Interactive comment on “What determines the sign of the evapotranspiration response to afforestation in the European summer?” by Marcus Breil et al.

Anonymous Referee #1 Received and published: 10 September 2020

The paper deals with the afforestation effect on evapotranspiration rate (ET) of the European continent. The paper uses a Regional Climate Model COSMO-CLM to compare ET changes due to a scenarios of afforestation of the whole European landscape. Five different variables, that are dependent on three land cove types (two forests types and grassland) are used in the model to deduce the ET rate per unit area for the continent. The model finds that what mainly governs the ET rate in the summer time is the water saturation difference between the ecosystem surface and the above air. In southern Europe, where solar radiation burden is high, grassland ecosystem ET is higher than forest ET because the grassland surface temperature is higher than that of the forest ecosystems, thus the water deficit there is higher. In northern Europe, forests ET is higher and this due to higher absorb radiation by the forest ecosystem, while a small surface temperature difference exists between the different ecosystem types. It is an interesting, conceptual paper that tries to help resolving an ongoing question of the effect of land cover change on ecosystems ET rate, in particularly by the change from a grassland to a forest ecosystem across a wide climatic conditions. As such the paper is within the scope of the journal and of high interest for wide disciplinary communities. However, I find two major weak points in the paper that require serious revisions:
- Thanks for your assessment. We hope that we are able to respond satisfactorily to your comments and clear the open issues you raised.

1. Model results vs. ground base measurements results. As the authors rightly wrote, based mainly on runoff measurements, forest ecosystems ET are mostly higher than grass ecosystems ET and the differences are functions of many variables, partially presented by the authors. Based on what I am familiar with, in most (if not all) Mediterranean dryer parts, summer ET in forest is higher than that of any paired grasslands sites. See, for example, papers on California (Ryu, et al., 2008, and Baldocchi et al., 2009) and for the Eastern Mediterranean region (Rohatyn, 2018), which seem not to agree with the paper main results. An important part of the explanation for the lower ET in grassland ecosystems in summer in such regions, is that the grassland is mainly annuals, which are dying toward the summer while the trees keep evaporating all year long. This is likely the adaptation of annuals grassland plant types to the regional dry climatic conditions. In wetter regions, the ET difference, based on FluxNet data, are less pronounced, and the paper is in agreement with studies that show that the ET differences depends on local conditions. This leads to the next comments.
- We agree, that a lot of observation-based studies indicate higher ET rates of forests in comparison to grasslands in Mediterranean regions. In the revised manuscript, this issue is pointed out more clearly.

Lines (346-351):
“In this context, the simulated increase in evapotranspiration with afforestation for large parts of Central and Northern Europa are in line with observations (e.g. Duveiller et al., 2018), while the simulated reduction in evapotranspiration in the Mediterranean is not reflected by observations (e.g. Rohatyn et al., 2018). One potential explanation for these deviations between the CCLM-VEG3D model results and observations is the missing consideration of summertime senescence of grasslands in Mediterranean regions and the associated reduction in grassland evapotranspiration (Ryu et al., 2008).”

However, a direct comparison of observational data with our model results is difficult, due to the different spatial scales of the data. While observational data reflect the local differences between forest and grassland transpiration rates, in our simulation setup, large-scale forestation scenarios are applied to analyze the general transpiration responses to forestation in an idealized and isolated way. It is therefore very difficult to assess the model results quantitatively and qualitatively.

Lines (379-384)
“However, a direct comparison of the CCLM-VEG3D model results with observational data is generally difficult, due to the different spatial representativity of the data. While observational data (satellite data as well as data from eddy covariance flux towers) reflect the local transpiration responses to forestation (Bright et al., 2017), in the CCLM-VEG3D simulation setup, large-scale forestation scenarios are applied to analyze the general transpiration responses to forestation in an idealized and isolated way. Therefore, it is difficult to assess the CCLM-VEG3D model results quantitatively and qualitatively in comparison to observations”

Furthermore, the aim of the study is not to reproduce observed transpiration rates. We rather want to understand the reason for the contradicting evapotranspiration responses to forestation existing in observations and model results. In this context, we are able to introduce a physically consistent explanation for this phenomena, in which the evapotranspiration responses are described as an interplay of two factors, namely the reduced vapor pressure deficit in forests facing their evapotranspiration facilitating biogeophysical characteristics. Since the weighting of both factors is differently pronounced in each model, and furthermore, depends on latitude and forest type, deviating evapotranspiration responses are observed and simulated. Thus, in comparison to observations, it seems that in our model the weighting of both factors is not absolutely correct for the Mediterranean (as far as we can assess it, regarding the different spatial scales). This aspect is also further emphasized in the revised manuscript

Lines (374-378):
“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), potentially explaining differences between the CCLM-VEG3D results and observations, especially in Southern Europe (Rohatyn et al., 2018).”

2. Comment for the conceptual aspects.
a. As the Authors rightly mention, vegetative ecosystem is much more complicated than described by the 5 parameters present in Table 1. However, it seems, there are several important mechanisms that could override the dominant effect of the increase in water saturation deficit presented by the paper. Ranking the importance of the different mechanisms, function of the local climatic conditions, on plants types, its ages, its density, soil conditions, are avoided. Among those important factors, there is insufficient consideration in the paper of factors such as: the phenology effects (e.g., the annuals life span; see above), the structural effects on the transpiration rate (trees are multi–layers, which has an effect on the leaf to air temperature difference and VPD within the canopy, on light intensity, and more), the understory contribution to the ecosystem ET, etc. Obviously, the model cannot include all of these effects, but should at least be discussed, with respect to the difference between the model finding and measurements results, and to provide possible explanations, and possibly how to better simulate these additional factors.
- you are right, VEG3D does not include these effects and thus, is not able to reflect the whole complexity of the soil-vegetation-atmosphere system. In the revised manuscript these model deficiencies and their potential impact on the differences to observations are discussed in more detail.

Lines (314-319):
“Climate simulations with incorporated Land Surface Models (LSMs) are an appropriate method to analyze the reasons for these varying evapotranspiration rates of forests and grasslands. However, models constitute only a simplified description of reality and thus, cannot represent the complex biogeophysical processes in nature comprehensively. For instance, VEG3D does not consider the effects of the multilayer canopy structure of trees (effects of shaded and unshaded leaves; Bonan et al., 2012) or the influence of the understory on evapotranspiration rates, which can contribute substantially to total evapotranspiration in forests (e.g. Yepez et al., 2003).”

Lines (348-351):
“One potential explanation for these deviations between the CCLM-VEG3D model results and observations is the missing consideration of summertime senescence of grasslands in Mediterranean regions and the associated reduction in grassland evapotranspiration (Ryu et al., 2008).”

b. Feedbacks between the vegetation and the atmosphere. It should be possible for a paper, where the results are based on a regional climatic model (COSMO), to discuss some vegetation-atmosphere feedbacks. For example, it is shown that the sensible heat flux is higher at the southern parts of the continent, this should dry the air and raises its temperature and may increase the leaf to air VPD for the forest model runs. Or, what is the effect of the higher ET (by the grass) on cloudiness and Rn? Referring to such effects could be of a valuable to such model-based paper.
- you are right. Since sensible heat fluxes are increased in the FOREST simulation, air temperatures are increased and in this way also the capability of the atmosphere to carry water vapor (Breil et al., 2020). But due to the intense vertical mixing within the boundary layer and the associated increased heat capacity of the atmosphere in comparison to the surface, the warming of the atmosphere is less pronounced than the cooling of the surface in the FOREST simulation. The vapor pressure deficit is consequently all over Europe reduced in FOREST, although sensible heat fluxes are increased.
Furthermore, we agree that evapotranspiration changes can affect the cloud cover and thus, the net short-wave radiation. This feedback is now discussed in detail in the revised manuscript.

Lines (266-273):
“Differences in evapotranspiration as seen for the FOREST and GRASS runs (Figure 2), inevitably affect the atmospheric conditions in these simulations. For instance, the increased evapotranspiration rates in Northern Europe in FOREST lead to an increased cloud cover in this region (Figure 5a). The incoming solar radiation is consequently reduced in comparison to GRASS. However, since the albedo of the trees in the FOREST simulation is lower than the albedo of grassland in the GRASS run, the reduction of the incoming solar radiation is compensated and net short-wave radiation is slightly increased in Northern Europe (Figure 5b). For the rest of the European continent, this albedo effect is even stronger pronounced and the net short-wave radiation is considerably increased, since cloud cover is not changed compared to GRASS. But this increased radiative energy input does not result in higher surface temperatures”

Lines (282-285):
“Due to the increased evapotranspiration rates in ROUGH in Northern Europe (Figure 2b), cloud cover is increased in this region in comparison to the FOREST run (Figure 5c). The net short-wave radiation is consequently slightly reduced (Figure 5d). But for the rest of the European continent, net short-wave radiation in FOREST and ROUGH is on the same high level, due to the unchanged albedo values.”

Minor comments:

1. Since the effect of higher ET by forest is a puzzle for most readers and the explanation is through the higher surface temperature of the grass ecosystem, it is suggested to move this text to an earlier

part of the results section, including Fig.5 b & e. Does the model calculate the leaves' skin temperature, and if so, how?

- Thanks for your suggestion, but we would like to maintain the current structure to keep the logical order of the manuscript.

Yes. The leaf temperature is calculated by solving the energy balance of the vegetation layer iteratively.

2. The paragraph, starting in line. 163 is unclear.

- paragraph is rephrased.

"In Southern and Central Europe, evapotranspiration is reduced in the FOREST run compared to the GRASS simulation (Figure 2a). The evapotranspiration reduction in FOREST 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 rates in FOREST coincide with regions covered by deciduous forest (Figure 1). This indicates that differences in evapotranspiration rates between forests and grassland are affected by the prevailing forest type in a region. Thus, the different vegetation characteristics (a-f) of deciduous and coniferous forest, must have an impact on the intensity of the evapotranspiration response to afforestation. But since both forest types have lower resistance values (higher *c* values) than grasslands, both forest types should also stronger promote transpiration than grasslands, which seems to be in contradiction to the reduced evapotranspiration rates of deciduous forests in Central Europe. Therefore, the resistance values of the different forest types cannot solely explain the opposing transpiration signals."

3. Line 182. It is likely that soil ET rate is affected by soil layers deeper than 5 cm. This sentence is questionable. And for line 187 - the soil contribution to ET could be very important (up to several ten percent of total ET).

- we agree, it is possible that soil depths deeper than 5 cm can be affected by soil evaporation, but the contribution is decreasing with depth. A depth of 5 cm is therefore a meaningful reference to evaluate the contribution of soil evaporation to total evapotranspiration. Furthermore, you are right, in general, the contribution of soil evaporation to total evapotranspiration can be very important. Both statements are therefore specified in the revised paper.

Lines (199-201):

"Differences in the upper 5 cm of the soil (Figure 3b) are used as an indicator for differences in the soil evaporation, since this process is executed through the soil surface (although soil evaporation can also be affected by soil depths deeper than 5 cm)."

Lines (205-206):

"The contribution of soil evaporation to total evaporation is therefore low in both simulations"

The important message of this comparison is that the contribution of soil evaporation to the total evapotranspiration does not differ between FOREST and GRASS and, therefore, differences in the evapotranspiration rates must be caused by differences in the transpiration rates.

4. Figure 3, units for the soil humidity values are unclear. Also note that part 'c' is noted twice in the caption (instead of 'd').

- units are changed in [%] and the caption is revised.

5. Figure 4 units are unclear.

- units are clarified in the caption.

6. To better understand the different effecting parameters on ra and rc between the ecosystems types it is suggesting to add Wwilt and Wroot values to table 2.

- W_{wilt} is the permanent wilting point and depends on the soil type. Therefore, W_{wilt} is in in each grid point identical in all three simulations. W_{root} is the water content within the rooted soil depth. This quantity is different at each grid point and changes at each time step of the simulation. Thus, it is from our point of view not meaningful to include these quantities in table 2.

Papers:

Rohatyn, S., et al. (2018). "Differential Impacts of Land Use and Precipitationon "Ecosystem Water Yield"." Water resources research 54(8): 5457-5470.

Baldocchi Dennis, Qi Chen, Xingyuan Chen, Siyan Ma, Gretchen Miller, Youngryel Ryu, Jingfeng Xiao, Rebecca Wenk and John Battles (2009). “The Dynamics of Energy, Water and Carbon Fluxes in a Blue Oak (Quercus douglasii) Savanna in California,USA”, in: “Ecosystem Function in Global Savannas: Measurement and Modeling at Landscape to Global Scales” – edited by Michael J. Hill and Niall P. Hanan, CRC/Taylor and Francis.

Ryu Youngryel, Dennis D. Baldocchi, Siyan Ma and Ted Heh (2008), “Interannual variability of evapotranspiration and energy exchange over an annual grassland in California”, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113.

Interactive comment on “What determines the sign of the evapotranspiration response to afforestation in the European summer?” by Marcus Breil et al.

Anonymous Referee #2
Received and published: 28 September 2020

The authors have identified an important, and poorly understood, aspect of the effects of afforestation/deforestation in temperate latitudes on climate: do forests increase or decrease evapotranspiration (ET) compared with grasslands? Some observational studies suggest forests have greater rates of ET; some show the opposite. Many modeling studies show forests increase ET; others do not. The topic is fraught with confusion. I had hoped this manuscript would clarify the science and provide a strong, insightful understanding of forest ET and the factors controlling ET. However, by using a poorly documented model, and by not adequately describing the model, the rationale for parameterizations and parameter values, and the limitations of the model, the manuscript does not clarify the science and, instead, adds more confusion to the literature.
- thank you very much for your detailed comments. We hope that our responses will help to dissolve potential confusions.

1. I have several concerns about the VEG3D model. From the few equations given in the manuscript, it appears to be a highly simplified land surface model. There is nothing wrong with that! But I suspect the findings of the study do not extend to more complex land surface models. The authors need to provide a thorough description of the model, justify the parameterizations used in the model, and justify parameter values. They also need to discuss how the simplifications of VEG3D might limit the generality of the results. This is not the first time this issue has arisen. VEG3D was used in a previous study by the lead author:

Breil, M., and Coauthors, 2020: The Opposing Effects of Reforestation and Afforestation on the Diurnal Temperature Cycle at the Surface and in the Lowest Atmospheric Model Level in the European Summer. J. Climate, 33, 9159–9179

In full disclosure, I was a reviewer of that manuscript and noted in my review thatVEG3D is a poorly documented model, is not widely known by the scientific community, and has not been tested in temperate forest/grassland simulations in comparison with flux tower measurements. That does not mean that the model is deficient or in-appropriate for this study, but the description of ET provided in the current manuscript reveals some non-standard formulations in the model that likely limit the generality of the results.
- in the revised version of the manuscript, the applied parameterizations and parameter values are discussed in more detail (see answers to the following comments).

1a. The authors describe the aerodynamic resistance ra used in the transpiration equation (eq 3). This is not a standard formulation of aerodynamic resistance (I have never seen it before). The resistance depends on wind speed at the top of the canopy, leaf area index, and some undescribed parameters. Classic textbooks on micrometeorology and boundary layer meteorology formulate the resistance using integrated flux-profile relationships between the apparent source/sink in the canopy (at a height equal to the roughness length [z0] plus displacement height [d]) and the lowest model level in the atmosphere

[z]:ra = [ln(z-d)/z0]ˆ2 / (kˆ2 * u)

u is wind speed at z. Depending on the specific model, z0 can be either that for momentum or for scalars, and ra is adjusted for atmospheric stability. What is the justification for eq 3, which seems to go back to two very old papers (Deardorff, 1978; Taconet et al., 1986)? Why is this equation used rather than classic boundary layer theory? It seems from eq 3 that roughness length only enters the model through wind speed at the top of the canopy (uaf), but there is no equation for uaf. It appears to go back to Goudriann's old work. This is very important, because the key outcome of the study is that surface roughness is the primary difference between forests and grasslands. Readers must understand precisely how surface roughness is used in the model and why particular formulations are used in the model.

- we are sorry that Eq. (3) caused that much confusion. This is exactly the opposite of what we intended, by using a simple description of r_a. We thought that this formulation would keep the section clear and understandable. Obviously, this was not the case. The description of r_a is therefore refined as follows:

Lines (86-105):

"In r_a, the turbulent atmospheric conditions for the transfer of water vapor are reflected, which are calculated by means of an empirical parameter C_{leaf} and the friction velocity u*:

$$r_a=\frac{C_{leaf}}{u*} \qquad \text{Eq. (3)}$$

C_{leaf} describes an empirical interrelation between the turbulent exchange and the Leaf Area Index (LAI) (Taconet et al., 1986), in relation to the leaf geometry, represented by the plant specific parameter c_{veg} (a) (Goudriaan, 1977):

$$C_{leaf}=\frac{1+0.5*LAI}{0.04*LAI*c_{veg}} \qquad \text{Eq. (4)}$$

u* is classically derived from the Monin-Obukhov Similarity Theory (Monin and Obukhov, 1954) and as such mainly dependent on z_0:

$$u*=k\frac{(v_{z_a}-v_{z_0})}{\ln\left(\frac{z_a}{z_0}\right)+\Psi\left(\frac{z_a}{L*}\right)+\Psi\left(\frac{z_0}{L*}\right)} \qquad \text{Eq. (5)}$$

where z_a is the height of the lowest atmospheric model level and z_0 is the roughness length. v_{za} and v_{z0} are consequently the wind velocities at the respective heights. k is the Karman-constant. $L*$ is the Monin-Obukhov length and Ψ is a stability-function according to Businger et al., (1971), establishing empirical relationships in turbulent motion, which depend on the atmospheric stratification. According to Goudriaan (1977), r_a and consequently its contribution to the transfer coefficient c, is primarily influenced by one vegetation parameter: the surface roughness (b)."

In comparison to the previous version, it is shown that r_a depends on u* and the empirical parameter C_{leaf}, representing an empirical interrelation between the turbulent exchange and the Leaf Area Index (LAI), in relation to the leaf geometry. The calculation of r_a is therefore totally in line with the classic boundary layer theory.

In connection with the empirical C_{leaf} parameter, a plant specific parameter c_{veg} is now introduced, representing the leaf geometry. This parameter was not mentioned in the previous version of the manuscript, since its impact on r_a is small in comparison to the surface roughness (Goudriaan, 1977). But due to the refinement of this section, this parameter is now additionally introduced and discussed in the course of the manuscript.

Admittedly, the description of the empirical vegetation parameter C_{leaf} is not the latest one. But this does not mean that the produced results are not valid. On the contrary; within the scope of several model-intercomparison studies, it could be demonstrated that VEG3D produces comparable results to more recent LSMs (e.g. Davin et al., 2020; Breil et al., 2020; Krinner et al, 2018).

1b. The formulation of canopy resistance to transpiration (eq 4) is also somewhat odd. It goes back to an equation in Deardoff (1978), in which canopy resistance depends on a specified minimum resistance that is modified for solar radiation and soil moisture. Most current-generation land surface models use an approach that couples photosynthesis and stomatal conductance through the Farquhar et al. (1980) photosynthesis model and semi-empirical stomatal conductance models such as proposed by Ball-Berry or Medlyn. In addition to light and soil moisture effects on stomatal conductance, those models also include temperature and vapor pressure deficit (VPD) effects on stomatal conductance. The VEG3D model ignore those latter two effects. That exclusion greatly limits the generality of the main finding of the study (that VPD, as modified by surface roughness, is a key determinant of differences in ET between forests and grasslands). The response of stomata to VPD is not considered (i.e. stomata close as VPD increases). Nor are the indirect effects of VPD on stomata through leaf temperature considered. Again, readers need to know why eq 4 is used in contrast with more common stomatal conductance models and what the implications of eq 4 are for the main findings of the study.

- You are right, temperature and vapor pressure deficit effects on stomatal conductance are not considered in VEG3D. These particular capabilities of trees can certainly affect evapotranspiration rates in regions with pronounced differences in the saturation deficit between forests and grasslands, like Southern Europe.

Interestingly, the results of model-intercomparison studies show that LSMs, in which these stomatal effects are integrated, exhibit comparable evapotranspiration responses as VEG3D (e.g. Davin et al., 2020). For instance, in the framework of the LUCAS, simulations with the classic model VEG3D and the more sophisticated Community Land Model under the same atmospheric boundary conditions, show similar spatial patterns of increased or reduced evapotranspiration rates with afforestation (Davin et al., 2020).Thus, the differences in the model complexity (effects of shaded and unshaded leaves or the vapor pressure dependency of stomata closure) cannot be the main reason for the simulated differences in evapotranspiration responses of forests and grasslands. These different evapotranspiration responses must rather be caused by a fundamental mechanism, which is simulated in both, classic as well as complex LSMs. This is now emphasized in the manuscript.

Lines (34-37):

"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 and an associated stomata closure (Leuzinger et al., 2005)."

Lines (351-357):

"Another possible reason for the disagreement between the simulation results and the observations is the missing consideration of vapor pressure effects on the stomatal resistance in CCLM-VEG3D. For instance, in Southern Europe the saturation deficit of forests is particularly lower than for grasslands. In contrast to the simulated trees in CCLM-VEG3D, real trees are potentially able to adapt to this lower saturation deficit, by further reducing the stomatal closure and thus the transfer coefficient. In line with the introduced evapotranspiration concept, the transpiration facilitating characteristics of forests (2) would be further enhanced, counteracting the reduced saturation deficit (1) in Southern Europe and thus, would increase forest evapotranspiration."

Lines (314-328):

"Climate simulations with incorporated Land Surface Models (LSMs) are an appropriate method to analyze the reasons for these varying evapotranspiration rates of forests and grasslands. However, models constitute only a simplified description of reality and thus, cannot represent the complex biogeophysical processes in nature comprehensively. For instance, VEG3D does not consider the effects of the multilayer canopy structure of trees (effects of shaded and unshaded leaves; Bonan et al., 2012) or the influence of the understory on evapotranspiration rates, which can contribute substantially to total evapotranspiration in forests (e.g. Yepez et al., 2003). Furthermore, VEG3D does not consider the impact of temperature and vapor pressure deficit on stomata closure, potentially affecting evapotranspiration rates in regions with pronounced differences in saturation deficit between forests and grasslands. But the results of model-intercomparison studies show that more sophisticated LSMs, in which these biogeophysical effects are integrated, exhibit comparable evapotranspiration responses to afforestation as VEG3D (e.g. de Noblet-Ducoudré et al. 2012; Davin et al., 2020). For instance, in the framework of the LUCAS project, simulations with the classic model VEG3D and the more sophisticated Community Land Model under the same atmospheric boundary conditions, show similar spatial patterns of increased or reduced evapotranspiration rates with afforestation (Davin et al., 2020). Thus, the differences in the model complexity (effects of shaded and unshaded leaves or the vapor pressure dependency of stomata closure) cannot be the main reason for the simulated differences in evapotranspiration responses of forests and grasslands. These different evapotranspiration responses must rather be caused by a fundamental mechanism, which is simulated in both, classic as well as complex LSMs."

In order to get to the bottom of these fundamental processes, the use of a less complex model can even be beneficial. In such a model, the degrees of freedom are reduced and functional interrelations can consequently be deduced more easily. For this reason, we are able to show in the manuscript that the driving force behind evapotranspiration (saturation deficit) is already reduced in forests (in comparison to grasslands), due to their inherent biogeophysical characteristics (z_0). Depending on latitude and forest type, therefore, forests can have lower evapotranspiration rates than grasslands.

1c. The term (1+0.5*LAI)/LAI is common to both ra and rc. What does this term represent? It seems to be a scaling term for canopy LAI (i.e, from a leaf resistance to a canopy resistance). Aerodynamic resistance is commonly expressed per unit ground area. Why does ra need to be scaled by LAI?
- This term represents an empirical interrelation between the turbulent exchange and the vegetation specific characteristics *LAI* and the leaf geometry (Taconet et al., 1986). The term accounts for the fact that the turbulent exchange is proportional to the LAI with a low exchange for small LAIs and an increasing exchange with increasing LAI (but the interrelation has an upper limit; 0.5).

2. The authors emphasize that differences between forest and grassland arise in terms of five model parameters: surface roughness, albedo, root depth, leaf area index, and minimum stomatal conductance.

2a. The justification for several parameter choices goes back to papers by Garratt (1993) and Henderson-Sellers (1993). There has been a lot of model development since then. How do these parameter choices compare with values used in the current generation of land surface models?
- the used model parameters in VEG3D are very similar to the parameters used in other Land Surface Models as it is shown in Breil et al., (2020) (see table below). The albedo and z_0 values are totally in line with the values in other models. The LAI values in VEG3D are higher than in the other models. But the relative LAI differences between the different land use classes (coniferous forest, deciduous forest, grassland) are again comparable. For instance, the relative difference in the contribution of the LAI to r_a (caclulated via Eq. (4)) between coniferous and deciduous forest is 0.97 in VEG3D. If one would use instead the LAI values used in the Community Land Model (CLM), the relative difference would be 0.96. A similar picture is drawn for the relative differences between coniferous forests and grasslands. In VEG3D, the relation is 0.81, while the use of the

CLM values would result in a relation of 0.83. Thus, it can be stated that the parameter values in the respective LSMs lead to comparable physical dependencies.

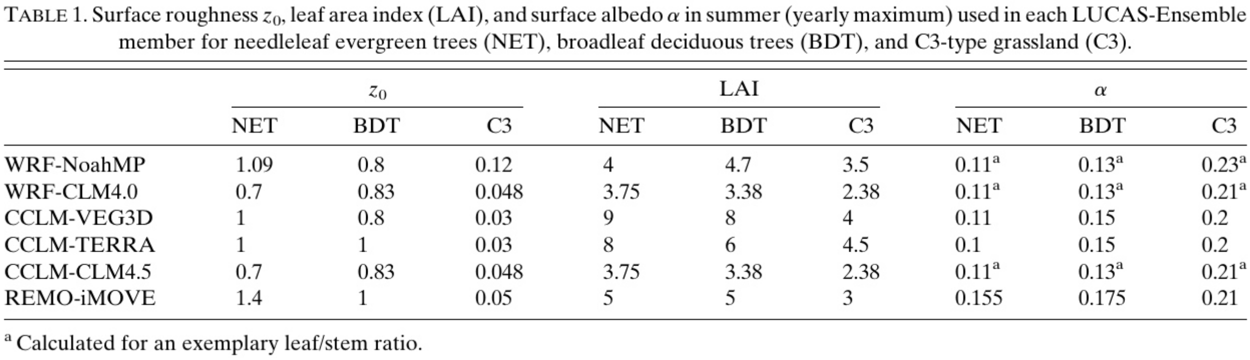

TABLE 1. Surface roughness z_0, leaf area index (LAI), and surface albedo α in summer (yearly maximum) used in each LUCAS-Ensemble member for needleleaf evergreen trees (NET), broadleaf deciduous trees (BDT), and C3-type grassland (C3).

	z_0			LAI			α		
	NET	BDT	C3	NET	BDT	C3	NET	BDT	C3
WRF-NoahMP	1.09	0.8	0.12	4	4.7	3.5	0.11^a	0.13^a	0.23^a
WRF-CLM4.0	0.7	0.83	0.048	3.75	3.38	2.38	0.11^a	0.13^a	0.21^a
CCLM-VEG3D	1	0.8	0.03	9	8	4	0.11	0.15	0.2
CCLM-TERRA	1	1	0.03	8	6	4.5	0.1	0.15	0.2
CCLM-CLM4.5	0.7	0.83	0.048	3.75	3.38	2.38	0.11^a	0.13^a	0.21^a
REMO-iMOVE	1.4	1	0.05	5	5	3	0.155	0.175	0.21

[a] Calculated for an exemplary leaf/stem ratio.

2b. Table 2 shows only a small difference in rmin between forest and grassland, and no difference between coniferous and deciduous forest. What is the justification for the parameter values? Are there physiological measurements that support them? The values for rmin are very important to the results of the study. The relative contributions of aerodynamic resistance and canopy resistance to total resistance determine the model sensitivity to roughness length. The fact that rmin is similar for all vegetation precludes physiological differences in stomatal conductance from determining differences in ET.
- the parameter values used in VEG3D are based on the results of several studies (see figure below from the review paper of Garratt (1993)). The range of r_{min} values is, in this context, quite large for the different land use types. Therefore, in VEG3D an average r_{min} value is used for each vegetation type. In general, r_{min} values of forests are smaller than r_{min} values of grasslands. r_{min} values of coniferous forests are on the same level as r_{min} values of deciduous forests. The generally lower r_{min} values of forests in comparison to grasslands are an important point in the study. Due to this, r_{min} of forests also facilitates transpiration as the other vegetation specific characteristics do in VEG3D and thus counteracts the reduced vapor pressure deficit.

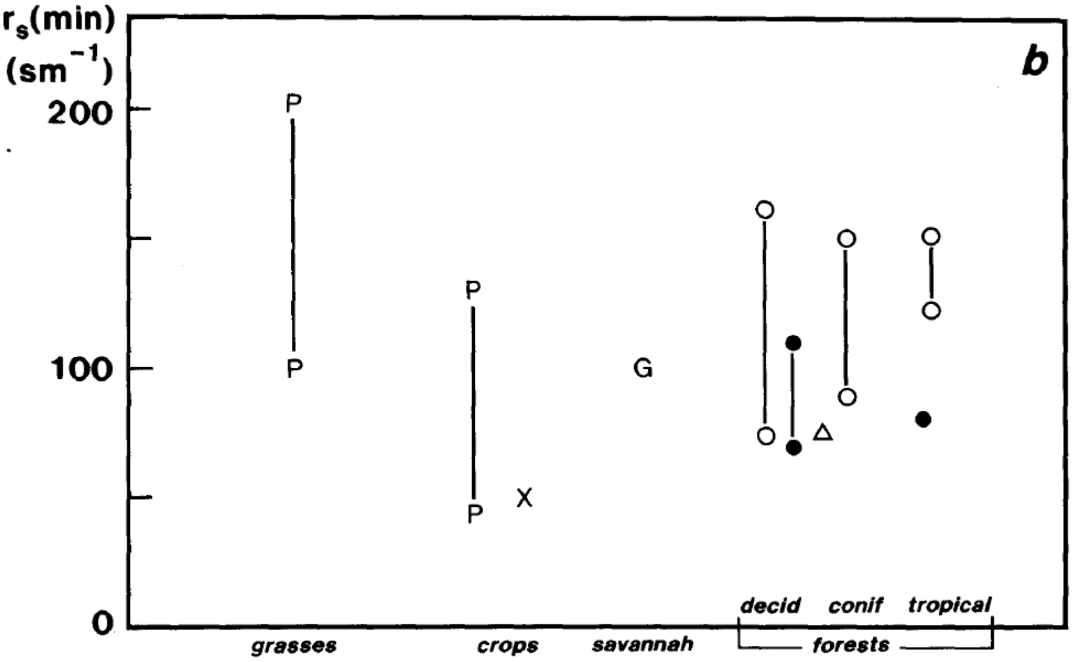

FIG. 4. Variation of unconstrained stomatal resistance r_s^* and minimum surface resistance r_s(min) with vegetation type, based on observations, literature values and model-specified values. Symbols are as follows: (a) (○) from Dorman and Sellers (1989); (●) from Shuttleworth et al. (1984b) for 3 forest sites; (×) from Sellers and Dorman (1987) for barley; (N) from Noilhan and Planton (1989) for maize (showing a wide range in resistance), oats (anomalously high) and a pine forest; 1) barley, 2) wheat, 3) maize, 4) spruce forest are all from Sellers and Dorman (1987). (b) (○) from Dorman and Sellers (1989); (●) from Shuttleworth et al. (1984b); (×) from Sellers and Dorman (1987) for maize; (△) from Sellers and Dorman (1987) for spruce; (G) from Garratt (1978) for subtropical savannah; (P) from Perrier (1982).

2c. No details are given on how root depth affects transpiration, or how the root depth parameter is used in the model. The root depth of deciduous forest is twice that of coniferous forest. Is this the reason for the differences between deciduous and coniferous forests when they are converted to grassland?
- Thanks for raising this important aspect. As described in section 3.2, differences between coniferous and deciduous forests are caused by the lower c value in deciduous forests in comparison to coniferous forests (statement with respect to Central Europe, where opposing evapotranspiration responses occur between coniferous and deciduous forest for the same latitude and vapor pressure deficit).
Both forests types have higher c values than grassland. Since the vapor pressure deficit is in Central Europe for both forest types smaller than for grassland (and thus the driving force for evapotranspiration), the c value of coniferous forest must be higher than the one of deciduous forest, leading to higher ET in coniferous forests and lower ET in deciduous forests in comparison to grasslands. Deeper roots (as for deciduous forests), lead in times of a reduced water availability to increased c values. So if the root depths would be the reason for the different responses, deciduous forests should have higher ET than coniferous forests. Thus, the impact of the root depths on the c calculation must be smaller than the impact of e.g. the albedo and the LAI (albedo is higher and LAI is lower in deciduous forest and the c values consequently smaller). This discussion is now included in the manuscript.

Lines (244-258):
"In Central Europe, the saturation deficit in the FOREST run is comparable to Northern Europe. But in contrast to Northern Europe, regions of increased evapotranspiration are simulated as well as regions of reduced evapotranspiration compared to the GRASS simulation (Figure 2a). As already mentioned in section 3.1, the regions of increased evapotranspiration coincide with regions covered by coniferous forests, while regions of reduced evapotranspiration are covered by deciduous forests. Since the saturation deficit reduction in the FOREST run is comparable for both forest types in Central Europe (Figure 4a), these different evapotranspiration responses to afforestation must be associated with differences in the transfer coefficient c (Eq. 1). The transfer coefficient c of coniferous forest must therefore be higher than the one of deciduous forest. In a coniferous forest LAI is increased and albedo is reduced in comparison to a deciduous forest, while in deciduous forest the root depth and c_{veg} are increased. Thus, both forest types have characteristics which lead to high c values. However, since evapotranspiration in Central Europe is higher for coniferous forests than for deciduous forests, the impact of LAI and the albedo (pronounced in coniferous forests) on c must be higher than the impact of the root depth and c_{veg} (pronounced in deciduous forests). As a result, the impact of the higher transfer coefficient c of coniferous forests surpasses the effects of the lower saturation deficit in Central Europe in the transpiration flux calculation and evapotranspiration is increased, while for deciduous forests the impact of the reduced saturation deficit is dominating and evapotranspiration is reduced."

We are absolutely aware that these parameter values are associated with uncertainties and that the use of only two different forest types is simplified. Therefore, we do not intend to assess the transpiration rates of individual forest types. The aim of this study is to explain the different evapotranspiration rates of forests and grasslands in a physically consistent way. In this context we can show that the evapotranspiration response generally depends on the forest characteristics (without assessing specific forest types).

2d. No details are given for albedo. What is the radiative transfer parameterization in the model? Land surface models typically simulate radiative transfer for visible and near-infrared wavebands and for direct and diffuse radiation. Albedo is a complex result of leaf and stem reflectances, leaf and stem area index, solar zenith angle, and soil moisture. Because only a single albedo is listed as a parameter in Table 2, this makes me think there is no such complex radiative transfer

parameterization in VEG3D and instead the model uses a bulk surface albedo that is prescribed as a parameter. Readers need further information.
-You are right, in VEG3D a bulk approach is used for the albedo. This is clarified in the revised manuscript (Lines 115-116).

3. A striking aspect of Figure 2 is the difference between coniferous and deciduous forests when replaced with grassland. Summer latent heat fluxes are larger in coniferous forest compared with grassland but are smaller than grassland in deciduous forest. This pattern is universally consistent throughout the domain, except for southern Spain and Turkey (smaller latent heat fluxes compared with grassland in a mostly coniferous forest region). The authors acknowledge the influence of forest type (lines165-166), but for the most part discuss their results in terms of Northern Europe versus Southern/Central Europe. For example, the authors frame their conclusions as: "In Northern Europe evapotranspiration is increased with afforestation, in Southern and Central Europe evapotranspiration is decreased" (lines 261-262). The differing results of coniferous and deciduous forests are not even mentioned in the abstract. I would like to see more of a discussion of coniferous versus deciduous forests.
- thanks for this suggestion. A central message of this study is that the interplay between factor 1 (vapor pressure deficit) and factor 2 (high c values due to transpiration facilitating characteristics of forests) is controlled by two determinants. These are the latitude (Lines 337-348) and the forest type (Lines 358-369). This is also stated in the last sentence of the abstract (Line 27). Apparently, we were not able to express this clearly in the manuscript. Therefore, we add some discussion to our original statements.

Lines (244-258):
“In Central Europe, the saturation deficit in the FOREST run is comparable to Northern Europe. But in contrast to Northern Europe, regions of increased evapotranspiration are simulated as well as regions of reduced evapotranspiration compared to the GRASS simulation (Figure 2a). As already mentioned in section 3.1, the regions of increased evapotranspiration coincide with regions covered by coniferous forests, while regions of reduced evapotranspiration are covered by deciduous forests. Since the saturation deficit reduction in the FOREST run is comparable for both forest types in Central Europe (Figure 4a), these different evapotranspiration responses to afforestation must be associated with differences in the transfer coefficient c (Eq. 1). The transfer coefficient c of coniferous forest must therefore be higher than the one of deciduous forest. In a coniferous forest LAI is increased and albedo is reduced in comparison to a deciduous forest, while in deciduous forest the root depth and c_{veg} are increased. Thus, both forest types have characteristics which lead to high c values. However, since evapotranspiration in Central Europe is higher for coniferous forests than for deciduous forests, the impact of LAI and the albedo (pronounced in coniferous forests) on c must be higher than the impact of the root depth and c_{veg} (pronounced in deciduous forests). As a result, the impact of the higher transfer coefficient c of coniferous forests surpasses the effects of the lower saturation deficit in Central Europe in the transpiration flux calculation and evapotranspiration is increased, while for deciduous forests the impact of the reduced saturation deficit is dominating and evapotranspiration is reduced.”

Lines (358-369):
“On the other hand, the simulation results show that the balance between factor (1) and (2) is differently pronounced for different forest types. In Central Europe, for instance, deciduous and coniferous forests are showing opposing evapotranspiration responses to afforestation, although they are facing a comparable saturation deficit (1). Differences in the evapotranspiration rates must consequently be associated with differences in the transfer coefficients (2). A deciduous forest, for instance, has a lower LAI and higher albedo values than a coniferous forest (Table 2). The transfer coefficient is consequently lower and factor (2) is becoming weaker. The impact of the saturation deficit (1) is therefore dominating the effects of factor (2) and the transpiration rates of deciduous

forests are reduced compared to grassland in Central Europe. But for coniferous forest, which are facing a similar saturation deficit (1), the impact of factor is increased (2), due to their higher LAI and lower albedo values. The transpiration rates are consequently higher for coniferous forests in this region. These results are also in line with observation-based studies, showing that evapotranspiration rates differ between different forest types (e.g. Brown et al., 2005), whereby higher evapotranspiration rates are generally assigned to coniferous forests (e.g. Teuling, 2018). Furthermore, Marc and Robinson, (2007) showed that also the age of the forest affects evapotranspiration."

As already mentioned in our response to comment 2c, we do not intend to give specific statements about the evapotranspiration rates of individual forest types, due to the uncertainties related to the used parameter values.

3a. What, specifically, are the differences between these forests that cause the results? One generally thinks of coniferous forests as having a more conservative water-use strategy than deciduous forests (seen, for example, in higher stomatal resistance). But both forests have the same minimum resistance. Is the different response related to rooting depth? In their analysis of soil water (Figure 3), the authors suggest it is not but the analysis is not definitive. It would be better to look at the soil moisture stress term in canopy resistance.
- as already mentioned in comment 2c, the different behavior of coniferous and deciduous forests in Central Europe is mainly caused by the higher albedo values and lower LAI values.
In Figure 3, two important features of the FOREST and GRASS simulations can be seen; (1) the contribution of soil evaporation to total evapotranspiration is the same for forests and grasslands and differences in total evapotranspiration must consequently be caused by transpiration, (2) the available amount of soil water for evapotranspiration is higher for forests than for grasslands. Figure 3a shows that this water amount is lower in coniferous forests than in deciduous forests in Central Europe, due to the more shallow roots. As already discussed in comment 2c, this should lead in deciduous forests to a higher c value compared to coniferous forests, if all other vegetation characteristics would be the same. But since albedo is higher and LAI is lower, this effect of the root depths on the c value is compensated.

3b. Are the results consistent with observations? What do flux towers show? What does MODIS ET show (but remember that MODIS ET is a modeled product).
- as discussed in section 4, the model results have comparable features to observations (dependency to the latitude (Li et al., (2015), to the forest type (Teuling, 2018) and the increased evapotranspiration rates in Northern Europe (Duveiller et al., 2018), Lines 345-347; Line 366-369). The validity of a direct and detailed comparison with paired measurement sites is from our point of view limited. In contrast to the local impacts of land use on the evapotranspiration rates as reflected in observations, in our simulations large-scale forestation scenarios are applied reflecting the general and idealized evapotranspiration responses to forestation. This is also true for the comparison with satellite-based data (e.g. MODIS), although general features of such data (e.g. latitude dependency) are reproduced.

Lines (379-384)
"However, a direct comparison of the CCLM-VEG3D model results with observational data is generally difficult, due to the different spatial representativity of the data. While observational data (satellite data as well as data from eddy covariance flux towers) reflect the local transpiration responses to forestation (Bright et al., 2017), in the CCLM-VEG3D simulation setup, large-scale forestation scenarios are applied to analyze the general transpiration responses to forestation in an idealized and isolated way. Therefore, it is difficult to assess the CCLM-VEG3D model results quantitatively and qualitatively in comparison to observations"

Therefore, the aim of our study is rather to introduce a concept of the physical reasons for the deviating evapotranspiration responses of forests and grasslands, than reproducing observed evapotranspiration rates of coniferous and deciduous forests in specific regions.

4. The crux of the study is Figure 4, which shows the difference in saturation deficit between the forest and grassland simulations. Saturation deficit decreases for forests throughout Europe, with a particularly large decrease in latitudes south of about 40N. The authors discuss the results in light of VPD, resistances, and other parameters that affect transpiration (lines 219-234). No data or figures are provided to justify the interpretation. Skeptical readers need to see more evidence that supports the argument if they are to believe the study.
- As stated in Eq. 1, evapotranspiration is controlled by two factors, (1) the vapor pressure deficit and (2) the transfer coefficient c. Since forests have all over Europe a higher c value than grasslands (table 1 and table 2), lower evapotranspiration rates can only be explained by a lower vapor pressure deficit. Regions of higher or lower evapotranspiration rates than grasslands must therefore inevitably be caused by the interplay of both factors.

5. Figure 5d: Why does net shortwave radiation change when roughness length is changed to that of grassland?
- The albedo is identical in the FOREST and the ROUGH simulation. Therefore, differences in the net short-wave radiation must be caused by atmospheric processes. In Northern Europe, the cloud cover is increased in FOREST (Figure 5c in the revised manuscript), due to the higher evapotranspiration rates in comparison to ROUGH and thus, net short-wave radiation is reduced (Figure 5d). In consequence, the temperature reduction in FOREST is comparatively strong pronounced (Figure 6c) and the increase in evapotranspiration is attenuated (Figure 2b). In the revised paper, this atmospheric feedback process is included.

Lines (266-272):
“Differences in evapotranspiration as seen for the FOREST and GRASS runs (Figure 2), inevitably affect the atmospheric conditions in these simulations. For instance, the increased evapotranspiration rates in Northern Europe in FOREST lead to an increased cloud cover in this region (Figure 5a). The incoming solar radiation is consequently reduced in comparison to GRASS. However, since the albedo of the trees in the FOREST simulation is lower than the albedo of grassland in the GRASS run, the reduction of the incoming solar radiation is compensated and net short-wave radiation is slightly increased in Northern Europe (Figure 5b). For the rest of the European continent, this albedo effect is even stronger pronounced and the net short-wave radiation is considerably increased, since cloud cover is not changed compared to GRASS.”

Lines (282-288):
“Due to the increased evapotranspiration rates in ROUGH in Northern Europe (Figure 2b), cloud cover is increased in this region in comparison to the FOREST run (Figure 5c). The net short-wave radiation is consequently slightly reduced (Figure 5d). But for the rest of the European continent, net short-wave radiation in FOREST and ROUGH is on the same high level, due to the unchanged albedo values. The reduced surface roughness in ROUGH reduces all over Europe the sensible heat transport into the atmosphere (Figure 6d). Thus, the high radiative energy is not as efficiently transformed and transported into the atmosphere as in FOREST, with the consequence that the surface temperatures are increased, similarly to the GRASS simulation (Figure 6c).”

6. Lines 288-290: The authors state that "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)". Li et al used MODIS ET, which is a modeled product. What did Duveiller et al base their analysis

on? And, remember, that the more striking aspect of Figure 2 is not the latitudinal dependence but the difference between coniferous and deciduous forests. What do observations say about that difference?

- Duveiller et al., (2018) use also MODIS data, which is as you already mentioned not completely observation-driven. Regarding the evapotranspiration differences between coniferous and deciduous forests, therefore, we think that it is the best to rely in this case on direct measurements, such as lysimeter data. Evapotranspiration rates from these data sets are quite in contradiction to satellite/model products. For instance, while satellite/model products assign higher evapotranspiration rates to deciduous forests (Duveiller et al., 2018), direct measurements at lysimeter stations assign higher evapotranspiration rates to coniferous forests (Teuling, 2018).

Lines (366-369):

"These results are also in line with observation-based studies, showing that evapotranspiration rates differ between different forest types (e.g. Brown et al., 2005), whereby higher evapotranspiration rates are generally assigned to coniferous forests (e.g. Teuling, 2018)."

Additional References:

Businger, J. A., Wyngaard, J. C., Izumi, Y., and Bradley, E. F., (1971): Flux-Profile Relationships in the Atmospheric Surface Layer, *J. Atmos. Sci.*, 28, 181–189.

Krinner, G., and Coauthors, (2018): ESM-SnowMIP: assessing snow models and quantifying snow-related climate feedbacks. *Geoscientific Model Development*, *11*, 5027-5049.

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

Marcus Breil[1], Edouard L. Davin[2], Diana Rechid[3]

[1]Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany
[2]Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland
[3]Climate Service Center Germany, Helmholtz-Zentrum Geesthacht, Hamburg, Germany

Correspondence to: Marcus Breil (marcus.breil@kit.edu)

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 and an associated stomata closure (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:

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

$q_s(T_{scf})$ 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 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 are calculated by means of an empirical parameter C_{leaf} and the friction velocity u_*:

$$r_a = \frac{C_{leaf}}{u_*} \qquad \text{Eq. (3)}$$

C_{leaf} describes an empirical interrelation between the turbulent exchange and the Leaf Area Index (LAI) (Taconet et al., 1986), in relation to the leaf geometry, represented by the plant specific parameter c_{veg} (a) (Goudriaan, 1977):

$$C_{leaf} = \frac{1 + 0.5 * LAI}{0.04 * LAI * c_{veg}} \qquad \text{Eq. (4)}$$

u_* is classically derived from the Monin-Obukhov Similarity Theory (Monin and Obukhov, 1954) and as such mainly dependent on z_0:

$$u_* = \frac{k\left(v_{z_a} - v_{z_0}\right)}{\ln\left(\frac{z_a}{z_0}\right) + \Psi\left(\frac{z_a}{L_*}\right) + \Psi\left(\frac{z_0}{L_*}\right)} \qquad \text{Eq. (5)}$$

where z_a is the height of the lowest atmospheric model level and z_0 is the roughness length. v_{z_a} and v_{z_0} are consequently the wind velocities at the respective heights. k is the Karman-constant. L_* is the Monin-Obukhov length and Ψ is a stability-function according to Businger et al., (1971), establishing empirical relationships in turbulent motion, which depend on the atmospheric stratification. According to Goudriaan (1977), r_a and consequently its contribution to the transfer coefficient c, is primarily influenced by one vegetation parameter: the surface roughness (b).

In r_c, the plant physiological processes of transpiration are considered. Soil water is thereby extracted by the roots and transported into the leaves. 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):

$$r_c = r_{min}\frac{1+0.5*LAI}{LAI}\left(\frac{S_{max}}{S+0.03*S_{max}}+\left(\frac{w_{wilt}}{w_{root}}\right)^2\right) \qquad \text{Eq. (6)}$$

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 (c). In VEG3D, a bulk surface albedo with prescribed parameter values is used, depending on the vegetation type. 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 (d). Furthermore, r_c is controlled by the *LAI* (e) and a plant specific stomata coefficient r_{min} (f), representing plant specific stomatal resistance characteristics (Deardorff, 1978).

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

- Trees have generally larger leaves than grass. The leaf geometry parameter c_{veg} is therefore higher for forests than for grasslands (Taconet et al., 1986). Thus, r_a is reduced and transpiration is facilitated.
- 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). 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.

Thus, each of the six factors (a-f), 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-f) is investigated. For this, an idealized model study is conducted, to explore the reasons for the uncertain effects of afforestation in European summer.

Table 1: The impact of the different influencing factors on transpiration of forests in comparison to grasslands

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

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 six vegetation parameters (a-f). 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 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.

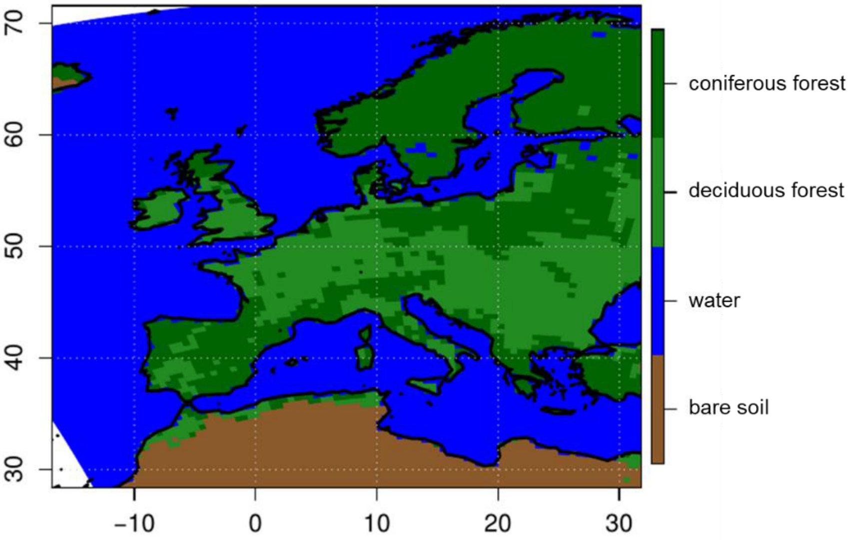

Figure 1: **S**patial distribution of the land use classes used in the FOREST experiment.

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

	Albedo	*LAI*	r_{min}	root depth (density < 2%)	z_0	c_{veg}
Coniferous forest	0.11	9	120	1.0 m	1.0 m	1.75
Deciduous forest	0.15	8	120	2.0 m	0.8 m	2.1
Grassland	0.2	4	150	0.5 m	0.03 m	1.2

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 in FOREST 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 rates in FOREST coincide with regions covered by deciduous forest (Figure 1). This indicates that differences in evapotranspiration rates between forests and grassland are affected by the prevailing forest type in a region. Thus, the different vegetation characteristics (a-f) of deciduous and coniferous forest, must have an impact on the intensity of the evapotranspiration response to afforestation. But since both forest types have lower resistance values (higher *c* values) than grasslands, both forest types should also stronger promote transpiration than grasslands, which seems to be in contradiction to the reduced evapotranspiration rates of deciduous forests in Central Europe. Therefore, the resistance values of the different forest types cannot solely explain the opposing transpiration signals.

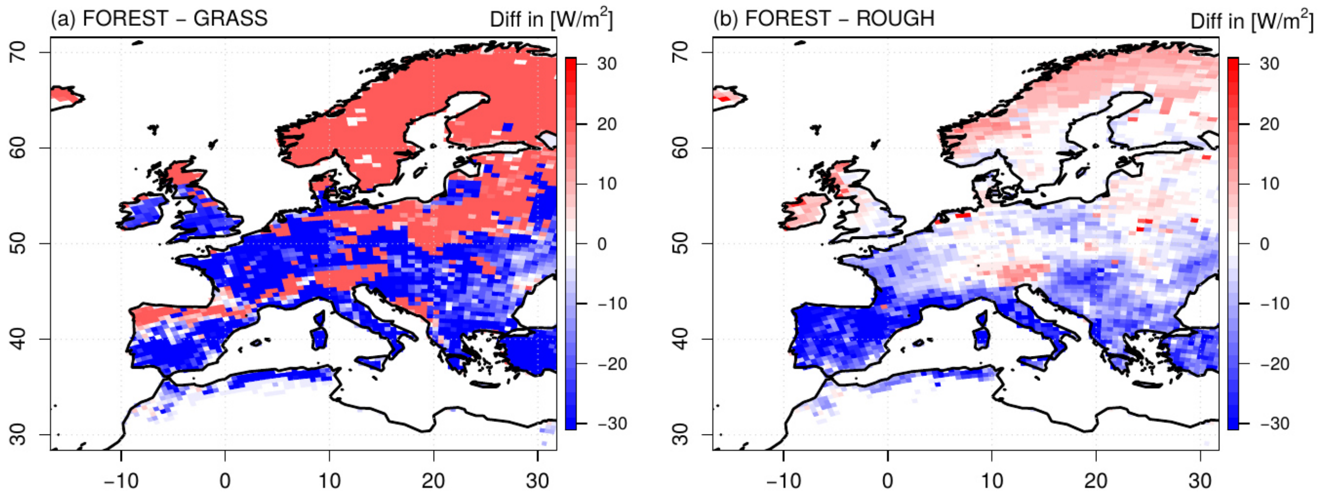

Figure 2: Differences in mean seasonal latent heat fluxes in summer between the FOREST and the GRASS experiment (a), and the FOREST and the ROUGH experiment (b), over the simulation period 1986-2015.

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) are used as an indicator for differences in the soil evaporation, since this process is executed through the soil surface (although soil evaporation can also be affected by soil depths deeper than 5 cm). 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 evapotranspiration is therefore low in both simulations. 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).

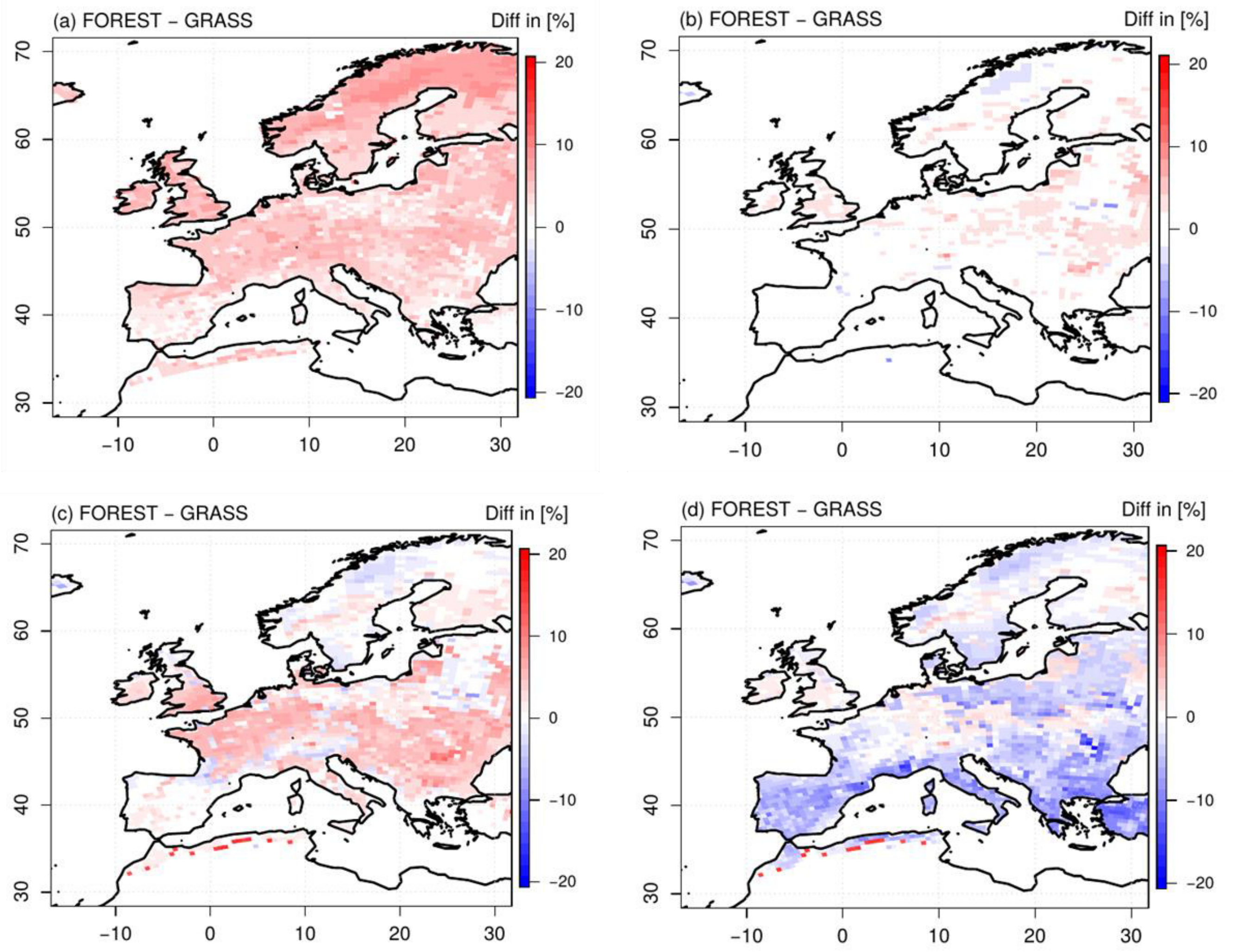

Figure 3: Differences between the FOREST and the GRASS experiment in summer for the available soil water amount for evapotranspiration (soil water content – residual soil water content) within the rooted soil column (a), and the upper soil layers (until 5 cm depth) (b), a soil depth of 15 cm (c), a soil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

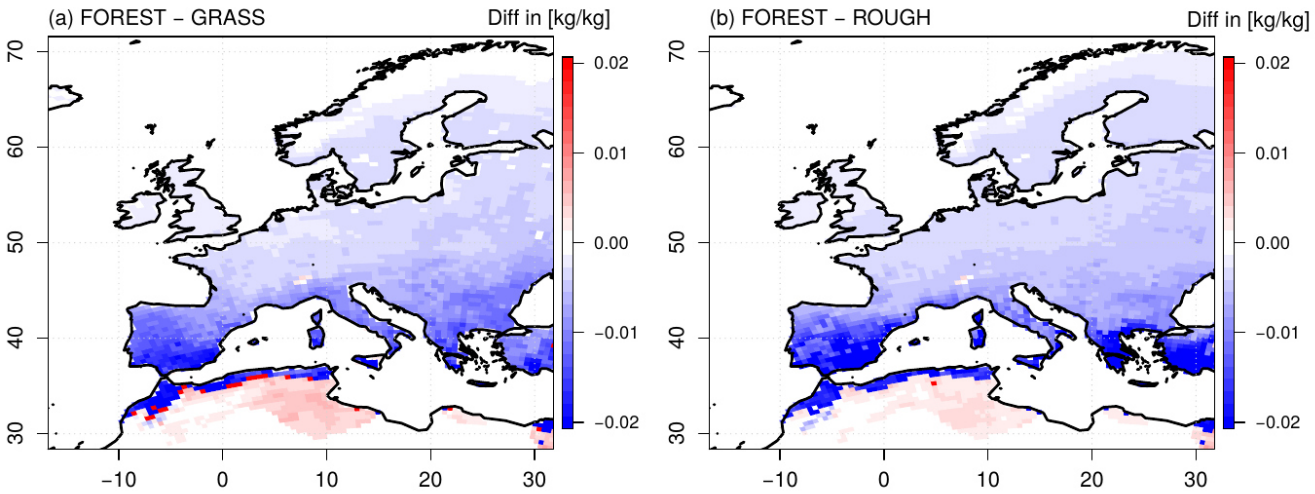

Figure 4: Differences in mean saturation deficit [in kg water vapor per kg wet air] between the vegetation and the atmosphere in summer between the FOREST and the GRASS experiment (a), and the FOREST and the ROUGH experiment (b), over the simulation period 1986-2015. The saturation deficit is calculated 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 high *LAI* and low albedo values and thus, low r_c and high c values. 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 Northern Europe, regions of increased evapotranspiration are simulated as well as regions of reduced evapotranspiration compared to the GRASS simulation (Figure 2a). As already mentioned in section 3.1, the regions of increased evapotranspiration coincide with regions covered by coniferous forests, while regions of reduced evapotranspiration are covered by deciduous forests. Since the saturation deficit reduction in the FOREST run is comparable for both forest types in Central Europe (Figure 4a), these different evapotranspiration responses to afforestation must be associated with differences in the transfer coefficient c (Eq. 1). The transfer coefficient c of coniferous forest must therefore be higher than the one of deciduous forest. In a coniferous forest *LAI* is increased and albedo is reduced in comparison to a deciduous forest, while in deciduous forest the root depth and c_{veg} are increased. Thus, both forest types have characteristics which lead to high c values. However, since evapotranspiration in Central Europe is higher for coniferous forests than for deciduous forests, the impact of *LAI* and the albedo (pronounced in coniferous forests) on c must be higher than the impact of the root depth and c_{veg} (pronounced in deciduous forests). As a result, the impact of the higher transfer coefficient c of coniferous forests surpasses the effects of the lower saturation deficit in Central Europe in the transpiration flux calculation and evapotranspiration is increased, while for deciduous forests the impact of the reduced saturation deficit is dominating and evapotranspiration is reduced.

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

Differences in evapotranspiration as seen for the FOREST and GRASS runs (Figure 2), inevitably affect the atmospheric conditions in these simulations. For instance, the increased evapotranspiration rates in Northern Europe in FOREST lead to an increased cloud cover in this region (Figure 5a). The incoming solar radiation is consequently reduced in comparison to GRASS. However, since the albedo of the trees in the FOREST simulation is lower than the albedo of grassland in the GRASS run, the reduction of the incoming solar radiation is compensated and net short-wave radiation is slightly increased in Northern Europe (Figure 5b). For the rest of the European continent, this albedo effect is even stronger pronounced and the net short-wave radiation is considerably increased, since cloud cover is not changed compared to GRASS. But this increased radiative energy input does not result in higher surface temperatures (Figure 6a; 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 6b), 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 5c-d and Figure 6c-d). Due to the increased evapotranspiration rates in ROUGH in Northern Europe (Figure 2b), cloud cover is increased in this region in comparison to the FOREST run (Figure 5c). The net short-wave radiation is consequently slightly reduced (Figure 5d). But for the rest of the European continent, net short-wave radiation in FOREST and ROUGH is on the same high level, due to the unchanged albedo values. The reduced surface roughness in ROUGH reduces all over Europe the sensible heat transport into the atmosphere (Figure 6d). Thus, the high radiative energy is not as efficiently transformed and transported into the atmosphere as in FOREST, with the consequence that the surface temperatures are increased, similarly to the GRASS simulation (Figure 6c).

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.

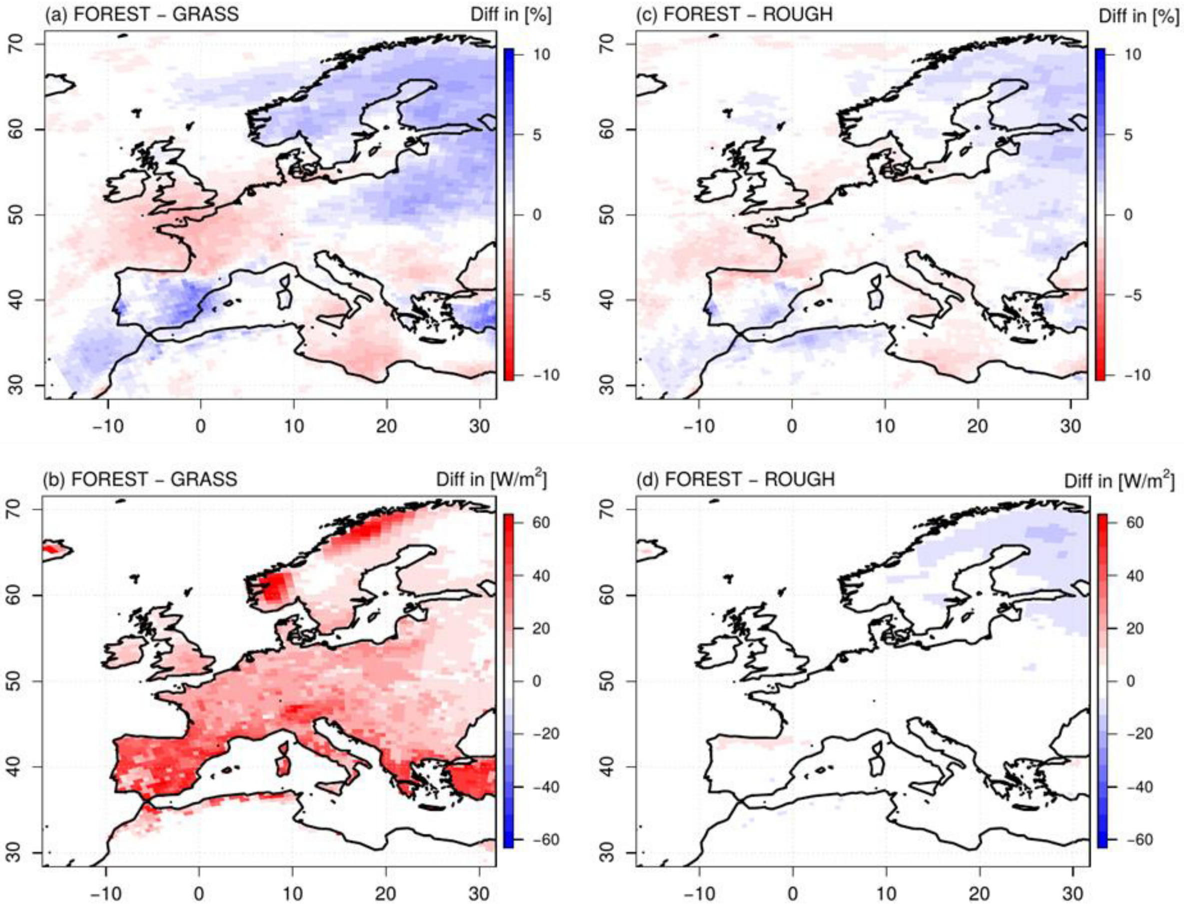

Figure 5: Differences in mean seasonal cloud cover (a,c), net short-wave radiation (b,d), in summer between the FOREST and the GRASS experiment (a-b), and the FOREST and the ROUGH experiment (c-d), over the simulation period 1986-2015.

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).

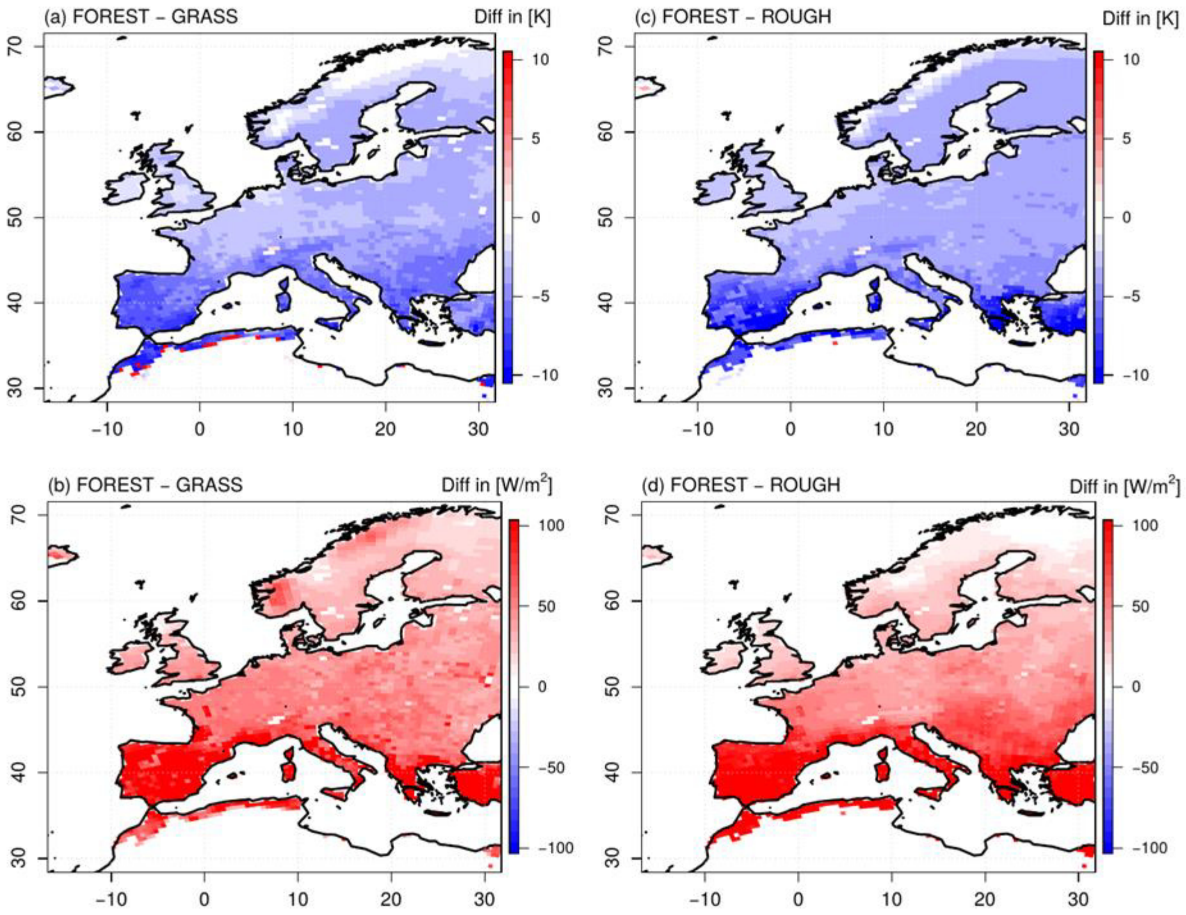

Figure 6: Differences in mean seasonal mean daily maximum surface (top of vegetation) temperature (a, c), mean seasonal sensible heat fluxes (b, d) in summer between the FOREST and the GRASS experiment (a-b), and the FOREST and the ROUGH experiment (c-d), over the simulation period 1986-2015.

Climate simulations with incorporated Land Surface Models (LSMs) are an appropriate method to analyze the reasons for these varying evapotranspiration rates of forests and grasslands. However, models constitute only a simplified description of reality and thus, cannot represent the complex biogeophysical processes in nature comprehensively. For instance, VEG3D does not consider the effects of the multilayer canopy structure of trees (effects of shaded and unshaded leaves; Bonan et al., 2012) or the influence of the understory on evapotranspiration rates, which can contribute substantially to total evapotranspiration in forests (e.g. Yepez et al., 2003). Furthermore, VEG3D does not consider the impact of temperature and vapor pressure deficit on stomata closure. But the results of model-intercomparison studies show that more sophisticated LSMs, in which these biogeophysical effects are integrated, exhibit comparable evapotranspiration responses to afforestation as VEG3D (e.g. de Noblet-Ducoudré et al. 2012; Davin et al., 2020). For instance, in the framework of the LUCAS project, simulations with the classic model VEG3D and the more sophisticated Community Land Model under the same atmospheric boundary conditions, show similar spatial patterns of increased or reduced evapotranspiration rates with afforestation (Davin et al., 2020). Thus, the differences in the model complexity (effects of shaded and unshaded leaves or the vapor pressure dependency of stomata closure) cannot be the main reason for the simulated differences in evapotranspiration responses of forests and grasslands. These different evapotranspiration responses must rather be caused by a fundamental mechanism, which is simulated in both, classic as well as complex LSMs. In order to investigate that, in the presented study, an additional sensitivity simulation was performed with CCLM-VEG3D, in which the surface roughness of forests was reduced to grassland (ROUGH). In this way, this fundamental mechanisms behind the varying evapotranspiration rates of forests and grasslands could be revealed:

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). In this context, the simulated increase in evapotranspiration with afforestation for large parts of Central and Northern Europa are in line with observations (e.g. Duveiller et al., 2018), while the simulated reduction in evapotranspiration in the Mediterranean is not reflected by observations (e.g. Rohatyn et al., 2018). One potential explanation for these deviations between the CCLM-VEG3D model results and observations is the missing consideration of summertime senescence of grasslands in Mediterranean regions and the associated reduction in grassland evapotranspiration (Ryu et al., 2008). Another possible reason for the disagreement between the simulation results and the observations is the missing consideration of vapor pressure effects on the stomatal resistance in CCLM-VEG3D. For instance, in Southern Europe the saturation deficit of forests is particularly lower than for grasslands. In contrast to the simulated trees in CCLM-VEG3D, real trees are potentially able to adapt to this lower saturation deficit, by further reducing the stomatal closure and thus the transfer coefficient. In line with the introduced evapotranspiration concept, the transpiration facilitating characteristics of forests (2) would be further enhanced, counteracting the reduced saturation deficit (1) in Southern Europe and thus, would increase forest evapotranspiration.

On the other hand, the simulation results show that the balance between factor (1) and (2) is differently pronounced for different forest types. In Central Europe, for instance, deciduous and coniferous forests are showing opposing evapotranspiration responses to afforestation, although they are facing a comparable saturation deficit (1). Differences in the evapotranspiration rates must consequently be associated with differences in the transfer coefficients (2). A deciduous forest, for instance, has a lower LAI and higher albedo values than a coniferous forest (Table 2). The transfer coefficient is consequently lower and factor (2) is becoming weaker. The impact of the saturation deficit (1) is therefore dominating the effects of factor (2) and the transpiration rates of deciduous forests are reduced compared to grassland in Central Europe. But for coniferous forest, which are facing a similar saturation deficit (1), the impact of factor is increased (2), due to their higher LAI and lower albedo values. The transpiration rates are consequently higher for coniferous forests in this region. These results are also in line with observation-based studies, showing that evapotranspiration rates differ between different forest types (e.g. Brown et al., 2005), whereby higher evapotranspiration rates are generally assigned to coniferous forests (e.g. 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), potentially explaining differences between the CCLM-VEG3D results and observations, especially in Southern Europe (Rohatyn et al., 2018). However, a direct comparison of the CCLM-VEG3D model results with observational data is generally difficult, due to the different spatial representativity of the data. While observational data (satellite data as well as data from eddy covariance flux towers) reflect the local transpiration responses to forestation (Bright et al., 2017), in the CCLM-VEG3D simulation setup, large-scale forestation scenarios are applied to analyze the general transpiration responses to forestation in an idealized and isolated way. Therefore, it is difficult to assess the CCLM-VEG3D model results quantitatively and qualitatively in comparison to observations. Thus, with this study, it is not intended to answer the question whether in specific regions 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.

Acknowledgements. LUCAS is supported by WCRP CORDEX as a Flagship Pilot Study. MB acknowledges funding by the Federal Ministry of Education and Research in Germany (BMBF) under the ClimXtreme research program. ELD acknowledges support from the Swiss National Science Foundation (SNSF) through the CLIMPULSE project. All simulations were performed at the German Climate Computing Center (DKRZ).

References

Bonan, G. B.: Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444-1449, 2008.

Bonan, G. B., Oleson, K. W., Fisher, R. A., Lasslop, G., & Reichstein, M.,: Reconciling leaf physiological traits and canopy flux data: Use of the TRY and FLUXNET databases in the Community Land Model version 4. *Journal of Geophysical Research: Biogeosciences*, *117*(G2), 2012.

Breil, M., and Schädler, G.: Quantification of the uncertainties in soil and vegetation parameterizations for regional climate simulations in Europe. *Journal of Hydrometeorology*, *18*(5), 1535-1548, 2017.

Breil, M., and Coauthors: The opposing effects of afforestation on the diurnal temperature cycle at the surface and in the atmospheric surface layer in the European summer. Journal of Climate, under review, 2020.

Bright, R. M., Davin, E., O'Halloran, T., Pongratz, J., Zhao, K., and Cescatti, A.: Local temperature response to land cover and management change driven by non-radiative processes. *Nature Climate Change*, *7*(4), 296, 2017.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of hydrology*, *310*(1-4), 28-61, 2005.

Businger, J. A., Wyngaard, J. C., Izumi, Y., and Bradley, E. F.,: Flux-Profile Relationships in the Atmospheric Surface Layer, *J. Atmos. Sci.*, 28, 181–189, 1971.

Chen, L., Dirmeyer, P. A., Guo, Z., and Schultz, N. M.: Pairing FLUXNET sites to validate model representations of land-use/land-cover change. *Hydrology & Earth System Sciences*, *22*(1), 2018.

Davin, E. L., and Coauthors: Biogeophysical impacts of forestation in Europe: first results from the LUCAS (Land Use and Climate Across Scales) regional climate model intercomparison, Earth Syst. Dynam., 11, 183–200, 2020.

Deardorff, J. W.: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *Journal of Geophysical Research: Oceans*, *83*(C4), 1889-1903, 1978.

Dee, D. P., and Coauthors: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the royal meteorological society*, 137(656), 553-597, 2011.

Duveiller, G., Hooker, J., and Cescatti, A.: The mark of vegetation change on Earth's surface energy balance. *Nature communications*, *9*(1), 679, 2018.

Garratt, J. R.: Sensitivity of climate simulations to land-surface and atmospheric boundary-layer treatments-a review. *Journal of Climate*, *6*(3), 419-448, 1993.

Goudriaan, J.: *Crop micrometeorology: a simulation study* (Doctoral dissertation, Pudoc), 1977.

Harper, A. B., and Coauthors: Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature communications*, *9*(1), 2938, 2018.

Henderson-Sellers, A.: A factorial assessment of the sensitivity of the BATS land-surface parameterization scheme. *Journal of climate*, *6*(2), 227-247, 1993.

Intergovernmental Panel on Climate Change: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/report/srccl/, 2019.

Jacob, D., and Coauthors: EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional environmental change*, 14(2), 563-578, 2014.

Lejeune, Q., Seneviratne, S. I., and Davin, E. L.: Historical land-cover change impacts on climate: comparative assessment of LUCID and CMIP5 multimodel experiments. *Journal of Climate*, *30*(4), 1439-1459, 2017.

Leuzinger, S., Zotz, G., Asshoff, R., & Körner, C.: Responses of deciduous forest trees to severe drought in Central Europe. *Tree physiology*, *25*(6), 641-650, 2005.

Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., and Li, S.: Local cooling and warming effects of forests based on satellite observations. *Nature communications*, *6*, 6603, 2015.

Liu, H., Randerson, J. T., Lindfors, J., & Chapin III, F. S.: Changes in the surface energy budget after fire in boreal ecosystems of interior Alaska: An annual perspective. *Journal of Geophysical Research: Atmospheres*, *110*(D13), 2005.

Marc, V., and Robinson, M.: The long-term water balance (1972-2004) of upland forestry and grassland at Plynlimon, mid-Wales. *Hydrology and Earth System Sciences Discussions*, *11*(1), 44-60, 2007.

Meier, R., and Coauthors: Evaluating and improving the Community Land Model's sensitivity to land cover. *Biogeosciences*, *15*(15), 4731-4757, 2018.

Monin, A. and A. Obukhov: Basic laws of turbulent mixing in the surface layer of the atmosphere. *Contrib. Geophys. Inst. Acad. Sci*. USSR, 151 (163), e187, 1954.

Niu, G. Y., and Coauthors: The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. Journal of Geophysical Research: Atmospheres, 116(D12), 2011.

de Noblet-Ducoudré, and Coauthors: Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: results from the first set of LUCID experiments. *Journal of Climate*, *25*(9), 3261-3281, 2012.

Oleson, K. W., and Coauthors: Technical description of version 4.5 of the Community Land Model (CLM). Boulder, CO, 420 pp, 2013.

Rechid, D., E. Davin, N. de Noblet-Ducoudré, and E. Katragkou: CORDEX Flagship Pilot Study LUCAS - Land Use & Climate Across Scales - a new initiative on coordinated regional land use change and climate experiments for Europe. 430 19th EGU General Assembly, EGU2017, proceedings from the conference held 23-28 April, 2017 in Vienna, Austria., p.13172, Vol. 19 of, 13172, 2017.

Rockel, B., A. Will, and A. Hense: The regional climate model COSMO-CLM (CCLM). *Meteorologische Zeitschrift*, 17(4), 347-348, 2008.

Roe, S., and Coauthors: Contribution of the land sector to a 1.5° C world. *Nature Climate Change*, 1-12, 2019.

Rohatyn, S., Rotenberg, E., Ramati, E., Tatarinov, F., Tas, E., & Yakir, D.,: Differential impacts of land use and precipitation on "ecosystem water yield". *Water Resources Research*, *54*(8), 5457-5470, 2018.

Ryu, Y., Baldocchi, D. D., Ma, S., & Hehn, T.,: Interannual variability of evapotranspiration and energy exchange over an annual grassland in California. *Journal of Geophysical Research: Atmospheres*, *113*(D9), 2008.

Schenk, H. J., and Jackson, R. B.: Global distribution of root profiles in terrestrial ecosystems. *ORNL DAAC,* 2003.

Sonntag, S., Pongratz, J., Reick, C. H., and Schmidt, H.: Reforestation in a high-CO2 world—Higher mitigation potential than expected, lower adaptation potential than hoped for. *Geophysical Research Letters*, *43*(12), 6546-6553, 2016.

Taconet, O., Bernard, R., and Vidal-Madjar, D.: Evapotranspiration over an agricultural region using a surface flux/temperature model based on NOAA-AVHRR data. *Journal of Climate and Applied Meteorology*, *25*(3), 284-307, 1986.

Teuling, A. J., and Coauthors: Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geoscience*, *3*(10), 722, 2010.

Teuling, A. J.: A forest evapotranspiration paradox investigated using lysimeter data. *Vadose Zone Journal*, *17*(1), 2018.

Von Randow, C., and Coauthors: Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia. *Theoretical and Applied Climatology*, *78*(1-3), 5-26, 2004.

Wicke, W., and Bernhofer, C.: Energy balance comparison of the Hartheim forest and an adjacent grassland site during the HartX experiment. *Theoretical and applied climatology*, *53*(1-3), 49-58, 1996.

Williams, D. and Coauthors: Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers. *Water Resources Research*, *48*(6), 2012.

Yepez, E. A., Williams, D. G., Scott, R. L., & Lin, G.,: Partitioning overstory and understory evapotranspiration in a semiarid savanna woodland from the isotopic composition of water vapor. *Agricultural and Forest Meteorology*, *119*(1-2), 53-68, 2003.

Zhang, L., Dawes, W. R., and Walker, G. R.: Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water resources research*, *37*(3), 701-708, 2001.