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Hydrological impact assessment of afforestation and change in tree-species composition — A regional case study for the Federal State of Brandenburg (Germany)

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Summary Policy changes are often implemented without the assessment of their full environmental impact. We investigate the hydrological effects of changes in forest area triggered by shifts in European agricultural policy, and changes in species composition caused by decisions of regional forest authorities. The scenarios were modelled for the Federal State of Brandenburg (Germany) on a 50 m grid scale using the SWIM (Soil Water Integrated Model) model utilising spatially-explicit land-use patterns.

The results suggest a negative impact of afforestation on abandoned arable land (9.4% total state area) on the regional water balance, causing an increase in mean annual evapotranspiration of 3.7% at 100% afforestation when compared to no afforestation. The relatively small annual change covers a much more pronounced seasonal effect, leading to an increase in evapotranspiration by 25.1% in spring with a strong feedback to other hydrological components. In contrast, a change in species composition in existing forest

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(29.2% total state area) from predominantly Scots Pine to Common Oak decreased the evapotranspiration by 3.4%, accompanied by a much weaker but apparent seasonal pattern. The changes show a high spatial heterogeneity that is masked by a linear mean response for the total state area.

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Introduction

Changes in agricultural subsidies have far reaching consequences not only for the economic structure of agricultural production but also for the environment (e.g. Winter and Gaskell, 1998; Stoate et al., 2001; Berendse et al., 2004; Boellstorff and Benito, 2005). This is particularly true in regions where agricultural production reaches the edge of environmental capacity. Changes in monetary support may lead to abandonment of production on a significant percentage of agricultural land, leading to a change in land-use and consequently in landscape structure. A change in landscape structure has implications for the functions of a landscape and its ability to provide resources (e.g. Zhang et al. (2001) and Brown et al. (2005)). Water supply, especially from groundwater, is a very important resource in many areas of Central Europe (e.g. Berkhoff, 2007; Hattermann et al., 2005, 2006; EU, 2003a). It is therefore essential to evaluate how changes in landscape structure affect hydrology in order to identify potential feedback mechanisms. The Strategic Environmental Assessment Directive (2001/42/EC) focuses on the environmental effects of future plans and programmes, like, for example, the change in subsidies (EU, 2006). An important possible consequence of subsidy change that needs to be evaluated, is the change from agricultural land to forest, since forests have a strong impact on hydrological landscape properties. This impact is caused by a unique combination of high surface roughness, large leaf area and highly effective root systems for water uptake, causing higher evapotranspiration rates in forests compared to other vegetation types under comparable environmental conditions (Lyr et al., 1992; Flemming, 1994; Nepstad et al., 1994; Hutjes et al., 1998; Le Maitre et al., 1999; Feddes et al., 2001; Zhang et al., 2001; Brown et al., 2005; Jackson et al., 2005). Trees also alter the regional runoff characteristics by the temporal interception of rain which reduces peaks in surface runoff, making forests important for water storage, especially during convective rain events (Johnson, 1990; Lyr et al., 1992; Bäeumler and Zech, 1999; Zhang et al., 2001; Niehoff et al., 2002).

In contrast to agricultural production, forestry in Europe is far less regulated by European legislation and therefore decisions are made by regional authorities and stakeholders. However, these decisions interfere with changes in agricultural production at the landscape level and only an integrated analysis can lead to sustainable land-use development.

The Federal State of Brandenburg, Germany was chosen as a case study because it represents a typical example where such changes may take place:

1. Brandenburg is dominated by poor sandy soils, low precipitation and negative climatic water balance during the summer, putting agricultural production at high risk of drought with a high demand for fertilizers and irrigation. The resulting high production costs can lead to an increase in areas that might not be used for agricultural production, and are available for afforestation under changing subsidies. Decreasing groundwater levels in many areas, in turn, restrict irrigation attempts (Gerstengarbe et al., 2003; Landgraf and Krone, 2002).
2. Forests covers 37% of the state area. The predominant tree species (79%) is Scots Pine (*Pinus sylvestris*) which causes problems such as a relative to deciduous species low groundwater recharge rate (Müller et al., 2002; Lasch et al., 2005; Fuerstenau et al., 2007), high risk of forest fires (Thonicke, 2003; Zebisch et al., 2005) as well as pests and diseases such as forest defoliator calamities (Hodar et al., 2003; MLUR-Brandenburg and Senatsverwaltung Berlin, 2002).
3. Due to the critical ecological preconditions, the projected rises in temperatures, as well as the decreasing summer precipitation, increase the risk of summer droughts, making water availability a crucial topic in Brandenburg. Furthermore, climate change could accelerate the process of the abandonment of arable land and further increase the risk of forest fires (Gerstengarbe et al., 2003; Zebisch et al., 2005).

The evaluation of policy-induced land-use changes is a critical issue in the development of sustainable land-use concepts (Wang and Cheng, 2000; Wechsung et al., 2000; Krysanova et al., 2005a,b; Fohrer et al., 2002). The study presented here aims to support the stakeholder/decision maker dialogue by evaluating the ecohydrological consequences of forest management and changes in the agro-economic environment on a spatial basis.

Material and methods

The study area

The Federal State of Brandenburg, which is located in the eastern part of Germany, is characterised by its glacially formed landscape that covers an area of 29,479 km^2. The mineral soils are mostly sandy and sandy loam. The sandy soils are covered by monocultures of Scots Pine, which is the dominant species and covers 79% of the state's forested area with a further 4% and 2% of the region covered by Oak (*Quercus robur* and *Q. petraea*) and Common Beech (*Fagus sylvatica*), respectively. Around 50% of the more fertile area of the state is used for agricultural production (1.339 million ha in 2002), where 77% is under crop production. Fifty percent of the crops are cereals, mainly rye and winter wheat

and 13% oilseeds. The central parts of the country that are dominated by boggy soils with high groundwater levels are mostly under grassland covering 22% of the agricultural land. The climate of the federal state is characterized by the transition from sub-oceanic in the north-western part to sub-continental conditions in the south-east. This climatic gradient is represented in a decrease of annual average precipitation from more than 600 in the northwest to less than 500 mm in the east and south-west and an increase in the annual temperature average and variability from the west to the east. The dominant river system of the state area is the Spree/Havel catchment that drains into the Elbe river at the Havelberg gauge. The Nuthe catchment in the boggy part of the state forms a part of this system as it discharges into the Havel river. A much smaller fraction of the area of the state drains into the Oder catchment and even less in the Neisse and Ucker catchmens. The Stepenitz and Schwarze Elster catchments are part of the state's river system. However, they contribute to the Elbe runoff downstream respectively upstream and separately from the Spree/Havel (LFE, 2000; MLUR-Brandenburg, 2003; Müller-Stoll, 1955; Scholz, 1962).

Modelling procedure

In the first step, the agricultural policy information system for German administrative units (RAUMIS with a resolution of district level based on a non-linear programming approach (Henrichsmeyer et al., 1996)) was used. In RAUMIS total agricultural area (AA) is divided in arable land and permanent grassland. These categories are fixed within the optimization procedure which reflects the required regional constancy of permanent grassland area. Arable crops including set-aside and idling compete for scarce arable land. Four grassland activities are implemented that are characterized by different yields and intensities to produce fodder. Idling of grassland is possible. Interrelationships between arable farming and grassland use occur via fodder production and the joint use of resources.

Regarding the adjustment behaviour of agriculture, profit maximisation is assumed and the optimal production structure is determined for farms within the region. In the applied non-linear setting, the positive mathematical programming (PMP)-Terms (Howitt, 1995) cause an implicit change of marginal costs of the activities dependent on the activity level. This approach ensures smooth adjustment behaviour. PMP-Terms are obtained from the base year calibration and represent not explicitly modelled effects such as nonlinear production function, crop rotation effects, heterogeneity of natural site conditions within model regions and risk aversion (Cypris, 2000).

RAUMIS takes into account the EU Common Agricultural Policy instruments such as production quotas, direct payment schemes, decoupling, set-aside, livestock densities, minimum farming and agri-environmental requirements. Currently, the model comprises indicators such as fertilizer surplus (nitrogen, phosphorus and potassium), pesticide expenditures, a biodiversity index, and greenhouse gas emissions. These indicators help to evaluate direct and indirect environmental impacts of policy driven changes in agricultural production.

The district level land-use trends were translated into a land-use pattern utilizing the PAGE-tool (pattern generator). PAGE disaggregates RAUMIS scenarios on district level to spatially-explicit raster maps of future land-use, applying a combination of rule-based and statistical approaches. First, a pixel wise suitability assessment for each respective land-use type is performed. Suitability is calculated as a function of natural conditions (soil quality, groundwater level, slope, and climate), spatial attributes (distances) and land-use restrictions (nature reserves). Second, the amount of land-use changes in comparison to current land-use is identified. And third, land-use change is allocated based on the current land-use map and the suitability assessment.

The resulting land-use map with 50 m raster resolution was the basis of the simulations of the eco-hydrological model SWIM (Soil Water Integrated Model). The SWIM model is described in detail in the SWIM model section. The SWIM model was used as the last element in the cascade of models to derive the spatial response of the eco-hydrological condition as affected by changes in the land-use pattern. The results of the simulations are displayed as a set of landscape response maps and functions.

Scenario definition

Based on the specific conditions of the state, we assumed two scenarios to be critical for future development. In the first scenario, the external driving force causing a change in the landscape structure is the reformation of the EU-Common Agricultural Policy (CAP) termed here the ''partial liberalisation scenario''. We assume this to be a plausible cause for changes for two reasons beyond those outlined above:

1. Firstly, rural cooperatives manage great areas (30% of the farms are greater than 100 ha (LDSP, 2005a)). These cooperatives are able to temporally set aside or fully cease production in large areas to optimize their production. On the other hand, if the large cooperatives stop production (due, for example, to insolvency) great areas may be permanently set aside. Both situations increase the probability of potential loss of agricultural area, which is then available for afforestation.
2. Secondly, a declining and aging population in peripheral regions leads to a loss in the qualified workforce (LDSP, 2005b) which may cause a loss of agricultural production and increase set-aside land.

Scots Pine had become dominant since the forest management of the last century focused on industrialised wood production, neglecting other services like groundwater recharge and biodiversity (Senat Berlin, 2006). Today, the central aim of the governmental forest management authority is to shift to mixed and deciduous forests that reflect the local environmental conditions. The target date for completion of the conversion is 2045, where an increase of deciduous tree species from 16% (1996) to 19% and of mixed stands from 14% to 37% will be achieved (LFE, 2000). We examined the consequences of even more ambitious targets for forest conversion of all pine forest to deciduous species, and investigated the landscape response.

Scenario I: partial liberalisation
As the name of the scenario indicates we assume only a part of the subsidy system to be more liberal. In this scenario, we suppose direct payments to stay in place but without any regulations like cross-compliances. Cross-compliance, in the case of European subsidies, is the principle that farmers need to comply with environmental protection requirements as a condition for benefiting from market support (EU, 2004). We also assume no further support will be available for cereals, milk, and beef prices. The scenario is based on elements of the mid-term-review (MTR) of AGENDA2000 (EU, 2003b) but does not explore the full spectrum of the landscape responses regarding changes in the European subsidy system. The reference scenario is a projection of agricultural production until 2010 under unchanged Agenda 2000 policy.

The results of the scenario simulated by the RAUMIS model is a dramatic shift in agricultural production, resulting in an increase in fallow land from 16.6% in the reference scenario to 47.3% for the total state agricultural area in the 'partial liberalisation'. This complete shift of production to favourable areas allows profitable production. A price increase of 1.5% for wheat (*Triticum aestivum*) but a decrease of the rye (*Secale cereale*) price by 19% in comparison with the reference scenario was assumed by the model in 2010. Relative to other states, rye comprises a high proportion of Brandenburg's cereal production. Thus, the decrease in rye areas reaches 67.1%, which contributes to an increase of set aside of 13.5% compared to the reference scenario. The second largest influence, with 4.3% of set aside land is related to a decrease in oil seed production by more than 73.4%. Thirdly, production in fodder maize (*Zea mays*) decreased by 37.2%, leaving 2.2% of arable land out of production. The remaining 10.7% contributing to the scenario prediction of 47.3% of set aside land, are evenly scattered over the other crops production types.

Because of the missing redirection of subsidies to maintain the rural landscape we assumed it will not be possible to compensate costs for landscape conservation and consequently parts or all of the set aside areas will fall into full cessation of farming and afforestation, or natural succession will take place.

Scenario II: forest management
Decades of preference for Scots Pine as the main tree species has resulted in 33% of monoculture pine forests growing on land that could potentially be used for deciduous and mixed stands. Using the governmental targets to change this situation to a more natural forest distribution, the scenario for the simulations leads to a stepwise shift from pine forest-dominated to 100% deciduous tree species. The spatial distribution for the base year was obtained from the biotope mapping. Then forest areas under Pine were converted to Oak in discrete 10% steps using the PAGE algorithm (Zebisch, 2003). Each of the resulting land-use datasets were then simulated separately using the SWIM model and the results were transferred to GIS for analysis.

Spatial data

The forest data were obtained from a biannual report published by the Federal Forest Agency (LFE, 2000). The forest data include average ages, DBH (diameter at breast height) and average stand volumes for the dominant tree species, Scots Pine and Oak, for the state area. The management information was taken from yield table data (Schober, 1987) assuming an average management regime for mean stand conditions for the area. Based on this information age distribution was classified using the biotope map provided by the Federal Environmental Agency (Landesumweltamt Brandenburg). The high resolution of this map was aggregated to the SWIM land-use classes, namely evergreen forest, deciduous forest and wetland forest. Soil information was obtained from a national agency for geo-sciences and resources (Bundesanstalt für Geowissenschaften und Rohstoffe) with a scale of 1:1,000,000 together with soil profile descriptions, providing the basic physical characteristics such as saturated conductivity and bulk density for 72 different soil types. Soil quality was based on a map in a 1:200,000 scale with seven classes (Brandenburger Ministerium für Umwelt, Naturschutz und Raumordnung).

An interpolated groundwater level map was used to initialise the groundwater model of SWIM, in order to take areas with groundwater levels above 2 m in consideration.

The digital elevation model which was supplied by federal land surveying office (Landesvermessungsamt) was aggregated to a 50 m grid resolution from a 25 m grid resolution.

The climate data observations were gathered from stations of the German Weather service and they were interpolated for the individual sub-basins using the inverse distance method based on the Euclidian distance between climate stations and centre point of the sub-basin.

The SWIM model

The SWIM model was used for the study because of its suitability for simulating the annual growth of natural vegetation, as well as a wide range of crops, and their hydrological interactions under current and future climate change conditions (Wechsung et al., 2000; Hattermann et al., 2004; Hattermann et al., 2005; Krysanova et al., 2005b; Wattenbach et al., 2005; Hattermann et al., 2006). It has been evaluated in various catchments within the landscape of the federal state to adapt the parameterization and process description to lowland conditions (Hattermann et al., 2004; Hattermann et al., 2005; Krysanova et al., 2005a; Wattenbach et al., 2005; Wechsung et al., 2000) and to enable us to employ it on administrative units instead of catchment boundaries.

The SWIM model was developed to simulate hydrology and water quality in river basins from 100 to 10,000 km^2 in size. It integrates hydrology, erosion, and nutrient dynamics at the watershed and regional scale. It follows a three level disaggregating scheme 'basin—sub-basin—hydrotope' and is coupled to the Geographic Information System GRASS (Neteler and Mitasova, 2007). A hydrotope or HRU (hydrological response unit) is defined by its unique combination of sub-basin, land-use and soil type (Krysanova and Müller-Wohlfeil, 1998). The vegetation growth is computed at this spatial level with a daily time step using a simplified version of the EPIC (Erosion Productivity-Impact Calculator) model (Williams et al., 1983). The EPIC version in SWIM does not in-

clude a forest model able to simulate forest water cycle interactions under the environmental conditions of the federal state. It was therefore extended by a more appropriate forest growth model by Wattenbach et al. (2005). The central element of the implemented forest module is an allometric relation for the ratio of leaf biomass to total biomass, given by an age-dependent exponential function. A forest stand is initiated for all hydrotopes as uniform, with an initial total above-ground biomass value and age. The above-ground biomass is calculated based on inventory data using the total stand stem volume to compute the woody biomass and the DBH to estimate the leaf biomass. All implemented approaches are discussed in detail by Hattermann et al. (2004), Hattermann et al. (2005), Krysanova and Müller-Wohlfeil (1998) and Wattenbach et al. (2005).

Applicability of the model

Table 1 shows a compilation of model results based on previously published studies (Hattermann et al., 2004; Habeck et al., 2005; Hattermann et al., 2006). The catchments represent typical lowland or mixed (lowland/loess) landscapes within or neighbouring the federal state. The results demonstrated the applicability of the SWIM model to simulate the long term water balance and dynamic for the landscape under study, and enabled us to use the parameterization for the appropriate model runs. Although the agreement is satisfying there remains a degree of uncertainty because of the discharge of brown coal mining water into the Spree river in the corresponding time period (Wechsung et al., 2000) as well as unrecorded small scale water management activities (Hattermann et al., 2006). The additional runoff from brown coal mining would be of an average 14 mm for the long term average at the Havelberg gauge (BMBF, 2002). However, Wattenbach et al. (2005) could demonstrate that the model reproduces the long term water balance at the Havelberg gauge, which covers most of drainage from the state's area reasonably well. As the aim of the study presented here was the representation of the long term water balance and its components we assume the model performance to be sufficient.

Application of the SWIM model for the state area

In order to run the SWIM model on the area of the federal state, the definition of sub-units was necessary. We used landscape units (Scholz, 1962) instead of sub-basins as they integrate not only hydrological aspects but also additional features like soils, geomorphology and biotope composition, which are all relevant for the subject of study. In the next step within each landscape unit, the hydrotopes were defined based on their unique combination of soil and land use. The resulting hydrotope map was then combined with the groundwater map to define the initial average ground water level. Each hydrotope was assumed as a homogenous tree stand unique in tree species, stand age, and initial biomass. Based on the age class resolution of the forest inventory data the new forest in the ''partial liberalization'' scenario had to be initialized as 15 years old with an initial mean biomass of 28,880 kg/ha for pine and 13,683 kg/ha for oak, respectively. The ''forest management'' scenario followed the same concept except we used the current age class distribution for the transformed deciduous forest to mimic the behaviour after one rotation period. The model was run using climatology for every sub-basin for the period 1951–1998.

Results and discussion

Results are plotted as graphs showing mean values in all cases and, if meaningful for the identification of processes, additional temporal minimum and maximum values. Values in all graphs are the average over the entire simulation period. These types of graphs are described by the term ''response function''. Response functions show the integrated

Table 1 Efficiencies (Nash and Sutcliffe, 1979) of observed against simulated monthly river discharge and the discharge balance (relative difference of simulated and measured discharge) for an 8 and 6 year period, respectively, for catchments within or covering parts of the Federal State of Brandenburg (1981–1988, *1981–1986)

River	Gauge station	Topography	Area [km^2]	Efficiency monthly	Difference in discharge [%]
Results of the calibrated model					
Spree	Bauzen	Mountains/loess	280	0.71	1
Löcknitz	Gadow*	Lowlands	447	0.82	−1
Stepenitz	Wolfshagen	Lowlands	574	0.86	−1
Jeetze	Luechow	Lowlands	1347	0.72	1
Nuthe	Babelsberg	Lowlands	1993	0.66	0
Saale	Calbe-Grizehne	Integrates all	23,687	0.87	−1
Elbe	Neu-Darchau*	Integrates all	80,258	0.94	−1
Results of the model in the validation period					
Loecknitz	Gadow*	Lowlands	447	0.81	6.6
Elbe	Neu-Darchau*	Integrates all	80,258	0.94	4.0
Nuthe	Babelsberg#	Lowland	1993	0.63	6.0

The first part of the table shows results of the calibrated model whereas the second part presents examples of validation runs 1987–1992, respectively, #1989–2000 (Hattermann et al., 2005, 2006).

sensitivity of a landscape to an external driving force (Zebisch et al., 2004). The maps represent the difference of the baseline simulation to the 100% implementation of the scenario. All values are averages over the total area of Brandenburg, or landscape unit area, respectively, integrating all land-use classes. The response in evapotranspiration within the maps has been classified based on the three dominant landscape attributes of the state, groundwater dominated areas (class I), soils with low fertility dominated by forests (class II) and fertile not groundwater influenced (class III). Class I is defined by a mean groundwater level for the unit above the mean over all units in the federal state. Class II contains all landscape units with soil quality lower than the average over all units in the state and with groundwater levels equal or below the mean for all units and with a higher percentage of forest than the mean for all units. Class III are all units with groundwater levels equal to, or below, the mean and fertile soils.

Scenario I: partial liberalization

The increase in forest area changes the mean annual water balance of the federal states total area by an increase in evapotranspiration (Fig. 1). Evapotranspiration as the largest efflux component of the regional water balance changes only slightly from 0.53% (10% afforestation) to 3.7% (100% afforestation) in the annual average over the entire simulation period.

This change, however, has a strong influence on the other components of the water balance, changing mean annual groundwater recharge from −1.4% (10% afforestation) to −9.8% (100% afforestation), and average annual runoff from −1.2% (10% afforestation) to −4.8% (100% afforestation), respectively.

In this case the comparison of the mean values does not reveal the full picture. If we consider the change in average annual minimum groundwater recharge a much more pronounced effect from −4.0% to −29.4% can be observed. The increase of forest area has only a moderate impact on the mean annual runoff. It does, however, alter the peak flow (maximum runoff) dramatically (up to −19.9%) (see Figs. 2 and 3).

The picture changes if the seasonal pattern is taken into consideration. The change in the annual mean is caused by a strong increase in evapotranspiration by 25.1% (100% afforestation) in spring (March–June), which is partially offset by a decrease in evapotranspiration of −6% over summer and autumn.

The analysis of the average monthly values (Figs. 4–6) underlines these findings as a slight change of evapotranspiration in spring (Fig. 4) causes more pronounced changes in the other hydrological components (Figs. 5 and 6). This seasonal pattern is important, as spring has the highest amounts of rainfall and is therefore essential for groundwater recharge (Fig. 7). Although the reaction of the groundwater component shows a time lag, caused by the transfer time the water needs to reach the aquifer from the surface, the reaction is clearly visible and dominant over the entire year. Quite crucial in this matter is the fact that the time lag causes the strongest decrease in recharge in mid summer where the water demand of the vegetation becomes critical as the soil water storage capacity becomes close to exhaustion. Thus, the lack in recharge can increase the severity of summer droughts by decreasing groundwater levels to such an extent that plant water uptake is impaired.

Overall, the aggregated response functions for the total state area show a smooth and almost linear response. However, this is masking a very heterogeneous response on the landscape unit level (Fig. 15). The response at this level can be classified in three categories. Class I incorporates most areas with the strongest response to the scenario as the class integrates lowland areas with a higher percentage of high groundwater levels (2.0 m below surface and above) than the average for the other units of the federal state.

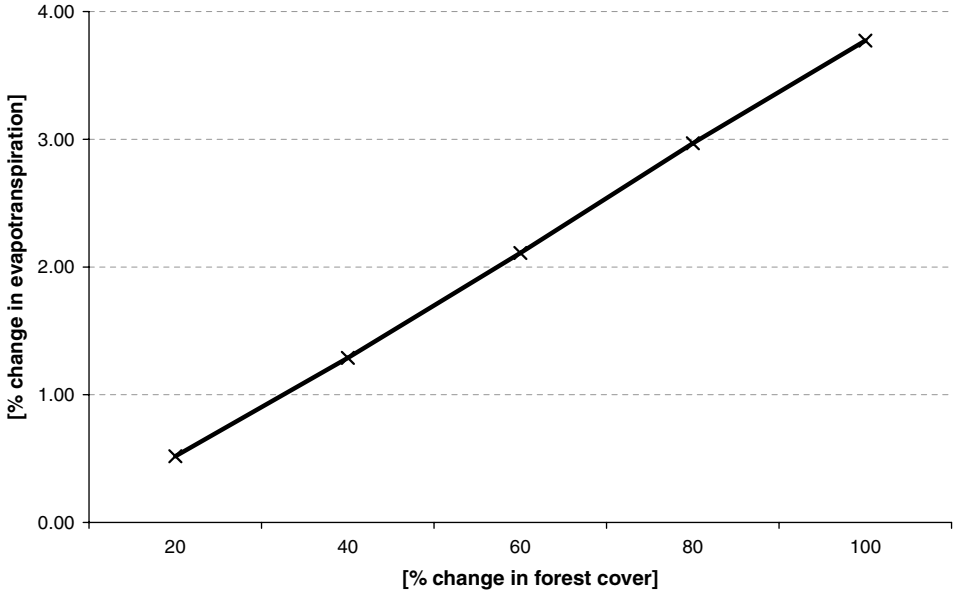


Figure 1 Change in the annual sum of evapotranspiration caused by an afforestation of ceased land in the ''partial liberalisation scenario'' for the total state area.

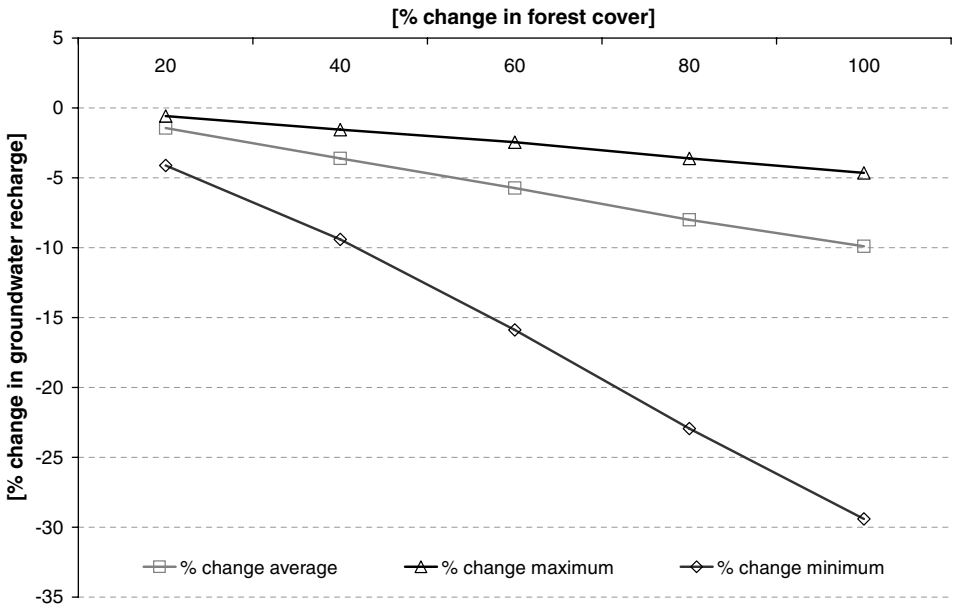


Figure 2 Change in the annual sum of groundwater recharge caused by an afforestation of ceased land in the ''partial liberalisation scenario''.

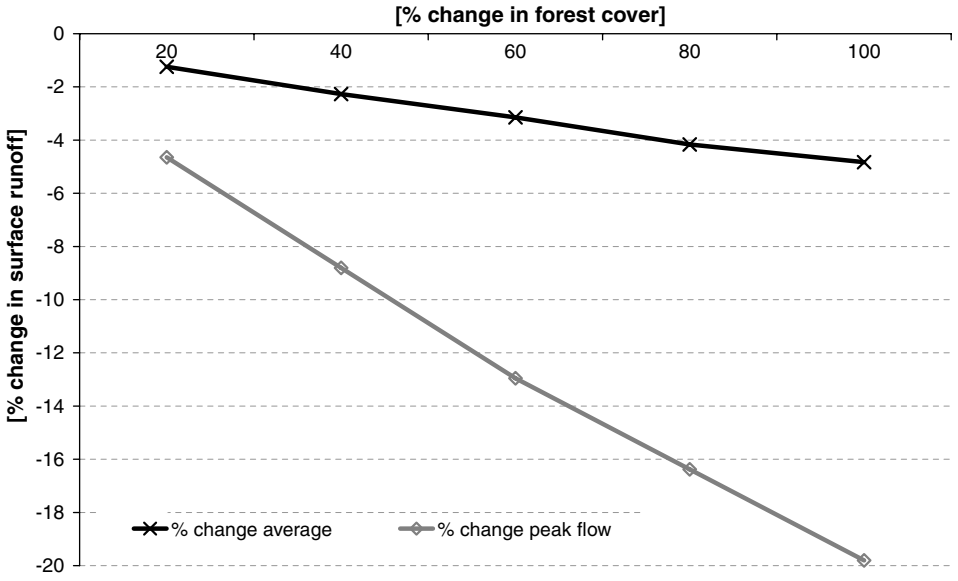


Figure 3 Change in the annual sum of runoff caused by an afforestation of ceased land in the ''partial liberalisation scenario'' for the total state area.

In these areas, trees are able to access the capillary rising zone of the shallow aquifer. The shift from fallow to forest increases evapotranspiration by up to 33 mm causing a reduction in runoff and groundwater recharge in a rather dramatic way. They are also areas where conversion takes place within the first steps of transforming agricultural land into forest as the high groundwater levels make them unsuitable for agriculture. However, their response is also highly correlated to the percentage of convertible land (fallow) on groundwater influenced soils. As an example, the area labelled ''1'' in Fig. 15A is groundwater influenced (class I), however, they belong to the boggy lowland areas where most of the peat soils are under grassland. Class II aggregates areas with dry sandy soils and lower soil fertilities than the states average. These areas are critical for the change in groundwater recharge as the low soil quality leads to a fast conversion into forest. The process is accelerated as these areas are rich in forest in the base year and conversion starts from the edges of these forests. Additionally, the corresponding forest class is pine forest, inducing an increase in interception of precipitation thus more evapotranspiration takes place and less groundwater re-

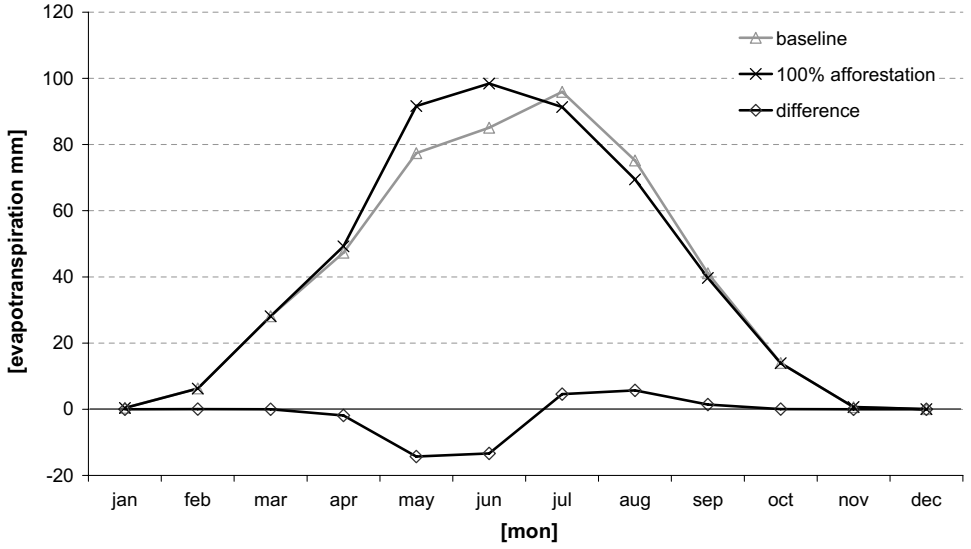


Figure 4 Change in the monthly average evapotranspiration (50 years) caused by an afforestation of ceased land in the ''partial liberalisation scenario'' for the total state area.

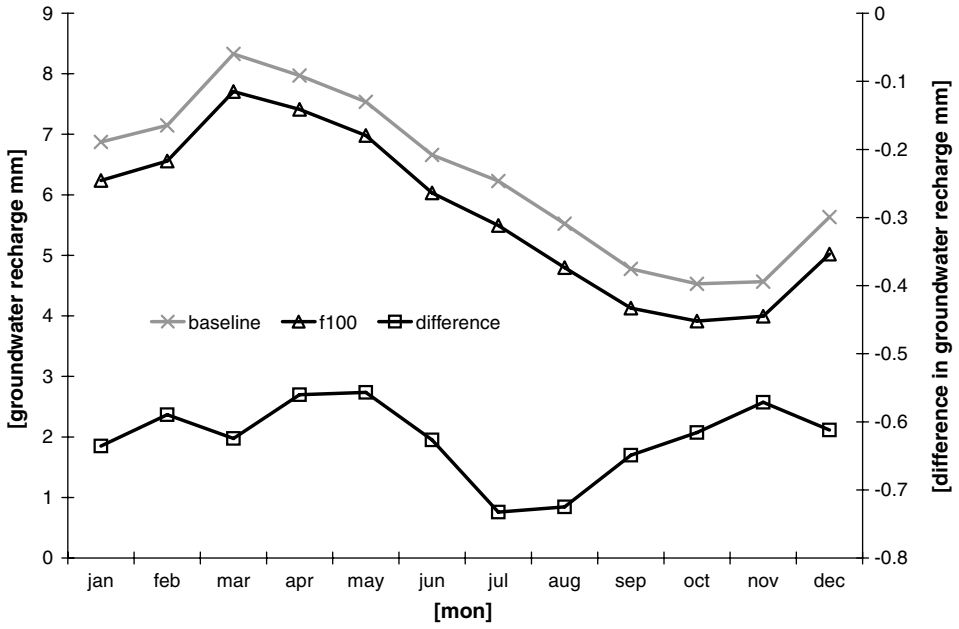


Figure 5 Change in the monthly average groundwater recharge (50 years) caused by an afforestation of ceased land in the ''partial liberalisation scenario'' for the total state area.

charge. However, as these areas already have a high percentage forest cover, their aggregated response on the landscape unit level is not very pronounced due to the lack of convertible land (e.g. Fig. 15: label 2).

Less crucial, and aggregated in the third class, are areas with good and moderate soil conditions (soil quality above the mean of all landscape units). They react only in the late phase of conversion when they are transformed into deciduous forest allowing water to drain into the aquifer during spring. Although the classes are not exclusive it is possible to categorize the complexity of the landscape response and to identify sensitive areas for land-use change impacts.

The review of Brown et al. (2005) allows us to relate the presented results to a global picture. Their review of global paired catchments studies confirms our qualitative results that an increase in forest area reduces the water yield within a catchment. It also reveals that the order of magnitude for our study is within the range of these experiments. Brown et al. (2005) cite the study of Bosch and Hewlett (1982) who compared the results of 94 experimental catchments situated in different regions of the world. Their estimated response of maximum water yield in the first 5 years for a conversion from non-woodland to coniferous types is 40 mm per 10% conversion and 25 mm for deciduous species,

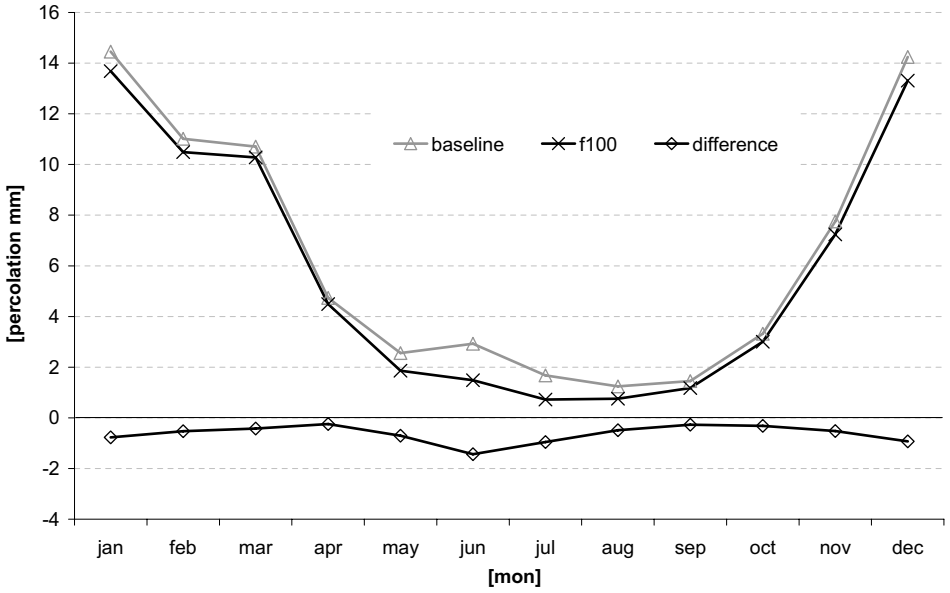


Figure 6 Change in the monthly average percolation recharge (50 years) caused by an afforestation of ceased land in the ''partial liberalisation scenario'' for the total state area.

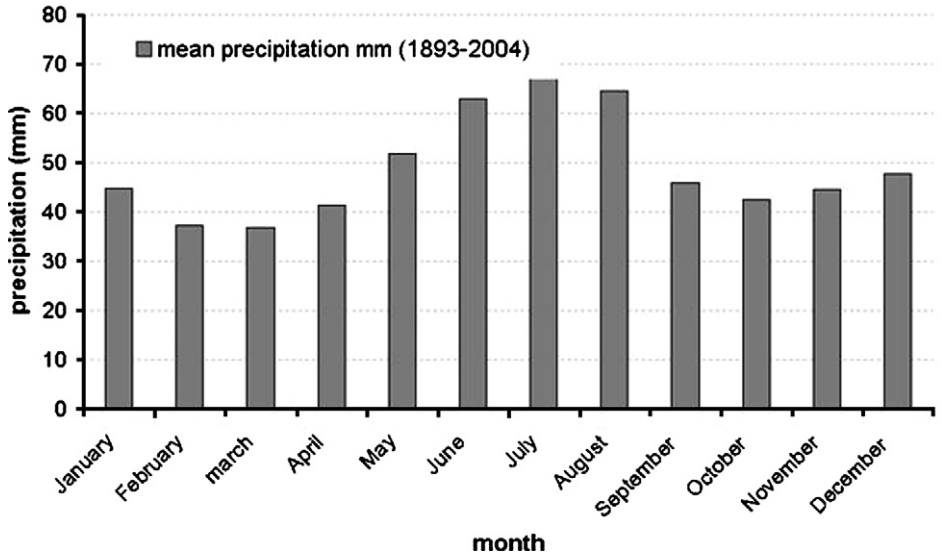


Figure 7 Average monthly precipitation for Potsdam (PIK, 2006). The highest precipitation values are observed in spring and early summer.

respectively. The SWIM simulations yielded a change of 16.5mm for the five year mean of the monthly maximum per year. If we consider only the five year mean, the change is 21.5 mm compared to the simulation with full afforestation of all ceased land which corresponds to 9.4% of the total state area. However, Brown et al. (2005) also conclude that the time period of 5 years used by Bosch and Hewlett (1982) is too short to show the full impact of a vegetation change as the new equilibrium state might be reached much later. They also argue that the use of the maximum leads to a high bias as a result of climate variability. The reviewed findings also agree with our results for the seasonal pattern of change. They summarize that for winter rainfall dominated catchments, the reduction in summer flow is proportionally much larger then in winter as we also see in our results.

Farley et al. (2005) demonstrated a quite conservative ratio of 14—15% for the change in runoff if it is expressed as a percentage of mean annual precipitation (MAP). The MAP for the Federal State of Brandenburg over the simulation period is 612 mm. The mean annual runoff for the area is 160 mm for the base line and 143 mm for the full afforestation of fallow, respectively. This is a difference of 2.8% if we relate the two runoff values to the MAP. The total area of the state which is affected by the change is 9.4%. The Farley et al. (2005) numbers are based on a change on 75%

of the catchments area. This gives a ratio of 7.9 to scale our scenario to 75% if we assume a linear trend as in Farley et al. (2005). If we now multiply 7.9 with the change of 2.8% it yields 22.1% which is relatively close to the values reported by Farley et al. (2005). The difference to the Farley et al. (2005) numbers might be explained by the fact that we changed from cropland directly to forest and not like in the catchments under study in Farley et al. (2005) from grass or scrubland into forest. Croplands are reported to have lower evapotranspiration rates than perennial vegetation (Larcher, 1994).

The main uncertainty in this study originates from the predicted landscape pattern and its interaction with the SWIM model. Zebisch et al. (2004) clearly showed that environmental conditions are not solely responsible for the distribution of landscape elements, but historical and current social conditions are important drivers as well. There may be a number of areas that we are identifying to be vulnerable, which may stay in production because of local economic or social reasons. Zebisch et al. (2004) showed that the pattern generator (PAGE) could reproduce the current land use with a spatial correlation of 0.7. Thus, we could assume the same accuracy/precision for future land-use patterns. However, the effect of the propagation of this uncertainty trough the SWIM model was not the subject of this study. The second source of uncertainty is the process description in the SWIM model itself. As we explained in section ''Applicability'', the model is robust in reproducing the hydrological properties, however, a landscape scale evaluation of other nonhydrological components was not part of this study.

Scenario II: forest management

The effect of the conversion of pine forests into deciduous forests is in the same order of magnitude as the ''partial liberalization'' scenario although it covers a greater area of conversion. In the forest scenario 29.2% of the total state area are converted from pine dominated forest to oak forest whereas only 9.4% of the total state area are converted from agricultural land to forest in the liberalisation scenario. The relative average aggregated response of the state shows a clear decrease in evapotranspiration by up to −3.44% at 100% conversion of pine to deciduous forest (Fig. 8). This clearly influences the runoff (+2.00%) (Fig. 9), as well as the groundwater recharge (+4.8%) (Fig. 10). The opposite occurs if the proportion of deciduous dominated forest is reduced to 20% where evapotranspiration increases slightly. The change in groundwater recharge (Fig. 9) shows a clear pattern where the increase in minimum recharge is stronger than the increase for the mean or maximum. This is a clear effect of the lower water interception storage of deciduous tree species which combined with a higher proportion of stem flow makes relatively small rain events more effective for recharge than evergreen cover. It also shows that a change towards deciduous species has exactly the opposite effect as the ''partial liberalization'' scenario and may compensate for part of its effects. There is, however, no change in peak flow although the transition towards deciduous species increases the mean surface runoff.

The results of the monthly averages (Figs. 10—13) show a similar picture in their seasonality if compared to the results of the ''partial liberalization'' scenario. However, the seasonality is less pronounced where the largest differences in the scenarios are between March and June when deciduous trees unfold their leaves. The scenario with a conversion to 100% deciduous trees exhibits a higher recharge than the base line run. The time lag in the reaction is again persistent leading to the difference in recharge from June to August.

The spatial analysis (Fig. 16) of the data shows a high spatial heterogeneity, similar to the ''liberalisation-scenario'' with a standard deviation of 11.2 and 12.1, respec-

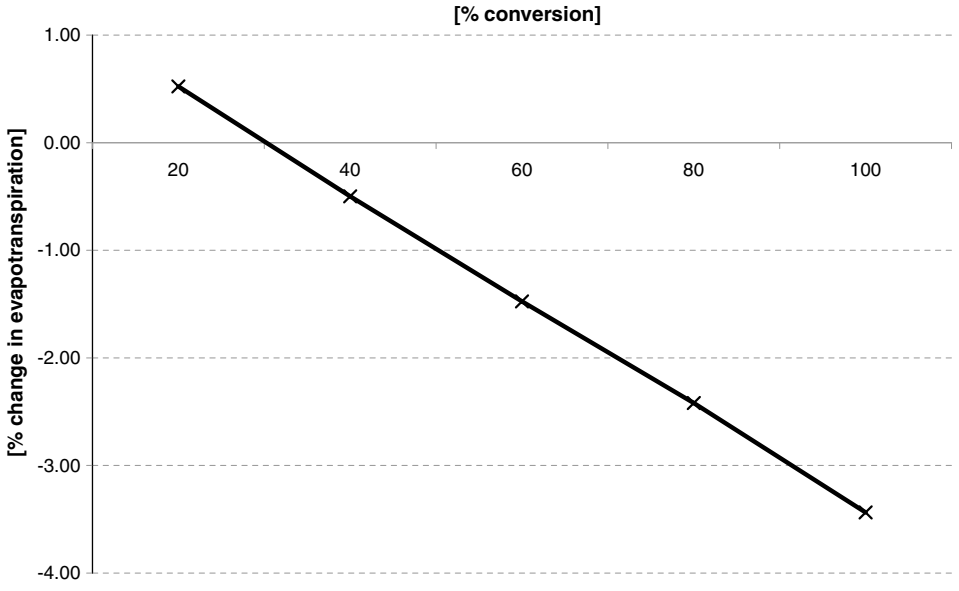


Figure 8 Change in the annual mean sum of evapotranspiration caused by an transformation of Scots Pine forest to Common Oak forest in the ''afforestation scenario'' for the total state area.

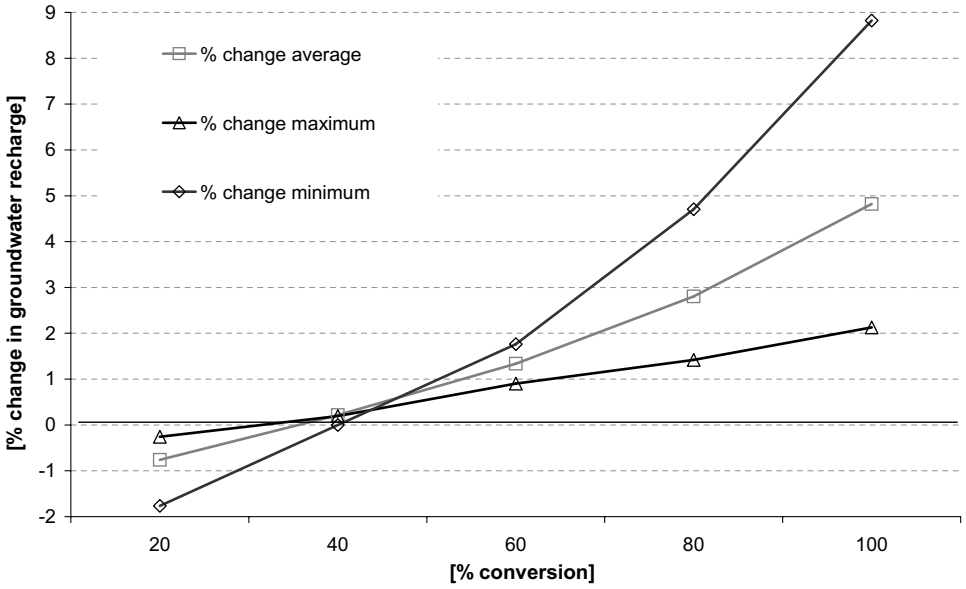


Figure 9 Change in the annual mean sum of groundwater recharge caused by an transformation of Scots Pine forest to Common Oak forest in the ''afforestation scenario'' for the total state area.

tively. In this case, the most sensitive areas are obviously those with a high percentage of forest where pine is the dominant species, which implicitly results from the scenario assumption (see detail Fig. 16 inset D and Fig. 14). However, only 60.8% of the variance is explained by the percentage of pine forest, which is clearly an effect of the aggregation to landscape units but also represents the effect of the soil type and groundwater access of vegetation.

The results are in good agreement with extensive measurement campaigns by Müller et al. (2002) which show the impact of pine monocultures on the water balance in forest stands and the increase in groundwater recharge by transforming them to deciduous forest types. If we compare the results with the compilation done by Brown et al. (2005) we find our results in good agreement. They are referring to the work of Sahin and Hall (1996) who analysed 145 catchments from different regions of the world comparing them based upon their dominant vegetation. They used the 5 year mean of change to compare the different catchments. They conclude that a reduction of forest to non-forest vegetation leads to an increase of water yields of 20–25 mm for evergreen and 17–19 mm per 10% for deciduous species. In our study we changed from evergreen to deciduous which should lead to a change between 3 mm and 6 mm according to those findings. For a change on 29% of the total area the predicted change would be between 8 mm and 16 mm. Therefore, our simulated change of 3.1 mm is clearly lower than these predicted changes.

The main uncertainty for the results of the second scenario results from the restricted process resolution of the SWIM model concerning forest structure and ground vegetation. We are assuming only one forest type for each land-use class and ground vegetation is taken into account only as additional interception storage. A number of regional studies gave clear evidence that the type of ground vegetation especially in Scots Pine stands is a major factor for the water balance (Lützke, 1991).

Policy implications

In general, we can conclude that the situation in Brandenburg is comparable to other regions with low climatic water balance (Brown et al., 2005). In such regions, precipitation and evapotranspiration are highly correlated (Zhang et al., 2001) and water is a limiting factor for growth. Most of the water is lost to the atmosphere by transpiration, and only a small amount contributes to runoff and groundwater recharge (Badeck et al., 2004). Based on this environmental precondition any land-use change that increases the forested area will increase evapotranspiration and decrease groundwater recharge. This needs to be considered if subsidy systems are changed like those in the ''partial liberalization'' scenario. In the study presented we assumed no cross-compliance, which implicitly showed the necessity of such measures. Under the specific condition of the federal state of Brandenburg a strictly economically oriented scenario leads to a very high percentage of up to 47.3% of abandoned land. If no monetary support is allocated to keep this land managed, like in Europe by cross-compliance, the probability of a stepwise afforestation as assumed in the ''partial liberalization'' scenario is very high. As the low amount of rain, limiting agricultural production, is one of the main reasons for the high percentage of ceased land, this conversion from agriculture to forest can interact with the environmental conditions and lead to a feedback mechanism as we see a decrease in groundwater recharge caused by the interaction of forested areas with low precipitation.

Groundwater recharge is an important environmental service as the groundwater levels in the state are already decreasing (Landgraf and Krone, 2002) or are at risk to decrease in future (Gerstengarbe et al., 2003; Zebisch et al., 2005). Therefore, we can conclude that cross-compliance is a necessary measure in such a region where agricultural production is at the limits of the environmental capacity.

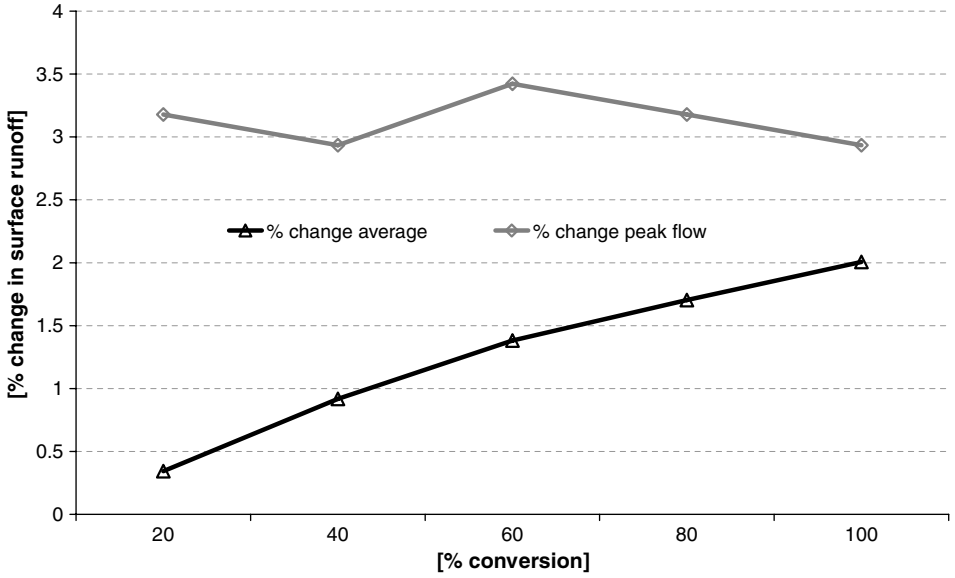


Figure 10 Change in the annual sum of runoff caused by an transformation of Scots Pine forest to Common Oak forest in the ''afforestation scenario'' for the total state area.

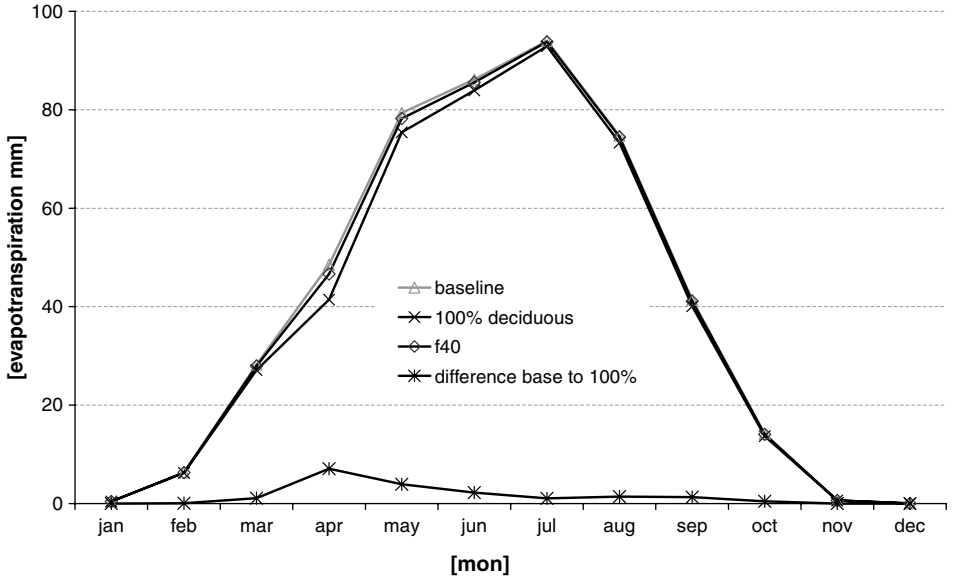


Figure 11 Change in the monthly average evapotranspiration (50 years) caused by an transformation of Scots Pine forest to Common Oak forest in the ''afforestation scenario'' for the total state area. ''f40'' represents the nearest approximation of the target of regional forest authorities if we consider mixed forest as deciduous dominated.

If we consider future Climate Change effects, the picture becomes even more evident. The predictions for the federal state are a further increase in summer dryness (Gerstengarbe et al., 2003; Zebisch et al., 2005). Therefore, a decrease in agriculture production will enforce the above-mentioned feedback by increasing the percentage of fallow land leading to increasing forest areas that decreases groundwater recharge. In particular, the regional pattern of set aside land need to be in the focus of directing cross-compliance. Areas forest cover is already high and/or with high groundwater levels are particularly sensitive to change. This indicates a necessity to direct the subsidies in such regions to prevent a further enforcement of the mentioned feedback. If we take into account that these regions already have low population density and if the population decreases further (LDSB, 2005b) cross-compliance could be an important way to provide income to the rural community to maintain the current landscape pattern.

A further important aspect is related to the Kyoto Protocol as it allows the use of forestry related activities to meet the carbon sequestration commitments (Noss, 2001). If we assume an afforestation of ceased arable land would be counted as a potential carbon sink (Post and Kwon, 2000) the probability of our scenario assumption ''more forested

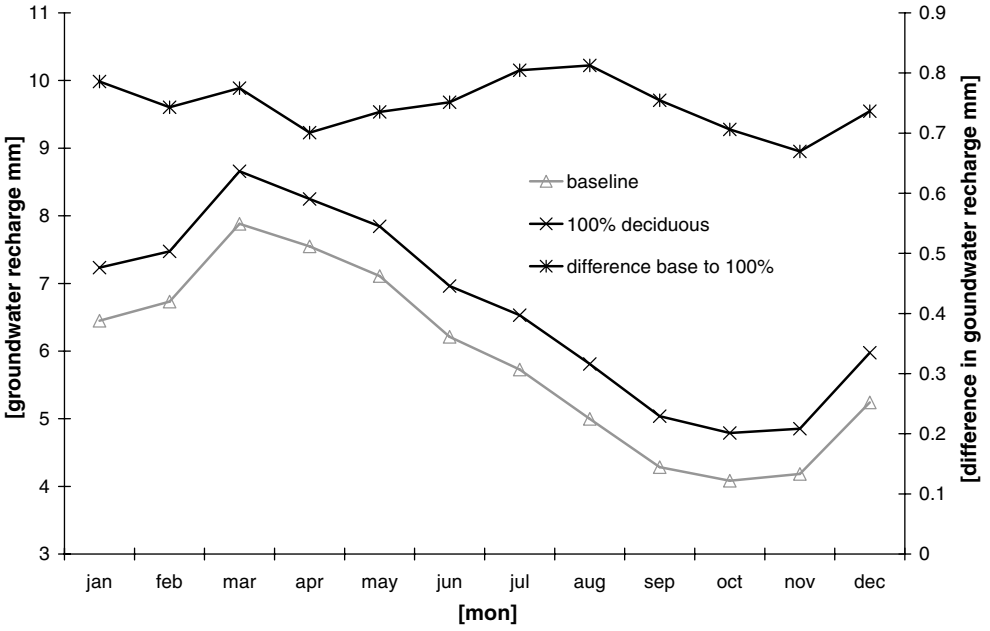


Figure 12 Change in the monthly average groundwater recharge (50 years) caused by an transformation of Scots Pine forest to Common Oak forest in the ''afforestation scenario'' for the total state area.

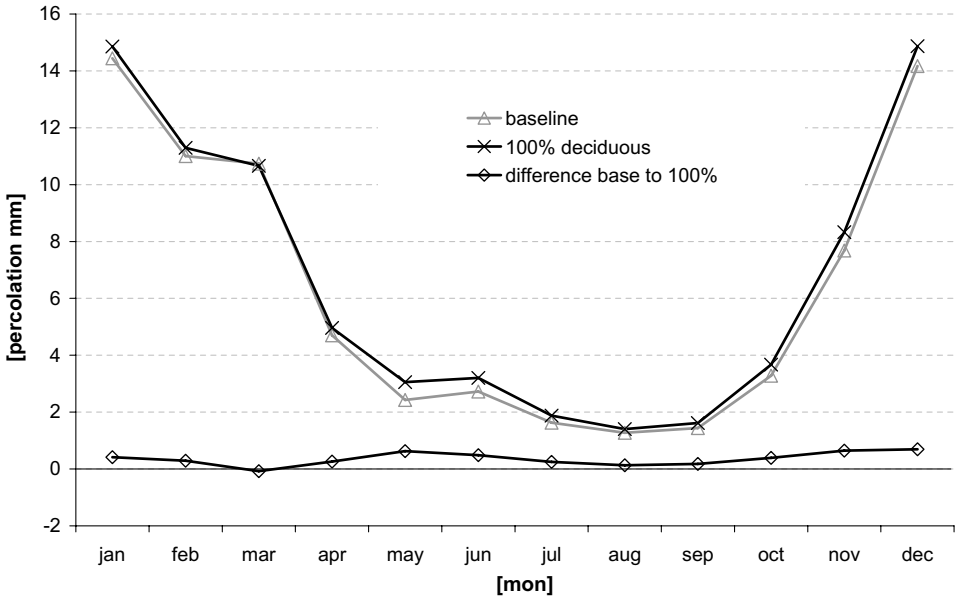


Figure 13 Change in the monthly average percolation (50 years) caused by an transformation of Scots Pine forest to deciduous forest in the ''afforestation scenario'' for the total state area.

area'' increases. However, as we showed, the result would be a loss in groundwater recharge that might contradict the sink function by falling groundwater levels exposing organic soils to decomposition. Therefore, a balancing of the two forest functions is necessary (Jackson et al., 2005).

The second scenario ''forest management'' provides us with the second important conclusion. The scenario clearly shows that legal measures introduced by regional forest authorities to support natural tree composition can also improve an essential public service like groundwater recharge. This service is especially significant under the specific environmental conditions of Brandenburg. It becomes even more important if we look at the predicted climatic development where groundwater recharge becomes more important as the climatic water balance gets smaller (Gerstengarbe et al., 2003; Zebisch et al., 2005). The effect of the ''partial liberalization'' scenario could be partly compensated by a change in tree species composition. However, as we could show the spatial distribution may contradict some of this compensating effect as the areas of the

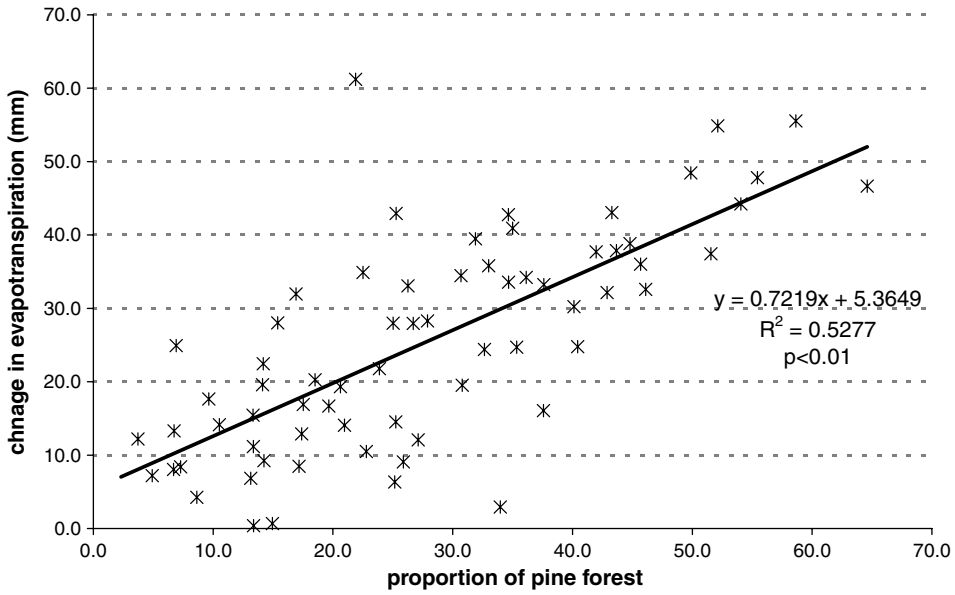


Figure 14 Correlation of proportion of Scots Pine dominated forest in the baseline scenario and change of evapotranspiration during conversion to Common Oak forest averaged for landscape units in the ''afforestation scenario''.

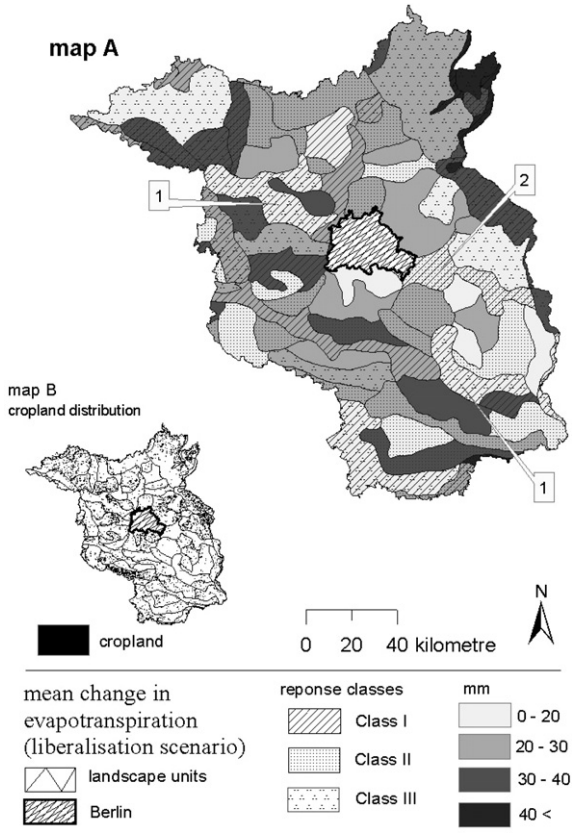


Figure 15 Map A — Effect of the ''Partial Liberalisation'' — scenario on the change of evapotranspiration for the total area of landscape units. The Class I integrates areas with high groundwater levels. Class II covers areas with low soil fertility and high percentage of forest. Class III are the remaining areas with good soil quality and low forest percentage. Inset map B — cropland areas.

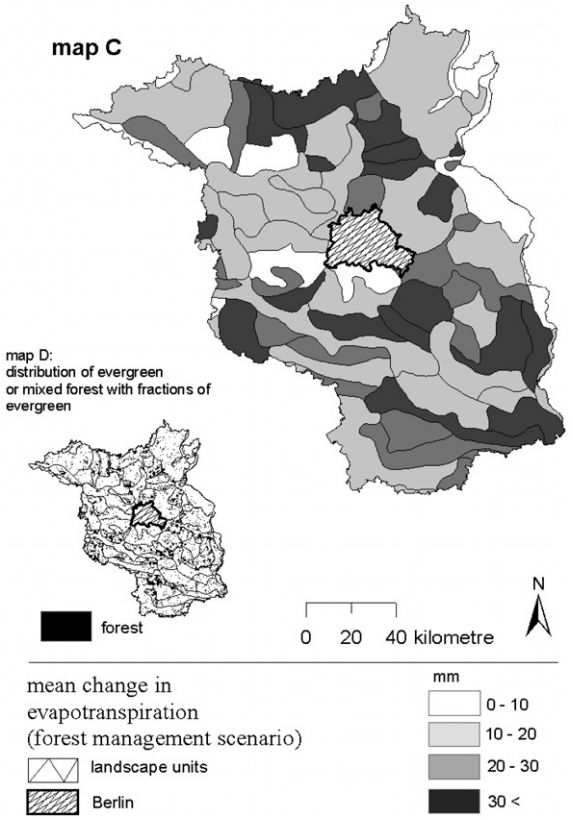


Figure 16 Map C — Effect of the ''Afforestation'' — scenario on the change in evapotranspiration for the total area of landscape units. Inset D shows in detail the areas of Scots Pine dominated forests underlining the causality of change in evapotranspiration and pine forest areas as assumed in the scenario. Inset D: evergreen or partly evergreen forest.

greatest change in the two scenarios do not necessarily match each other. Concerning the Kyoto protocol, we can also assume to get a benefit from this scenario in storing more carbon as the sequestration is higher in more natural forests because they are less vulnerable to Climate Change (Noss, 2001).

Our analysis shows the general interaction of policy-induced land-use change with other environmental services like the landscape water balance. This gives clear indication for Environmental Assessment (EA) procedures to evaluate the full spectrum of impacts of decisions that influence the land management including interaction of different levels of decision making. In order to further develop the Strategic Environmental Assessment Directive (2001/42/EC) our results suggest an integrated spatially explicit modelling as an appropriate tool to understand the complex landscape scale pattern of interaction. It seems to be essential to focus on ''win win'' strategies (Lal et al., 1998) as we could demonstrate in the ''forest management'' scenario. In this scenario a change from evergreen to deciduous species combined an increase in groundwater recharge with a potential increase in carbon storage.

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