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What determines the sign of the evapotranspiration response to afforestation in the European summer?

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Abstract. Uncertainties in the evapotranspiration response to afforestation constitute a major source of disagreement between model-based studies of the potential climate benefits of forests. Forests typically have higher evapotranspiration rates than grassland in the tropics, but whether this is also the case in the mid-latitudes is still debated. To explore this question and the underlying physical processes behind these varying evapotranspiration rates of forests and grasslands in more detail, a regional model study with idealized afforestation scenarios was performed for Europe. In the first experiment Europe was maximally forested and in the second one, all forests were turned into grassland.

The results of this modelling study exhibit the same contradicting evapotranspiration characteristics of forests and grasslands as documented in observational studies. But by means of an additional sensitivity simulation, in which the surface roughness of forest was reduced to grassland, the mechanisms behind these varying evapotranspiration rates could be revealed. Due to the higher surface roughness of a forest, solar radiation is more efficiently transformed into turbulent sensible heat fluxes, leading to lower surface temperatures (top of vegetation) than in grassland. The saturation deficit between the vegetation and the atmosphere, which depends on the surface temperature, is consequently reduced over forests. This reduced saturation deficit counteracts the transpiration facilitating characteristics of a forest (deeper roots, a higher LAI and lower albedo values than grassland). If the impact of the reduced saturation deficit exceeds the effects of the transpiration facilitating characteristics of a forest, evapotranspiration is reduced compared to grassland. If not, evapotranspiration rates of forests are higher. The interplay of these two counteracting factors depends on the latitude and the prevailing forest type in a region.

1 Introduction

Afforestation is frequently discussed as a potential strategy to mitigate the effects of human-induced climate change (e.g. Sonntag et al., 2016; Harper et al., 2018; Roe et al., 2019; Davin et al., 2020). One benefit of afforestation is that forests are generally able to take up more CO_2 than grasslands (IPCC, 2019). Another advantage is that forests can have a cooling effect on the land surface due to increased evapotranspiration rates compared to grasslands (e.g. Bonan, 2008; Bright et al., 2017; Duveiller et al., 2018). According to our present knowledge about the biogeophysical effects of forests and grasslands, this increased forest evapotranspiration is caused by deeper roots (Schenk and Jackson, 2003) and a higher Leaf Area Index (LAI, e.g. Henderson-Sellers, 1993) than in grassland, whose influence can be attenuated by a reduced photosynthetic activity of forests (Leuzinger et al., 2005). The evaporative cooling effect is particularly pronounced in the tropics (Von Randow et al., 2004) but is unclear at mid-latitudes (Bonan, 2008). While several observation-based studies show higher evapotranspiration rates of forests at mid-latitudes (e.g. Zhang et al., 2001; Li et al., 2015; Chen et al., 2018; Duveiller et al., 2018), some studies exhibit an opposite behavior of forests with reduced evapotranspiration rates compared to grasslands (e.g. Wicke and Bernhofer, 1996; Teuling et al., 2010; Williams et al., 2012). The actual evapotranspiration rates of forests and grasslands are therefore subject of controversial discussions within the scientific community (e.g. Teuling, 2018).

An adequate methodology to improve the understanding about this contradicting evapotranspiration responses, is the application of model simulations, in which factorial experiments are performed in order to disentangle the role of different processes. But also within executed model intercomparison studies, a number of models simulate increased evapotranspiration, some models simulate decreased evapotranspiration in forests during summer (de Noblet-Ducoudré et al. 2012; Lejeune et al., 2017; Davin et al., 2020). The mechanisms behind the diverging evapotranspirative behavior of forests and grasslands in the mid-latitudes are consequently still an unsolved issue. Thus, to be able to correctly assess the suitability of afforestation as an effective mitigation strategy in the mid-latitudes, the understanding of the biogeophysical processes in forests and grasslands need to be improved. Only if the evapotranspirative behavior of forests and grasslands can be properly explained, the impact of these land use types on the near surface climate conditions can be evaluated.

In this study, therefore, the question how afforestation can lead in some parts of the mid-latitudes to increased evapotranspiration rates in summer and in some regions to a reduction, will be further explored. For this, idealized and extensive afforestation scenarios are applied in regional climate simulations for Europe. This approach allows an isolated view on the biogeophysical processes in forest and grasslands on a large scale, which is not provided by selective point observations. The theoretical background of the transpiration flux calculation and the simulation setup of the afforestation experiments is provided in section 2. Based on the presented simulation results in section 3, a mechanism explaining the varying evapotranspiration rates of forest and grasslands is discussed in section 4.

2 Method

To investigate the processes determining the sign of the evapotranspiration response to afforestation in the mid-latitudes, simulations with the Regional Climate Model COSMO-CLM (Rockel et al., 2008), coupled to the Land Surface Model (LSM) VEG3D (Breil and Schädler, 2017) are performed for Europe. Since afforestation is primarily affecting the transpiration characteristics of a land surface, it is assumed that changes in total evapotranspiration in summer are mainly caused by changes in the transpiration rates as indicated e.g. by Meier et al., (2018). The focus of the paper will therefore be on the impact of afforestation on transpiration changes and evapotranspiration responses are tried to be explained by changes in the transpiration characteristics. According to this, in a first step, the theoretical background of transpiration is presented and its implementation in the LSM VEG3D is discussed in detail. Subsequently, the setup of the performed simulations is described.

2.1 Theoretical background

Transpiration can be described as a water flux from a vegetated land surface into the atmosphere. This flux is determined by two factors: (1) the saturation deficit between the vegetation and the atmosphere $q_s(T_{scf})$ - q_a, and (2) a transfer coefficient c:

$$Q = p * c(q_s(T_{scf}) - q_a) \qquad \text{Eq. (1)}$$

$q_s(T_{scf})$ depends on the surface temperature T_{scf} and is derived from the Magnus-Equation. The surface temperature is in this case the temperature at the top of the vegetation. p is the air density. In state of the art LSMs, the transfer coefficient c is generally regarded as a resistance that has to be overcome by the transpiration flux (e.g. Niu et al. (2011); Oleson et al. (2013)). In VEG3D, the LSM applied in this study, this drag coefficient is described through two resistances in series (Deardorff, 1978 and Taconet et al., 1986), an atmospheric resistance r_a, which is derived from the Monin-Obukhov Similarity Theory (Monin and Obukhov, 1954) and a canopy resistance r_c:

$$c = \frac{frac_{dry}}{r_c + r_a} \qquad \text{Eq. (2)}$$

$frac_{dry}$ represents the fraction of dry leaf surface.

In r_a, the turbulent atmospheric conditions for the transfer of water vapor are reflected, which depend on the Leaf Area Index (LAI) and the wind velocity at the canopy level u_{af}:

$$r_a = \frac{1 + 0.5 * LAI}{0.04 * u_{af} * LAI} \qquad \text{Eq. (3)}$$

According to Goudriaan (1977), u_{af} and consequently the contribution of r_a to the transfer coefficient c, is primarily influenced by one vegetation parameter: (a) the surface roughness.

In r_c, the plant physiological processes of transpiration are considered. Soil water is thereby extracted by the roots and transported into the leafs. There, the water is released through the stomata into the atmosphere. Plants are regulating this water flux by the closure of the stomata. In the case of high solar radiation, for instance, stomata can be opened to increase the evaporative cooling. On the other hand, in the case of limited water availability, the stomata can be closed and transpiration is reduced. These different canopy functions are described by r_c (Deardorff, 1978 and Taconet et al., 1986):

$$r_c = r_{min} \frac{1 + 0.5 * LAI}{LAI} \left(\frac{S_{max}}{S + 0.03 * S_{max}} + \left(\frac{w_{wilt}}{w_{root}} \right)^2 \right) \qquad \text{Eq. (4)}$$

r_c depends on the net short-wave radiation, whereby S is the actual net short-wave radiation and S_{max} constitutes a seasonally varying maximum short-wave radiation. Vegetation affects these components by the albedo parameter (b). Additionally, r_c depends on the soil water availability, which is described by the relation of the wilting point w_{wilt} to the soil water content within the rooted soil w_{root}. Vegetation affects the soil water content by the root depth parameter (c). Furthermore, r_c is controlled by the LAI (d) and a plant specific stomata coefficient r_{min} (e), representing plant specific stomatal resistance characteristics (Deardorff, 1978).

Thus, transpiration depends on five different vegetation parameters (a-e), besides the humidity gradient (1) (Table 1). In a forest, these vegetation characteristics are different to grassland:

- The surface roughness of a forest is higher than of grassland (Garratt, 1993; Henderson-Sellers, 1993). The turbulent mixing is consequently increased, what in turn reduces r_a and facilitates transpiration.

- A forest is characterized by lower albedo values than grassland (Garratt, 1993; Henderson-Sellers, 1993). Thus, the net short-wave radiation *S* is increased. This leads particularly in summer to a reduced canopy resistance $r_{c,}$, what facilitates transpiration.
- The roots in a forest reach deeper than in grassland (Schenk and Jackson, 2003). During dry summer conditions, therefore, the available amount of water for transpiration is increased in a forest. The water stress for the trees is consequently low, leading again to a reduced r_c.
- The *LAI* for forest is higher than for grassland (e.g. Henderson-Sellers, 1993). With a high *LAI*, more water can be transpired. The canopy resistance of forest is therefore again reduced. Furthermore, a high *LAI* increases interception, what additionally increases evapotranspiration.
- Values of r_{min} for forest and grassland vary in literature, but are on a similar level in VEG3D as stated by Garratt, (1993) and Henderson-Sellers, (1993). In the presented study, a lower r_{min} for forest is used than for grassland, leading to lower r_c values under the same boundary conditions.

Table 1: The impact of the different influencing factors on transpiration

Parameter	**Impact on transpiration**
surface roughness	facilitates transpiration
albedo	facilitates transpiration
root depth	facilitates transpiration
LAI	facilitates transpiration
stomatal resistance	facilitates transpiration
saturation deficit	attenuates transpiration

Thus, each of the five factors (a-e), which affect the transfer coefficient *c* (Eq. 2) in the transpiration flux calculation (Eq. 1) in VEG3D, is reduced in forest compared to grassland and thus, facilitates transpiration during summer. According to Eq. (1), a reduced transpiration in a forest must consequently be connected to a reduced saturation deficit between the vegetation and the atmosphere. In the following, therefore, the impact of this saturation deficit on the transpiration fluxes of forests and grasslands and its relations to the vegetation parameters (a-e) is investigated. For this, an idealized model study is conducted, to explore the reasons for the uncertain effects of afforestation in European summer.

2.2 Simulation Setup

As described in the previous section, transpiration depends on two factors, (1) the saturation deficit between the surface and the atmosphere and (2) the transfer coefficient *c*. (2) can thereby be described by two resistances r_a and r_c, which are controlled by five vegetation parameters (a-e). Now, the impact of all these components on the transpiration flux of forests and grasslands is investigated, by performing idealized afforestation simulations with a regional climate model.

For this, two extreme land use change scenarios for Europe are simulated. In the first experiment, Europe is completely covered with forest, where trees can realistically grow (FOREST), in the second experiment all forest is turned into grassland

(GRASS). By using this approach, the differences in transpiration between forests and grasslands can be isolated and analyzed on a large scale, which is not given in observation studies. In this way, the mechanisms leading to the different transpiration responses to afforestation in the European summer can be explored in detail.

In FOREST, two different forest types are used (coniferous and deciduous), in GRASS only one grassland class is applied. The spatial distribution of the two different forest types in FOREST is illustrated in Figure 1. Coniferous and deciduous forest, as well as grassland, have different vegetation characteristics, leading to different transpiration rates, as already described in section 2.1. The used vegetation parameters for each land use class are summarized in Table 2. The study is embedded in the LUCAS initiative (Rechid et at., 2017). The model domain is the Coordinated Downscaling Experiment-European Domain (EURO-CORDEX; Jacob et al., 2014), in a horizontal resolution of 0.44° (~50km). The simulations were driven by ERA-Interim reanalyses (Dee et al., 2011) at the lateral boundaries and at the lower boundary over sea. The simulation period is 1986-2015. A spin-up of six years was performed before 1986.

To be able to better distinguish between the effects of r_a and r_c on the respective transpiration fluxes, an additional sensitivity run with the FOREST setup is performed (ROUGH). In this simulation the surface roughness of forest is replaced by the surface roughness of grassland. All the other vegetation parameters of forest, like albedo or *LAI*, remained unchanged. Since the surface roughness is the only vegetation parameter that affects only r_a and not r_c, this sensitivity simulation gives the opportunity to draw conclusions about the impact of both resistances on the transpiration fluxes.

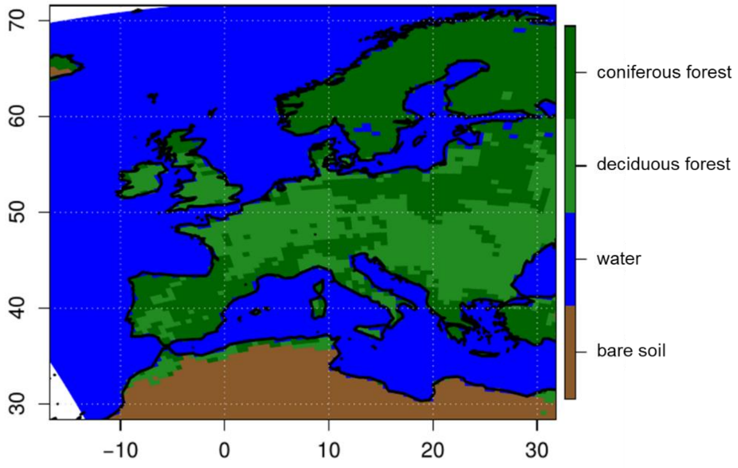

Figure 1: Spatial distribution of the land use classes used in the FOREST experiment.

Table 2: Vegetation parameters of the different land use classes.

	Albedo	*LAI*	r_{min}	root depth (density < 2%)	z_0
Coniferous forest	0.11	9 - 13	120	1.0 m	1.0 m
Deciduous forest	0.15	0.5 - 8	120	2.0 m	0.7 m – 0.8 m
Grassland	0.2	2 - 4	150	0.5 m	0.02 m – 0.03 m

3 Results

3.1 Evapotranspiration

In Southern and Central Europe, evapotranspiration is reduced in the FOREST run compared to the GRASS simulation (Figure 2a). The evapotranspiration reduction is in this context particularly strong in Southern Europe. But in Northern Europe the opposite is the case and evapotranspiration is increased in FOREST. In Central Europe, regions with reduced evapotranspiration are identical to regions covered by deciduous forest in the FOREST run (Figure 1). This regional evapotranspiration pattern indicates that the transpiration flux differences between forest and grassland are affected by the local forest type, which means the differences in the vegetation characteristics (a-e) between deciduous and coniferous forest. But both forest types have lower resistance values (higher *c* values) than grassland and should therefore both stronger promote transpiration. The resistance values of the forest types can consequently not be the main driver of the opposite transpiration signals.

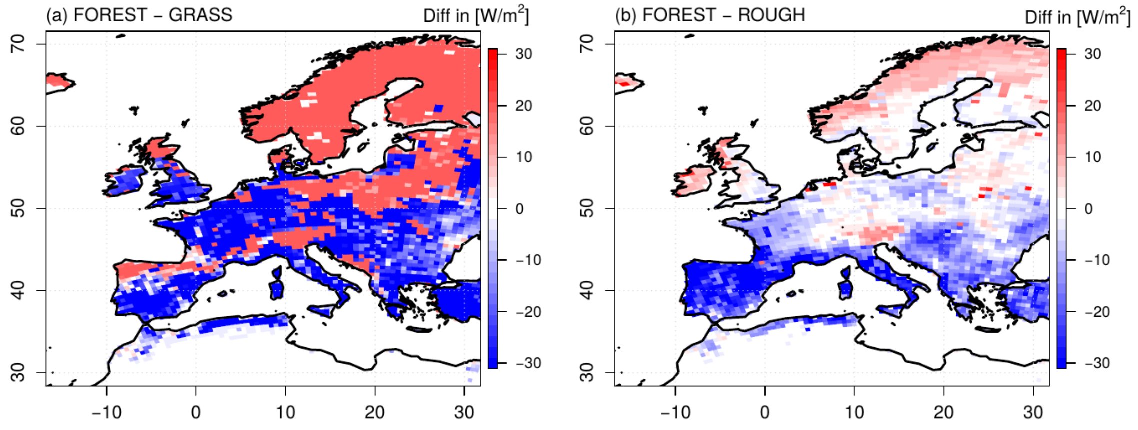

Figure 2: Differences in mean seasonal latent heat fluxes in summer between the FOREST and the GRASS experiment (a), and the FOREST and the ROUGH experiment (b), over the simulation period 1986-2015.

In general, differences in evapotranspiration rates are frequently connected to differences in the soil water contents and thus, differences in the amount of available water for evapotranspiration. But due to their deeper roots, forests have access to a larger amount of available soil water than grasslands (Figure 3a), so that the drought stress in summer is lower in the FOREST simulation than in the GRASS run. The reduced evapotranspiration rates in Central and Southern Europe in FOREST can consequently not be caused by lower soil water contents.

Furthermore, by means of differences in the soil water content, the contribution of transpiration and soil evaporation to total evapotranspiration can be indirectly assessed. Figure 3b-d show the differences in soil water contents between the FOREST simulation and the GRASS run for different soil depths. Differences in the upper 5 cm of the soil (Figure 3b) indicate on differences in the soil evaporation, since this process is executed through the soil surface. In a depth of 15 cm (Figure 3c) the maximum root density of grassland is located, in 75 cm depth (Figure 3d) the maximum of forest. Thus, differences in these soil depths refer to the contribution of transpiration to total evaporatranspiration in each simulation. Just slight differences occur between the FOREST and the GRASS simulation for the upper soil (Figure 3b). This is because the upper soil layers are in both simulations almost completely dry in summer. The contribution of soil evaporation to total evaporation is therefore low on average. This confirms the proposed assumption at the beginning of the study (section 2) that changes in total evapotranspiration in summer are mainly associated to transpiration. In a depth of 15 cm, almost all over Europe the soil is drier in the GRASS simulation (Figure 3 c), since grassland extracts water for transpiration mainly from this depth. The same applies to forest in 75 cm depth (Figure 3d). But since forest is, in contrast to grassland, able to extract water from these deeper soil layers, the available soil water amount for transpiration in summer is higher in FOREST than in GRASS (Figure 3a).

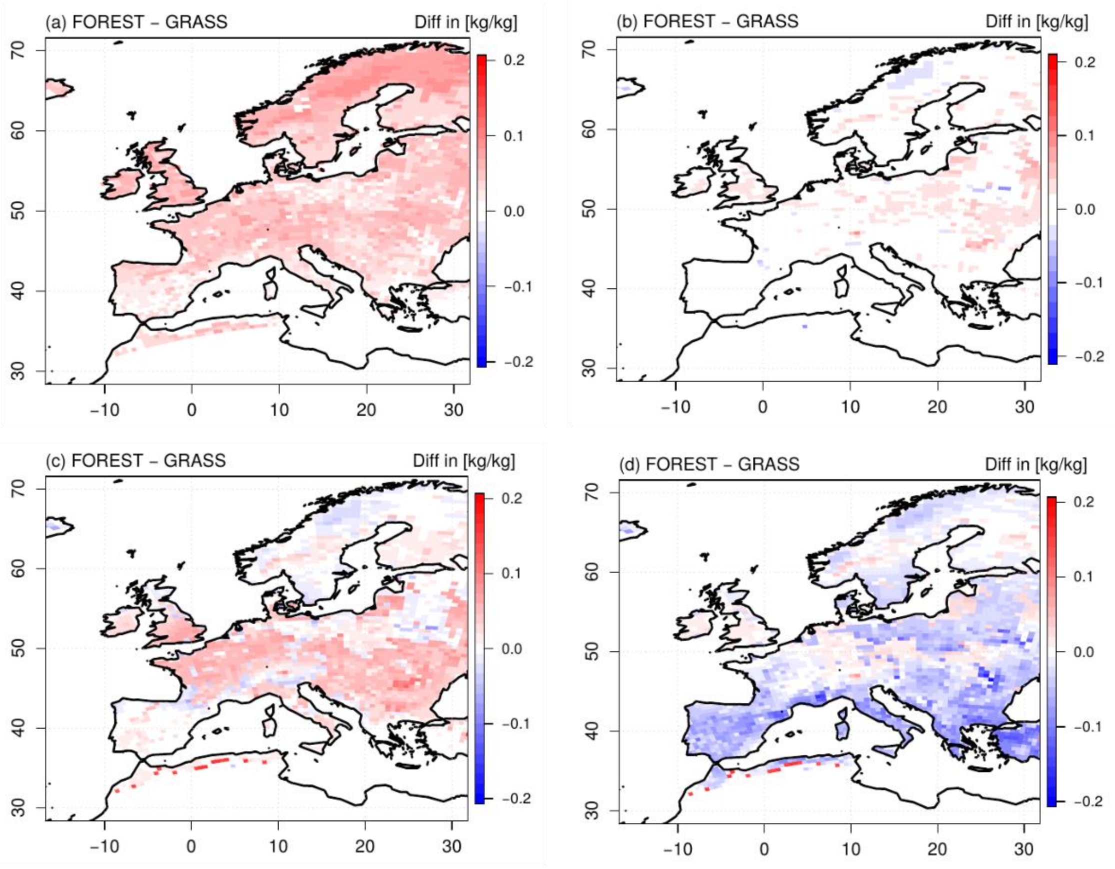

Figure 3: Differences between the FOREST and the GRASS experiment in summer for the available soil water amount for evapotranspiration (soil water content – residual soil water content) within the rooted soil column (a), and the upper soil layers (until 5 cm depth) (b), a soil depth of 15 cm (c), a soil depth of 75 cm (c), over the simulation period 1986-2015.

The ROUGH sensitivity simulation, with its reduced surface roughness, provides the opportunity to additionally investigate the impact of the resistance part r_a on the transpiration flux more precisely (Figure 2b). In general, a reduced surface roughness reduces turbulent mixing, which is manifested in an increased r_a. According to Eq. (2), this reduces the transfer coefficient c and transpiration is impeded. This should consequently lead all over Europe to reduced transpiration rates in ROUGH. But this is only the case in Northern Europe. In Southern Europe and large parts of Central Europe evapotranspiration is even increased compared to FOREST. Thus, the ROUGH simulation exhibits astonishingly comparable evapotranspiration patterns to the GRASS run and does not anymore behave like a forest simulation. Since an increase in r_a should have an opposite effect, its impact on the transpiration flux signal must be negligible, at least in Southern and Central Europe. But the generally strong effects of the surface roughness change on evapotranspiration indicates that surface roughness is playing a major role for evapotranspiration beyond its impact on r_a.

3.2 Saturation deficit

According to Eq. (1), the saturation deficit between the vegetation and the atmosphere is the driving force of transpiration, which is regulated by the transfer coefficient *c*. In the FOREST simulation, this saturation deficit is all over Europe reduced compared to the GRASS simulation (Figure 4a). Thus, all over Europe, the transpiration facilitating vegetation characteristics of a forest are facing a reduced driving force of transpiration.

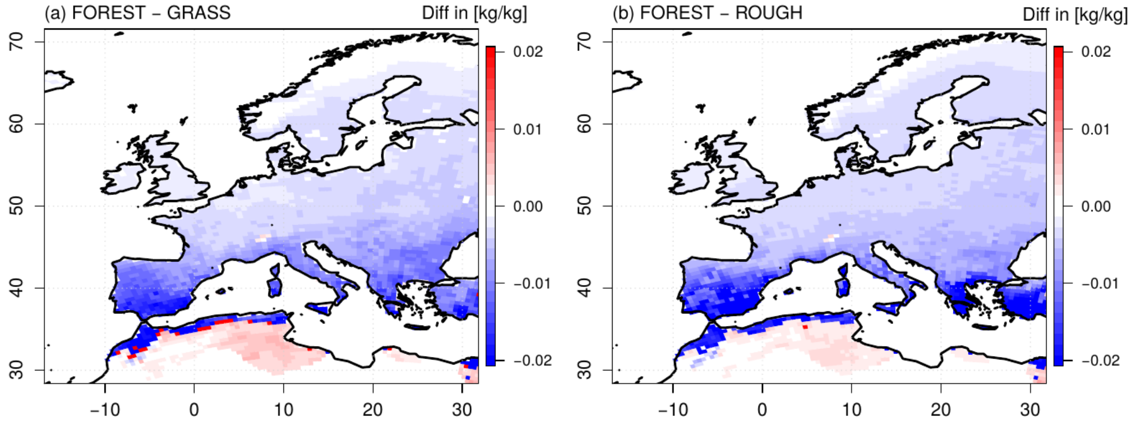

Figure 4: Differences in mean saturation deficit between the vegetation and the atmosphere in summer between the FOREST and the GRASS experiment (a), and the FOREST and the ROUGH experiment (b), over the simulation period 1986-2015. The saturation deficit is calculated for the daily maximum surface temperature (top of vegetation).

In Southern Europe, the reduction of the saturation deficit is particularly pronounced. As a result, the reduced saturation deficit exceeds the impact of the increased transfer coefficient in the transpiration flux calculation (Eq. 1) and evapotranspiration is reduced. In Northern Europe, on the contrary, the reduction of the saturation deficit in the FOREST simulation is less pronounced. As shown in Figure 1, Northern Europe is completely covered by coniferous forest in the FOREST simulation. Coniferous forest has a higher *LAI*, a lower albedo and roots that reach deeper than for deciduous forest. Thus, r_c is lower and *c* increased. In Northern Europe, a slightly reduced saturation deficit is consequently facing a high transfer coefficient. This higher transfer coefficient therefore exceeds the impact of the reduced saturation deficit in the flux calculation (Eq. 1) and evapotranspiration is increased. In Central Europe, the saturation deficit in the FOREST run is comparable to Northern Europe. But in contrast to the northern parts of Europe, large parts of Central Europe are covered by deciduous forest. The transfer coefficient *c* is consequently lower than in Northern Europe. As a results, the impact of the lower saturation deficit surpasses the effects of the transfer coefficient in the transpiration flux calculation and evapotranspiration is again reduced in FOREST. As described in section 3.1., surface roughness has only a minor impact on the extent of the transfer coefficient *c*. But its effects on the humidity gradients are large. As shown in Figure 4b, the reduction of the surface roughness in the ROUGH simulation, results all over Europe in increased saturation deficits, which are similar to the GRASS run. Thus, the surface roughness is the main driver for the different saturation deficits in FOREST and GRASS. The reasons for this surface roughness effect on the saturation deficits are described in detail in the next section.

3.3 Effects of surface roughness

A forest has lower albedo values than grassland (Table 1). The net short-wave radiation is consequently increased in FOREST compared to GRASS (Figure 5a). But this increased radiative energy input does not result in higher surface temperatures (Figure 5b. Since evapotranspiration mainly takes place during the day, here and in the following, the daily maximum temperatures are considered). All over Europe lower daily maximum surface temperatures are simulated in FOREST than in GRASS. These lower surface temperatures cannot be caused by an evaporative cooling, associated with increased latent heat fluxes as generally supposed (e.g. Bonan, 2008), since at least in Southern and Central Europe evapotranspiration is reduced in FOREST (Figure 2a). As stated by Breil et al., (2020), the lower surface temperatures in FOREST are mainly caused by increased sensible heat fluxes all over Europe (Figure 5c), which transform and transport the increased energy input from the net short-wave radiation into the atmosphere, without increasing the surface temperature.

These increased sensible heat fluxes are induced by the higher surface roughness of a forest compared to grassland, as demonstrated by the results of the ROUGH simulation (Figure 5d-f). The reduced surface roughness in ROUGH reduces all over Europe the sensible heat transport into the atmosphere (Figure 5f). Thus, the net short-wave radiation, which is due to the same albedo values on the same high level as in the FOREST run, (Figure 5d) is not as efficiently transformed and transported into the atmosphere, with the consequence that the surface temperatures are increased, similarly to the GRASS simulation (Figure 5e).

As described in Eq. (1), the saturation deficit between the surface and the atmosphere, depends on the surface temperature. Due to the increased surface roughness of a forest, this surface temperature is reduced compared to grassland. As a result, the saturation deficit of forest to the atmosphere is lower than for grassland (Figure 4a). Finally, this leads in Southern and Central Europe to a lower forest evapotranspiration (Figure 2a). Thus, the lower surface temperatures of forests compared to grassland are there not a result of evaporative cooling, but of the increased surface roughness. These lower surface temperatures, in turn, then even decrease forest evapotranspiration.

4 Discussion and Conclusions

In the framework of idealized regional climate simulations with CCLM-VEG3D for two extreme land use change scenarios (FOREST and GRASS), diverging evapotranspiration responses are simulated. In Northern Europe evapotranspiration is increased with afforestation, in Southern and Central Europe evapotranspiration is decreased. Especially the reduced forest evapotranspiration rates in Southern and Central Europe are in contradiction to the prevailing scientific doctrine that forest evapotranspiration is enhanced (e.g. Bonan, 2008), due to deeper roots (Schenk and Jackson, 2003) and a higher Leaf Area Index (Henderson-Sellers, 1993) than grassland. However, these results qualitatively reflect the varying evapotranspiration rates of forests and grasslands in European summer, documented in numerous observation and modelling studies (Zhang et al., 2001; Williams et al., 2012; Davin et al., 2020). By means of an additional sensitivity simulation, in which the surface roughness of forests was reduced to grassland (ROUGH), the mechanisms behind these varying evapotranspiration rates of forests and grasslands could be revealed:

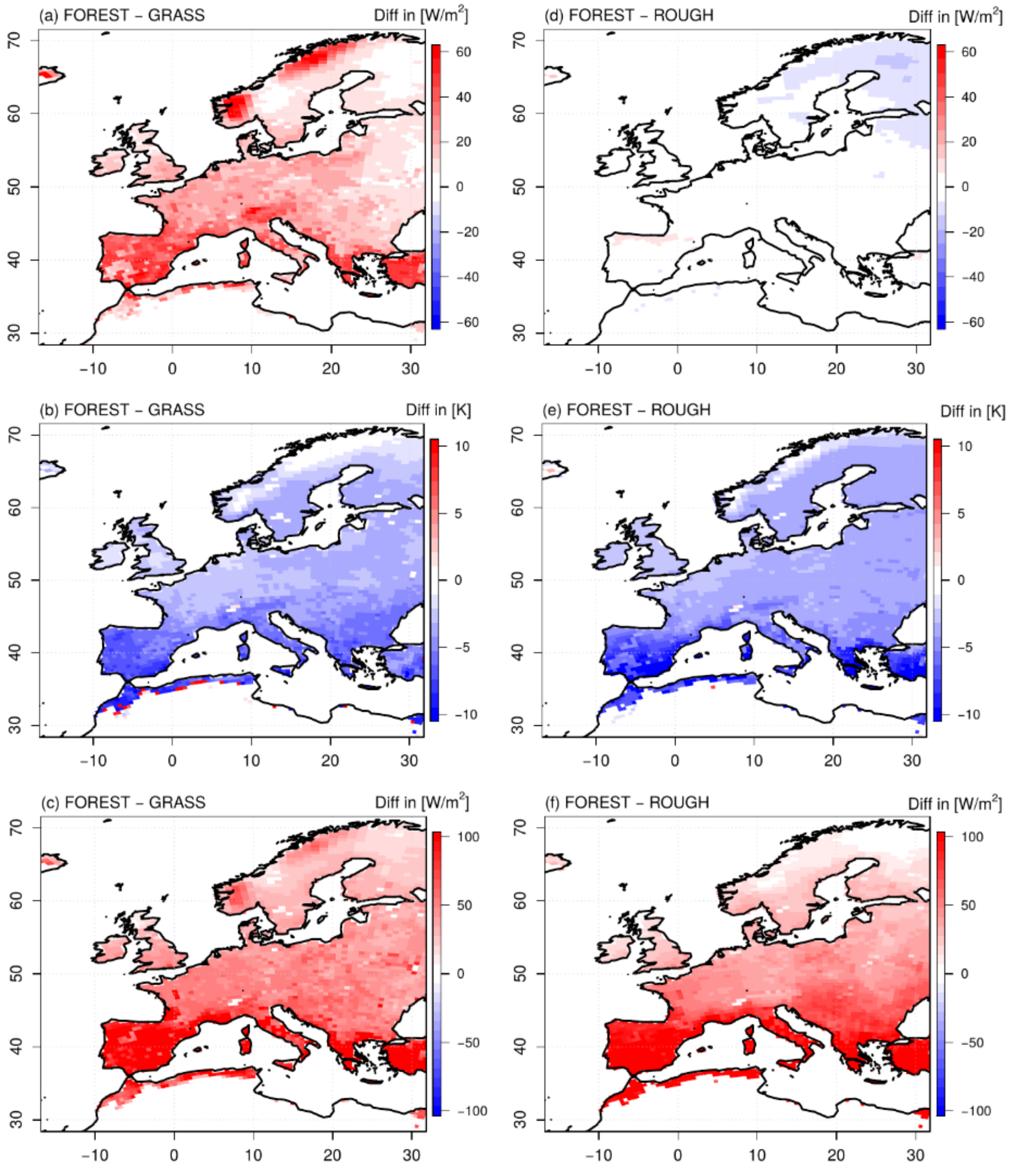

Figure 5: Differences in mean seasonal net short-wave radiation (a, d), mean daily maximum surface (top of vegetation) temperature (b, e), mean seasonal sensible heat fluxes (c, f) in summer between the FOREST and the GRASS experiment (a-c), and the FOREST and the ROUGH experiment (d-f), over the simulation period 1986-2015.

Due to a higher surface roughness, the daily maximum surface temperatures (top of the vegetation) of a forest are lower than of grassland (Breil et al., 2020). The saturation deficit between the vegetation and the atmosphere (1), which depends on these surface temperatures (Eq. 1), is consequently reduced and counteracts the transpiration facilitating characteristics of a forest ((2), high transfer coefficient due to deep roots, high LAI, low albedo). Therefore, the question whether forests or grasslands transpire more water, depends on the balance between the two factors (1) and (2).

The simulation results show that the interplay of these two forces depends, on the one hand, on the latitude. In the Southern Europe, with its intense solar radiation, the surface temperature is strongly increasing, if energy is not efficiently transformed into sensible heat fluxes by turbulent processes. Due to its low surface roughness, grassland is not able to transform the solar energy as efficient as forest. The surface temperature and thus also the saturation deficit (1) is consequently stronger increased than for forest. The impact of factor (1) therefore exceeds the effects of factor (2) and grassland transpiration is increased compared to forest. In Northern Europe, on the contrary, the incoming solar radiation is lower. Thus, the surface temperature differences and saturation deficits between forest and grassland (1) are not as pronounced as in the southern parts of Europe. The impact of factor (2) surpasses consequently the effects of factor (1) and forest transpiration is increased compared to grassland. The dependency of the evapotranspiration rates of forests and grasslands on the latitude is also documented in satellite observations (e.g. Li et al., 2015), showing for example higher evapotranspiration rates of grasslands in South-Eastern Europe, while in Central and Northern Europe evapotranspiration is lower than in forests (Duveiller et al., 2018).

On the other hand, the simulation results show that the balance between factor (1) and (2) is differently pronounced for different forest types. A deciduous forest, for instance, has a lower LAI and higher albedo values than a coniferous forest (Table 2). The transfer coefficient is consequently reduced and factor (2) is becoming weaker. In Central Europe, where deciduous forest is the prevailing forest type, the impact of the saturation deficit (1) is therefore dominating the effects of factor (2) and the transpiration rates are reduced compared to grassland. But in Northern Europe, where the saturation deficits (1) are of similar magnitude as in Central Europe, the prevailing coniferous forests increase the impact of factor (2), due to their higher LAI and lower albedo values. The transpiration rates are consequently higher for forest. These results are also in line with the studies, showing that evapotranspiration rates differ between different forest types (e.g. Brown et al., 2005; Teuling 2018). Furthermore, Marc and Robinson, (2007) showed that also the age of the forest affects evapotranspiration.

In this study, only the results of model simulations are presented, which obviously depend on the used parameterizations and parameters. In the specific CCLM-VEG3D setup, for instance, only two different forest types (coniferous and deciduous) are applied, which might not completely represent the whole variety of European forests. Generalizations, as well as under- or overestimations of certain physical processes can locally result. Therefore, this study does not claim for general validity. The transpiration rates of forests and grasslands depend on the weighting of the respective factors (1) and (2). Since this weighting is model-specific, slightly different evapotranspiration responses of forests and grasslands are anticipated for different model simulations. This can also be expected for observed evapotranspiration rates, since the biogeophysical characteristics of forests and grasslands vary also in nature (Garratt, 1993; Henderson-Sellers, 1993; Schenk and Jackson, 2003). Thus, with this study, it is not intended to answer the question whether observation-based studies are correct which show higher evapotranspiration rates of forests (e.g. Zhang et al., 2001; Li et al., 2015; Chen et al., 2018; Duveiller et al., 2018), or studies which document the opposite behavior (e.g. Wicke and Bernhofer, 1996; Teuling et al., 2010; Williams et al., 2012). In this study, rather a mechanism is presented that explains how these different transpiration responses of forests and grasslands can generally evolve in Europe and by which factors they are controlled. In this context, especially an explanation for the hardly comprehensibly lower evapotranspiration rates of forests during summer, can be provided in a physically consistent way.

Code availability. The coupled version of COSMO-CLM and VEG3D is available upon request from Marcus Breil.

Author contributions. MB designed the study. MB performed the model simulations and analysis. All authors (MB, ELD, DR) contributed to writing and revising the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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