as well as for the probability of droughts the possible effects of forest cover increase and regional differences have been analyzed. The magnitude of the climatic effect of maximal afforestation has been investigated relative to the magnitude of the climate change signal for three sub-regions.

An investigation of the uncertainties of this analysis due to internal model variability would require an ensemble of simulations. Nevertheless, only one control run and one emission scenario simulation were available. To test the significance of the climatic effects of maximal afforestation a Mann–Whitney-U-Test (Mann and Whitney 1947) was applied. This ranking test does not assume a normal distribution.

3. Results

3.1. Climate change due emission change

Climate change without any land cover changes has been analyzed for the A1B IPCC-SRES emission scenario according to the spatial distribution of the projected temperature anomalies ($\mathrm{d}T$) and relative precipitation decrease ($\mathrm{d}P$) in a 30 yr period at the end of the 21st century (2071–100) with respect to the 30 yr climate period 1961–90.

The southwestern part of Hungary is affected most by warming and drying. Here, the projected increase of the summer temperature can be larger than 3.5 °C and the decrease of the summer precipitation may exceed 25% (figure 4). For these two variables the smallest climate change signal was observed in the northeast.

The significant decrease of the mean summer precipitation sums resulted in more frequent dry summers. In the southwestern part of Hungary the total number of droughts may increase by eight in the time period 2071–100 compared to 1961–90 (table 2). Table 2 shows that not only the probability, but also the severity of dry summers is projected to increase. Towards the end of the 21st century in almost half of the investigated period the drought summers can be characterized by more than 40% relative precipitation decrease, whereas there were only three of these summers in 1961–90.

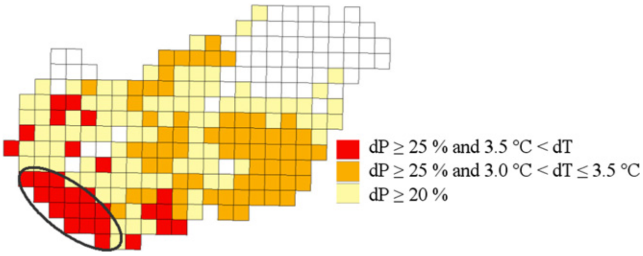

Figure 4. Spatial distribution of the relative precipitation decrease ($\mathrm{d}P$) and temperature increase ($\mathrm{d}T$) in summer (2071–100 versus 1961–90). The most affected region is marked.

Table 2. Change of the total number of dry summers and the number of summers in the different severity classes in the period 2071–100 compared to 1961–90, in the southwestern part of Hungary. $\mathrm{d}P$: relative precipitation decrease.

	Number of dry summers in 1961–90	Change in the number of dry summers 2071–100 versus 1961–90
$15\% < \mathrm{d}P \leqslant 25\%$	5	0
$25\% < \mathrm{d}P \leqslant 40\%$	5	−2
$40\% < \mathrm{d}P$	3	+10
Total	13	+8

3.2. Climate change due to maximal afforestation

For the summer months in 2071–100, effects of maximal afforestation on evapotranspiration, surface temperature and precipitation have been analyzed comparing the simulation results of the experiments with and without land cover changes. Forests have larger leaf area index and roughness lengths compared to other vegetated surfaces that support the enhanced rate of evapotranspiration. In the maximal afforestation simulation the 30 yr mean of the summer evapotranspiration rate can be 10–15% higher than for the present forest cover (figure 5). Within the investigated time period, the climatic effect of afforestation shows a relatively large interannual variability but it is systematic, i.e. the direction of the change remains the same during the period. Based on the results of the Mann–Whitney-U-test evapotranspiration changes are significant on a greater than 95% confidence level in the whole country, except for the southwestern part (90% confidence level). Due to the latent heat of vaporization (evaporative cooling), surface temperatures can be reduced by up to 1 °C in

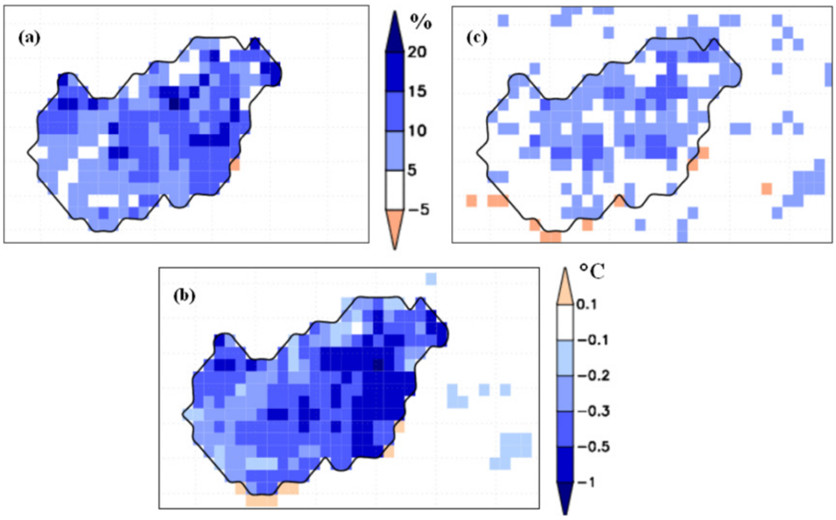

Figure 5. Change of evapotranspiration (a), surface temperature (b) and precipitation (c) due to maximal afforestation compared to the reference experiment (2071–100).

the eastern part of the country, 0.3–0.5 °C in the western part of the Hungarian lowland and in southwest Hungary, respectively and 0.1–0.3 °C over the mountainous areas (figure 5).

Changes of both evapotranspiration and surface temperature are localized over Hungary corresponding to the changes of the land surface parameters. They are determined primarily by local processes. In contrast to this, precipitation has a more complex behavior. It is influenced also by large-scale atmospheric circulation, thus the effects of afforestation are spread out over larger areas (figure 5). The 30 yr mean summer precipitation sum may increase by 10–15% for the maximal afforestation compared to the reference simulation. This effect is largest in the northeastern part of the country (figure 5), although the afforestation rate was smallest in this region. In the southern and western part of the country the change in precipitation is relatively low. In all of the grid boxes where precipitation increase exceeds 10% due to maximal afforestation, the changes are significant at the 85% confidence level. This indicates high interannual variability of precipitation within the investigated time period.

Based on the simulation results, the larger contiguous forest blocks resulted in cooler and moister conditions on the regional scale, for the entire summer period. Impacts of maximal afforestation on precipitation show weaker statistical significance than the effects on evapotranspiration and surface temperature.

3.3. Climate change due to emission change and maximal afforestation

For the summer precipitation sum the magnitude of the effect of forest cover increase has been compared to the magnitude of the projected climate change signal due to emission change. Simulation results have been analyzed for the country mean (Hungary) and for the following three regions (figure 1):

- southwest Hungary (SWH): the most affected area by warming and drying.
- southeast Hungary (SEH): the region with the largest increase of forest cover.
- northeast Hungary (NEH): the area in which the precipitation increasing effect of afforestation is simulated to be the largest.

In all three regions and for the whole of Hungary, the precipitation change caused by emission change and the precipitation change due to maximal afforestation have opposite effects (figure 6). This means that the projected climate change signal for precipitation can be reduced by the increase in forest cover.

The magnitude of the feedback of maximal afforestation on precipitation compared to the magnitude of the climate change signal is robust and differs among regions (figure 6). The 30% relative precipitation decrease due to climate change (2071–100 versus 1961–90) in southwest Hungary could hardly be compensated by forest cover increase. In southeast Hungary, the decrease of summer precipitation has been significantly weakened through afforestation. In the mountainous region of northeast Hungary, the projected drying in summer is the mildest (17%), where the largest precipitation increasing (9%) effect of maximal afforestation is observable. Here, for precipitation, more than half of the projected climate change signal could be relieved with enhanced forest cover (figure 6).

Effect of maximal afforestation on the probability and severity of droughts projected for the end of the 21st century. The spatial differences in the magnitude of the climatic effect of afforestation are observable also for droughts. For the country mean (not shown) and for the area most affected by climate change (SWH), the increase of forest cover would have only small effects on the probability of droughts in 2071–100 (table 3), but in northeast Hungary (NEH), the projected increase of the total number of droughts could be reduced, assuming maximal afforestation (table 3).

In northeast Hungary the probability of severe droughts above 40% precipitation decrease would not be diminished, but

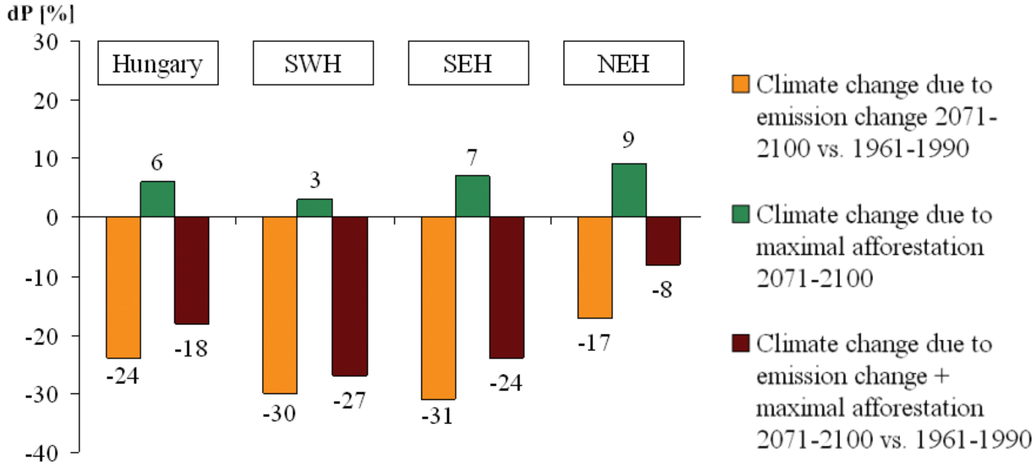

Figure 6. Change of the summer precipitation sum (dP) due to emission change (2071–100 versus 1961–90), due to maximal afforestation (2071–100) and due to emission change + maximal afforestation in the whole of Hungary and in the three investigated regions (SWH: southwest Hungary, SEH: southeast Hungary, NEH: northeast Hungary).

Table 3. Effect of maximal afforestation on the projected change of the total number of droughts in southwest Hungary (SWH) and northeast Hungary (NEH).

Change of the total number of dry summers	SWH	NEH
(a) Due to emission change	+8	+10
(b) Due to emission change + maximal afforestation	+7	+6

moderate drought summers between 25 and 40% precipitation decrease could be reduced via larger forested areas (not shown). Thus, it can be concluded that afforestation may influence moderate droughts but cannot eliminate severe droughts.

4. Summary and discussion

Applying the regional climate model REMO, a case study has been carried out for Hungary to investigate whether the projected climate change could be reduced assuming maximal afforestation (forests covering all vegetated areas). Under simulated climate change (2071–100) for the A1B emission scenario, the probability and severity of summer droughts are projected to be significantly higher; droughts might occur in every second summer. Based on the simulation results of the regional climate model REMO, afforestation in larger contiguous forest blocks could affect the simulated climate on a regional scale and may contribute to the reduction of the projected climate change in Hungary. For 2071–100, maximal afforestation simulation resulted in an increase of evapotranspiration (10–15%) and precipitation (up to 10–15%) as well as in a decrease of surface temperature (up to 1 °C). The statistical analysis of the results shows a higher level of significance for evapotranspiration and surface temperature than for precipitation due to larger interannual variability of the latter.

For precipitation, the magnitude of the effect of maximal afforestation relative to the climate change signal shows large spatial differences. The smallest changes were calculated in the southwestern region, in the area with the potentially strongest climate change. The largest effects are observed in the northeastern part of the country. Here, half of the projected precipitation decrease could be set off and the number of summer droughts could be reduced, assuming maximal afforestation.

In contrast to the studies of Heck *et al* (2001) for the Mediterranean region, for Hungary the evaporative cooling effect of forests dominates during the entire summer period. Assuming maximal afforestation in Hungary, the projected climate change could be mitigated but not fully compensated. This sensitivity study also shows that vegetation feedbacks have a weaker influence on atmospheric circulation in comparison to greenhouse gas forcing (Betts 2007, Göttel *et al* 2008, Wramneby *et al* 2010). Considering the regional scale of the analyses, the length of the investigated time period (30 yr) and the restricted extension of afforestation within the simulation domain (forest cover has been modified only in Hungary), the magnitude of the feedback on the precipitation is relatively large compared to the climate change signal. These analyses represent the first regional scale assessment of the climatic role of forests for long future time periods and their role in adapting to climate change in Hungary. Analyses concerning the spatial differences in the effect of afforestation can help to identify the areas where forest cover increase might be the most effective from the climatic point of view. Thus the simulation results could be an important basis of future forest policy.

This sensitivity study investigated the simulation results of a single regional climate model driven by one emission scenario. The simulated climatic feedbacks of land cover depend, however, not only on the climate, soil and vegetation characteristics of the studied region but also on the representation of the land surface in the climate model (see overview of Pitman 2003). There are differences among climate models in the parameters describing the land cover types and the role of these parameters in the vegetation–climate interactions. This determines the sensitivity of the model to land cover changes. As an example, in contrast to the feedback chain of the present study with REMO, in the land cover change analysis of Anav *et al* (2010) the simulated total evapotranspiration showed large sensitivity to the modification of stomatal resistance, which had a significant impact on the final conclusion of their study.

The basic differences among the models lie in the consideration of the biogeochemical processes, the vegetation dynamics and phenology that can have additional impacts influencing the simulated vegetation–atmosphere feedbacks. There are already regional climate model studies with coupled vegetation dynamics (e.g. Wramneby *et al* 2010). In the present simulations, the biogeochemical effects and the changes of vegetation distribution due to climate change were not considered, although the expected increase in droughts and consecutive dry periods may have a severe impact on forests in the studied region. For instance, at the beginning of the 21st century, recurrent droughts had already caused severe health decline of beech forests at the lower limit of their distribution in southwest Hungary (Berki *et al* 2009, Lakatos and Molnár 2009). This is the same region where this study projected the highest increase of the probability of extreme dry summers. Ecological models of forest distribution have already shown that this simulated tendency might lead to the drastic reduction of macroclimatically suitable areas for beech and the possible disappearance of this species from Hungary (Czúcz *et al* 2011, Mátyás *et al* 2010). Due to mass mortality (Berki *et al* 2009) it has to be assumed that forest species composition and structure will change in the exposed areas and there will be zones with no forest regeneration. This emphasizes the need for regional scale assessments of climate change effects taking into consideration future forest cover shifts. From a practical point of view, the understanding of the role of land cover in the climate system becomes more important with the expected land use change. Land cover characteristics are affected by climate change and human influence and show differences among regions. Therefore regional scale information is essential for future land use policies. These analyses have been extended for Europe and continued in the frame of the EC-FP7 project 'Climate Change—Terrestrial Adaptation and Mitigation in Europe (CC-TAME)'.

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