

We would like to express our gratitude to both the editor and the two anonymous referees for their positive remarks and constructive comments. Below is our response to the suggested corrections and point-by-point list of corresponding changes to the manuscript to referee #1 and referee #3. The referee's comments are cited in italics. Attached below is a marked-up version of the altered manuscript.

### **Author's response to anonymous referee #1 –corrections**

*The authors have answered my comments in a satisfactory manner. I only have some technical comments. Also, I have marked some typos. It seems the manuscript could benefit from a rigorous spell checker.*

1. *P 1, L 14 and elsewhere: "Arctic" instead of "arctic"*

-corrected

2. *P 1, L 21: "cause" instead of "causes"*

-corrected

3. *P 3, L 19: Atmospheric CO<sub>2</sub> doubling over which period? Currently it reads as if doubling occurs every decade.*

-According to Chapin et al. (2005), the heating effect of the change in summer albedo and increase in snow free season is found to be comparable in magnitude to the regional effect expected to occur over several decades from a doubling of atmospheric CO<sub>2</sub>. The citation was, as pointed out by the referee, somewhat unclear and has been re-written.

-Changes to manuscript: P 3, L 19: Re-written; “By analyzing a wide range of independent sets of measurement data, they found that the changes in terrestrial summer albedo enhances the high latitude warming which is increasing atmospheric heating locally by as much as 3 Wm<sup>-2</sup> per decade, comparable to the regional effects expected over multiple decades as result of an atmospheric CO<sub>2</sub> doubling.”

4. *P 4, L 26: "circulation" instead of "circulations"*

-corrected

5. P 10, L 4 and elsewhere: "10-year simulation" instead of "10 year simulation"

-corrected

6. P 10, L 24: "notably" instead of "notable"

-corrected

7. P 10, L 25: *Are the increase in albedo and decrease in LAI occurring throughout the year or only in winter when deciduous forest trees lose their leaves?*

- The increase in albedo and decrease in LAI resulting from the change from evergreen needle leaf forest to mixed forest along the southern border is occurring throughout the year, however varies seasonally (as presented in Fig. 10, thick stippled line marked "Ex2-Ex1"). As noted in the discussion, the albedo changes resulting from the vegetation shift is masked by snow during the winter months, and thereby expected to be underestimated in the current simulations. During the rest of the year the albedo changes are closely linked to the LAI changes, which are less in summer, when the mixed forest LAI reaches its peak values, and larger in the other seasons as the deciduous forest loose its leaves.

P 10, L 26: "year-round" added.

8. P 11, L 25: *There seems to be an increase in latent heat flux despite reduced wind speed. Please check if this is due to the different rooting depth of the vegetation and/or changes in albedo.*

-As we have tried to explain in the manuscript, the increase in latent heat is caused by increased LAI and absorbed radiation due to lower albedo, yielding higher rates of evapotranspiration, supported in part by more available soil moisture due to increased rooting depth. The increase in latent heat causes a moist boundary layer, and increased near surface air humidity, causing increases in summer precipitation. The lowered wind speed probably lowers the increase in latent heat flux to a certain extent, however not enough to counteract the other factors, and rather helps partition the excess radiative heating into latent- rather than sensible heat flux. The term "turbulent heat fluxes" does seem confusing here, and is changed accordingly, as the referee suggests.

- Changes to the manuscript; P 11, L 25: “turbulent heat fluxes” are changed into “sensible heat flux” for clarity.

9. P 12, L 24: *"shows" instead of "show"*

-corrected

10. P 12, L 30: *Isn't soil water content increasing when deeper forest roots can hold more water? I assume you mean "increasing" instead of "lowering" because the caption in Fig. 9 reads "Note that red colors indicate dryer-, and blue wetter conditions". I also assume the color bars in Fig. 9 need to be flipped. Soil moisture is also greatly affected by precipitation. A more detailed precipitation analysis could clarify this.*

- As the referee points out, the colors should be flipped in Figure 9, so that wetter conditions are shown in blue colors, drier in red, thereby matching the comment in the figure caption. As pointed out in the text, the increasing number of rooting layers due to the change in vegetation acts to increase the subtraction of water from the lower layer as compared to control simulation. The increase in transpiration and thus the latent heat flux from the forest compared to the previous tundra vegetation is in part supported by the water available in the lower soil layers, which is in turn reduced as compared to the control run.

-changes in manuscript; colors in Figure 9 are flipped.

11. P 13, L 11: *"circled" instead of "circeled"*

-corrected

12. P 13, L 13: *Ex2-Ex1 is positive, or am I missing something? Why is the increase in autumn and spring stronger than in summer and winter? Is this related to rainfall? It should be "increase" instead of "decrease".*

-The referee correctly points out it should say “increase”, as the albedo does increase due to the vegetation shifting from evergreen forest with low year-round albedo, to mixed forest with higher albedo. The albedo is closely related to the LAI, which differs most prominently in winter, autumn and spring, and less in summer, when the mixed forest reaches its maximum LAI values. However, in winter some of the effect on the albedo is masked by snow cover, which is further discussed as a possible weakness in the model parameterization

in the discussion chapter. As a result of these mechanisms the change in albedo is largest in spring and autumn.

-Change in manuscript; “decrease” is changed to “increase”.

13. P 13, L 23: “*statistically*” instead of “*satistically*”

- corrected

14. P 13, L 24: *No comma before “is”*

- corrected

15. P 14, L 6: *Can you comment on why the peak is in summer? Why is it not in winter, when deciduous trees are dormant and evergreen trees still active? I assume absolute values are largest in summer, so differences are also largest?*

-As the referee correctly points out, the absolute values are greatest in summer, which is reflected in the results for the anomalies. However, checking the results for the relative changes, shows that also the relative differences for the latent heat are largest in summer (July and August) with about a 25% increase in latent heat averaged over the areas with northward migrating evergreen forest. However, the relative decrease is also substantial in February, for both areas with mixed and evergreen forest northward migration, which is not showing in the absolute value anomalies. The large increase in summer is probably related to the lowered albedo, an effect that is masked by snow in winter (as mentioned in the discussion).

-Changes to the manuscript: P 14, L 6: Added: “Absolute values of the latent heat flux are largest in summer months, and so are the differences due to vegetation shifts, with a peak increase in July of on average as much as  $18 \text{ W m}^{-2}$ . ”

16. P 14, L 16: *Forests do not subtract moisture, they keep the soil moist and thus increase soil moisture compared to tundra, where moisture can not be stored and therefore leads to more runoff. Again, check the color bars in Fig. 9.*

-In our simulations the increased number of rooting layers combined with an increase in latent heat flux does lead to a decrease in lower layer soil moisture. This is, as the referee points out, contradictory to the moisture-preserving effect of forests. However, in this high latitude location, as pointed out in sect. 3.3, the evapotranspiration, and thus the effect on soil

moisture, is energy- rather than water limited, due to the high soil moisture content. In a water stress situation the forest might act to stabilize the lower layer soil moisture content as the referee suggested. However, no such situations occur within our simulation period, and we are therefore not able to test the theory here.

-changes to the manuscript; Colors in Figure 9 are switched.

17. P 16, L 14: "assumptions" instead of "assumtions"

-corrected

### **Author's response to anonymous referee #3 –corrections**

*Although simplified, the research is interesting and relevant to many researchers, including myself. It is well written, well conducted and the authors are aware of the simplifications they had to make to perform this research. It also includes numerous references to other studies, however the references are not given in chronological order within the text. I would thus suggest the authors to correct this minor technical error throughout the manuscript.*

We would like to thank the referee for taking time to review our manuscript. We greatly appreciate the positive remarks and the suggestion for improvement. We have followed the referee's suggestion and changed the references to chronological order throughout the manuscript.

# Sensitivity of regional European boreal climate to changes in surface properties resulting from structural vegetation perturbations

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## Abstract

Amplified warming at high latitudes over the past decades has led to changes in the boreal and Arctic climate system, such as structural changes in high latitude ecosystems and soil moisture properties. These changes trigger land-atmosphere feedbacks, through altered energy partitioning in response to changes in albedo and surface water fluxes. Local scale changes in the ~~arctic~~Arctic and boreal zone may propagate to affect large scale climatic features. In this study, MODIS land surface data are used with the Weather Research and Forecasting model (WRF V3.5.1) and Noah LSM, in a series of experiments to investigate the sensitivity of the overlying atmosphere to perturbations to the structural vegetation in the Northern European boreal ecosystem. Emphasis is placed on surface energy partitioning and near surface atmospheric variables, and their response to observed and anticipated land cover changes. We find that perturbations simulating northward migration of evergreen needle leaf forest into tundra regions causes an increase in latent rather than sensible heat fluxes during the summer season. Shrub expansion in tundra areas has only small effects on surface fluxes. Perturbations simulating the northward migration of mixed forest across the present southern border of the boreal forest, have largely opposite effects on the summer latent heat flux, i.e. leads to a decrease, and acts to moderate the overall mean regional effects of structural vegetation changes on the near surface atmosphere.

## 1 Introduction

Amplified warming at high latitudes over past decades has led to changes in the boreal and Arctic climate system, such as structural changes in high latitude ecosystems (Chapin et al.,

1 | [2010](#);Serreze and Barry, 2011;~~Chapin et al., 2010~~). This polar amplification of global  
2 | warming is in part due to a cascade of local feedback mechanisms that act to increase the  
3 | initial greenhouse gas forcing (~~Serreze and Barry, 2011~~;Overpeck et al., 1997;[Serreze and](#)  
4 | [Barry, 2011](#)). Extensive evidence gathered over the past decades, has established that changes  
5 | in high latitude ecosystems are part of these mechanisms, through redistribution of physical  
6 | surface properties controlling processes that act to amplify or reduce initial warming  
7 | ([Beringer et al., 2001](#);~~Bonan, 2008~~; ~~Beringer et al., 2001~~;Sturm et al., 2001;Chapin et al.,  
8 | 2005;[Bonan, 2008](#)). Important mechanisms include changes in surface energy and water flux  
9 | partitioning, which could affect regional or continental scale evapotranspiration-precipitation  
10 | feedbacks ([Eugster et al., 2000](#);Thompson et al., 2004;Beringer et al., 2005;~~Eugster et al.,~~  
11 | ~~2000~~), and surface albedo (e.g. Betts and Ball, 1997;Chapin et al., 2005;Serreze and Barry,  
12 | 2011). Physical changes may have the largest direct impacts on the local scale. However,  
13 | local scale feedbacks may propagate to regional and continental scales through cross-scale  
14 | links, and possibly lead to critical transitions in the large scale climate (Rietkerk et al., 2011).  
15 | Bonan (2008) suggests that the boreal forest might through its control on high latitude surface  
16 | albedo, especially during winter, have the highest biophysical effect of all biomes on the  
17 | mean global temperature. Also, by investigating the climate benefits of afforestation  
18 | mitigation strategies, Arora and Montenegro (2011) found that in high latitudes, the warming  
19 | effect of decreased surface albedo related to increased forest cover, dominated the cooling  
20 | effect of increased carbon sequestration, supporting similar findings of Betts et al. (2007).

21 | Several global vegetation modelling studies have predicted potential vegetation changes in  
22 | response to future warming and elevated CO<sub>2</sub> concentrations (e.g. [Lucht et al., 2006](#);Alo and  
23 | Wang, 2008;~~Strengers et al., 2010~~;Sitch et al., 2008;~~Lucht et al., 2006~~; [Strengers et al.,](#)  
24 | [2010](#);Jeong et al., 2011;Jeong et al., 2014). Common features in these studies include  
25 | migration of boreal forest towards higher latitudes and altitudes, i.e. northward expansion of  
26 | trees and shrubs into tundra ecosystems, and replacement of boreal forest by more temperate  
27 | vegetation species along the southern edges of the boreal zone. Soja et al. (2007) concluded  
28 | that substantial observational evidence across the circumpolar boreal region over the past  
29 | several decades, indicates that the biosphere in the region has already responded to climate  
30 | changes in accordance with modelled predictions, if not faster. They found upper and lower  
31 | tree lines in mountainous regions across Siberia to have altered in response to a warmer  
32 | climate, as predicted by global dynamic vegetation models (e.g. Jeong et al., 2011;Jeong et

1 al., 2014). Some of the observed changes to vegetation are increased biomass production in  
2 high latitude ecosystems as response to higher temperatures and longer growing season.

3 Several studies based on remote sensing have confirmed increased photosynthetic activity  
4 related to increased plant growth and increased growing seasons over the past decades  
5 (Myneni et al., 1997; [Bhatt et al., 2010](#); Piao et al., 2011; [Bhatt et al., 2010](#)). Bhatt et al. (2010),  
6 link increased high latitude ecosystem productivity to a decrease in near-coastal sea ice and  
7 summer tundra surface temperatures, supporting the findings of Jeong et al. (2014), who  
8 concludes that vegetation-atmosphere-sea ice interaction gives rise to additional positive  
9 feedback of the [Arctic](#) amplification, based on a series of coupled vegetation-climate  
10 model simulations under 2xCO<sub>2</sub> environment. In addition, the northward expansion of boreal  
11 and [Arctic](#) vegetation into to previously tundra covered regions, also referred to as the  
12 [Arctic](#) greening, is a widely observed feature across the [Arctic](#) region. Chapin et al.  
13 (2005) calculated that 2.3% of the treeless area in Northern Alaska has been converted to  
14 forest from tundra over the past 50 years, corresponding to an area of 11,600 km<sup>2</sup>. They  
15 highlight the importance of this redistribution in vegetation on surface albedo and  
16 temperatures. By analyzing a wide range of independent sets of measurement data, they found  
17 that the changes in terrestrial summer albedo enhances [the high latitude warming which is](#)  
18 [increasing atmospheric heating](#) locally by as much as 3 Wm<sup>-2</sup> per decade, comparable to [the](#)  
19 [regional effects expected long-term regional effects over multiple decades as result](#) of an  
20 atmospheric CO<sub>2</sub> doubling. Although the heating signal is mainly due to a prolonged snow  
21 free season, they expect that the expansion of shrubs and trees into the former tundra zones is  
22 likely to contribute to enhance summer warming in the future. Xu et al. (2013) found that a  
23 decrease of high latitude temperature seasonality equivalent to a climatic 4 degrees latitudinal  
24 shift equator-ward, has been observed in the [Arctic](#) region over the past 30 years. They  
25 estimate that a further diminishment in temperature seasonality equivalent to a full 20  
26 latitudinal degrees southward shift, could occur within this century.

27 However, not all boreal and [Arctic](#) sites respond to increased temperatures with an  
28 increased biomass production. A second type of response to warming is a reduction in  
29 photosynthetic activity, referred to as browning. Lloyd and Bunn (2007) observed that while  
30 most high latitude ecosystems have shown a positive trend in seasonal photosynthetic activity  
31 over the past few decades, some boreal ecosystems, mostly in the continental interior, showed  
32 significant downward trends in photosynthetic activity as response to increased temperatures,



1 especially in the last two decades. They explain this as a result of temperature stress, or  
2 temperature-induced moisture stress, related to increased rates of evapotranspiration.

3 Changes in surface vegetation properties have a direct effect on the surface fluxes of latent  
4 and sensible heat. The ratio between the two, the Bowen ratio (sensible to latent heat flux), is  
5 an important climatic measure and highly sensitive to surface physical properties ([Baldochi](#)  
6 [et al., 2000](#); Wilson et al., 2002; ~~[Baldochi et al., 2000](#)~~). For instance, based on an analysis of  
7 available data on surface energy balance of the [arcticArctic](#) and boreal ecosystems, Eugster et  
8 al. (2000) found that in general evergreen conifer forests have a canopy conductance half of  
9 that of deciduous forests, resulting in a higher sensible heat flux, and lower latent heat flux  
10 over evergreen conifer forests. They estimate a reduction in Bowen ratio in areas where a  
11 warming-induced shift from conifer forest to deciduous forest should occur. Arctic  
12 ecosystems, like light taiga and tundra ecosystems, also have a higher ground heat flux due to  
13 less shade by canopies, compared to forested sites (Yang et al., 1999). Thompson et al. (2004)  
14 conclude that the heating associated with more complex canopies may influence regional  
15 feedback processes by increasing boundary layer height through increased sensible heat flux.  
16 These findings were supported by Beringer et al. (2005), who measured warmer and drier  
17 fluxes moving along the transition zone from [arcticArctic](#) tundra to boreal forest. They found  
18 a relative increase in sensible heat flux resulting in an increase in Bowen ratio from 0.94 to  
19 1.22 going from tundra to forested sites. They also argue that shifting the vegetation type  
20 towards one with higher leaf area index, may cause a shift in the relationship between latent  
21 heat flux and the state of the overlying atmosphere ~~and mesoscale~~ [and mesoscale](#) weather  
22 systems through the link between transpiration and the vapor pressure deficit in the  
23 surrounding air. Shifting vegetation type was found to have less impact on the dependence on  
24 soil water content due to the low correlation to latent heat flux at all sites.

25 Changing vegetation and surface properties will through its control on surface fluxes of heat  
26 and moisture influence the planetary boundary layer, and general circulations patterns ([Pielke](#)  
27 [and Vidale, 1995](#); Beringer et al., 2001; ~~[Pielke and Vidale, 1995](#)~~; Liess et al., 2011). Recently,  
28 Liess et al. (2011) modelled whether or not changing vegetation cover in the [arcticArctic](#)  
29 zone could influence even mesoscale circulation patterns. They simulated the effects of a  
30 moderate northward forest replacement of shrub ecosystems along the southern tundra  
31 circumpolar border zone, on the summer time polar front. They estimated a regional  
32 broadening and strengthening of the polar jet stream of up to  $3 \text{ ms}^{-1}$ , and concluded that the  
33 effects of the regional forest expansion could reach even the stratospheric circulation.

1 Uncertainties within vegetation-climate modelling are large, especially with regard to future  
2 species redistribution and climate feedback (e.g. Friedlingstein et al., 2013). Investigating the  
3 response of the overlying atmosphere to specific structural changes in vegetation, may yield  
4 valuable information that might reduce uncertainties with regard to climate response to the  
5 complex present and future changes in boreal ecosystems. Limiting the uncertainties related to  
6 modelled potential vegetation changes, Snyder and Liess (2014) instead applied a one grid  
7 cell northward shift in boreal vegetation in a global climate model, to explore the response of  
8 the overlying atmosphere to a vegetation shift expected to occur within a century. This shift  
9 gave an annual warming of 0.3 °C mainly due to decreased surface albedo.

10 Changes in migration speed in response to climatic changes vary greatly across species types.  
11 As ecosystems consist of complex, co-dependent, compositions of wide ranges of species, the  
12 total ecosystem migration speed will be equally complex. However, cross-species  
13 observational studies confirm a general northward- and altitudinal shift in the boreal area, a  
14 trend matching climate change predictions (Parmesan and Yohe, 2003;Chen et al., 2011). On  
15 a global scale, Chen et al. (2011) derived a median cross species migrations rate of 16.9 km  
16 per decade, nearly doubling the estimate of Parmesan and Yohe (2003) who derived an  
17 average range shift of 6.1 km per decade in their meta-analyses based on some 1700 species  
18 across the globe. These average rates of migration estimates are often seen in contrast to those  
19 of dynamic vegetation models, which often assume strict relationships between species  
20 redistribution and altered climatic environment, yielding sometimes abrupt changes in species  
21 composition in large areas over short time spans. Many of these models simulate vegetation  
22 response to climate change based on accumulated values such as growing degrees days and  
23 accumulated precipitation values, forcing the vegetation to keep within their respective  
24 climate envelopes. In cases of rapid climatic changes, the vegetation may therefore move  
25 unrealistically fast into new areas, often within the timespan of a century. To assess two  
26 extreme scenarios, in which species follow their climatic environment completely, or do not  
27 move out of their current habitats at all in spite of changing climatic conditions, Mckenney et  
28 al. (2007) investigated potential migration scenarios of 130 North American tree species,  
29 based on future climate predictions. They found that on average, a northward distribution shift  
30 of between 330 km and 700 km depending on the species' ability to migrate at the same rate  
31 as their current climatic ~~conditions,conditions~~ was likely to occur by the end of this century,  
32 along with large decreases in future potential habitats.

1 In this study, we investigate the sensitivity of altered land cover properties on fine resolution  
2 surface fluxes and regional scale atmospheric response mechanisms by conducting two  
3 experiments with manually altered structural vegetation distribution. These experiments  
4 represent two potential future boreal and ~~arctic~~Arctic ecosystem changes, and are compared to  
5 a control present day state of vegetation distribution. An invariant vegetation distribution in  
6 each simulation aims to isolate effects of changes in land surface properties related to  
7 structural vegetation changes on the regional climate. Meteorological forcing data in both  
8 simulations matches that of the control run to further isolate the long term effects of  
9 vegetation changes on the overlying atmosphere.

## 11 2 Model and methodology

12 The Weather Research and Forecasting model (WRF V3.5.1) is a non-hydrostatic, mesoscale  
13 weather prediction system (Skamarock and Klemp, 2008). It is a model with a wide variety of  
14 applications, across scales ranging from large-eddy to global simulations. Simulation time  
15 scales vary between short-term case studies of a few hours or less, to regional climate studies  
16 spanning decades. In this study, WRF has been run with the Noah land surface model (Tewari  
17 et al., 2004), which is a ~~well-tested~~well-tested model widely used in the modelling  
18 community. In Noah, the ground surface consists of four soil layers, that are 10, 30, 60 and  
19 100 cm thick respectively, adding up to a total soil depth of 2 m. The top layer is a combined  
20 vegetation, snow and soil layer, and surface properties are dependent on soil- and vegetation  
21 category. Each vegetation category is assigned range values for parameters related to the  
22 vegetation's influence on land atmosphere interaction, such as the albedo, roughness length,  
23 stomatal resistance and leaf area index (LAI). The vegetation properties are further dependent  
24 on the greenness vegetation fraction, describing the vegetation density in each grid cell. The  
25 LSM controls the surface and soil water budget and computes surface water- and energy  
26 fluxes from the surface to the atmosphere. The turbulent fluxes are influenced by vegetation  
27 properties such as the stomatal resistance and LAI, and the surface ~~roughness~~roughness length  
28 in addition to the wind speed. The model is run at a spatial resolution of 27 km, with 52  
29 vertical layers. The time resolution is two minutes, and output is written every 3 hours. The  
30 model setup is further presented in Table 1. The choice of model configuration is based in part  
31 on sensitivity testing of various schemes (not shown), and in part out of considerations of  
32 available output variables of different parameterizations. A review of literature with regard to  
33 choices best suited for a cold region intermediate resolution simulation, and a consideration of

1 the NCAR cold climate medium resolution example setup (Skamarock et al., 2008), and the  
2 Polar WRF setup (Hines et al., 2011), also contributed to the current model configuration.

3 For the initial- and boundary conditions, we use the ERA Interim 6 hourly reanalysis.  
4 Boundary conditions for the years 2000-2010 are used for the simulations, where the first year  
5 is regarded a ~~spinup~~spin up year and not included in the analyses. The same boundary  
6 conditions are applied in all three simulations to isolate the effect of structural vegetation  
7 changes on the overlying atmosphere and climate. The ~~10-year simulation~~10-year simulation  
8 length was chosen in order to achieve a good estimate of the mean responses of the overlying  
9 atmosphere to vegetation changes without inter annual variation influencing the results.  
10 Although even longer simulations might be advantageous, 10 years was chosen as a  
11 compromise between length and computational cost while keeping high temporal and spatial  
12 resolutions in the simulations. The time period chosen as meteorological forcing (2001-2010)  
13 is coherent with the selected set of vegetation data and acts as a suitable reference period for  
14 present day conditions. As the meteorological conditions are only altered as response to the  
15 vegetation shifts inside the modelled domain, the simulation setup is not able to estimate  
16 downstream effects of vegetation perturbations.

17 For land use data, the MODIS IGBP modified 21 class land surface data is used. This dataset  
18 is available with the standard WRF package download. The dataset is based on the original 1  
19 km resolution MODIS IGBP vegetation map (Friedl et al., 2010), but excludes permanent  
20 wetland and has three tundra classes and lakes added by the Land Team at EMC/NCEP. To  
21 represent high latitude and altitude ecosystems more accurately, the vegetation category of  
22 open shrub land has been replaced by various tundra vegetation classes north of 60 degrees  
23 latitude in the modified MODIS dataset. This replacement results in an artificial shift in  
24 vegetation that can be detected along this latitude across a mountain plateau in southern  
25 Norway. In this study, the remaining grid cells of shrub land south of 60 degrees and west of  
26 15 degrees east, are adjusted into wooded tundra below-, and mixed tundra above the height  
27 of the local tree line, to achieve a vegetation distribution more consistent with local  
28 ecosystems in this area. This adjustment affects in total 12 grid cells representing 8748 km<sup>2</sup>.  
29 In the rest of the domain the vegetation shift along the 60 degree latitude has no abrupt shifts  
30 or other negative implications for the purpose of this study. The study area, which covers the  
31 northern European boreal zone, is shown in Fig. 1, represented by evergreen needle leaf forest  
32 as this is the dominant vegetation type in this area.

## 1 **2.1 Experiments**

2 The goal of the experimental setup is to investigate the sensitivity of the land-atmosphere  
3 interactions to changes in the vegetation distribution. Perturbations to the land cover aims to  
4 represent a northward migration of boreal ecosystems based on the aforementioned observed  
5 and anticipated features in vegetation migration patterns. Experiments are designed to induce  
6 atmospheric response and feedback mechanisms, while keeping perturbation complexity low  
7 enough to be able to identify the respective response mechanisms related to each of the  
8 applied vegetation shifts. The aim has been to induce moderate and realistic scale changes,  
9 representative of actual vegetation shifts on a century long timescale.

10 We isolate the effects of specific vegetation changes by applying simplified perturbations to  
11 the dominant vegetation categories as given by the selected set of land use data. The  
12 perturbations each represent a given trend of forest migration in this area. As such, the  
13 perturbations are not to be regarded as estimates of future state of vegetation distribution in  
14 the area under a specific climate scenario, rather adjustments based on observed and  
15 anticipated trends applied for the purpose of this sensitivity study. No assumptions are made  
16 with regard to changes in vegetation density after redistribution. A 10-year simulation period  
17 is used, and averages over this period are regarded as a good indicator of climate response to  
18 the perturbations. Assuming vegetation changes induced by a changing climate, this  
19 experimental setup is not relevant for an unlimited time span; rather it reflects moderate  
20 changes in simulated vegetation shifts. Keeping in line with the meta-analyses of migrations  
21 speeds across species and assuming a time horizon on the scale of about a century, an upper  
22 limit of a moderate 100 km vegetation migration is applied to vegetation redistribution.  
23 Perturbations related to vegetation shifts only imply changes in the biophysical properties of  
24 the surface, while biochemical, atmospheric and hydrological properties are not perturbed.  
25 The only difference between the simulations is the described changes in vegetation  
26 distribution and resulting feedback effects of these, as simulations are in all other aspects  
27 identical. As the vegetation cover is not able to react to meteorological forcing during the  
28 simulations (non-dynamical vegetation), the effects of the structural vegetation perturbations  
29 are one-way in this study, therefore all changes in the meteorological conditions as compared  
30 to the control simulation may be assumed a result of vegetation perturbations alone. The  
31 applied changes in dominant vegetation category for each experiment, as compared to the  
32 control simulation, are illustrated in Fig. 2.

### 1 **2.1.1 Experiment 1**

2 The main emphasis in the first experiment (hereafter Ex 1), is the widely documented feature  
3 of ~~arectic~~Arctic shrub expansion into tundra regions. This change involves increase in surface  
4 roughness and wintertime albedo, as documented by e.g. Chapin et al. (2005). This is also  
5 regarded the most rapid of the applied vegetation shifts, and as such occupies the largest area  
6 of applied changes. To represent this vegetation shift, a moderate change in tundra vegetation  
7 is applied by changing the areas covered by the vegetation category of “mixed tundra” into  
8 “wooded tundra”, thereby slightly increasing the roughness length, and reducing the  
9 wintertime albedo (Table 2). In addition, to account for another important trend in the  
10 northernmost latitudes of our domain, we have made a perturbation representing the  
11 northward migration of the boreal forest by applying the land use category of evergreen  
12 needle leaf forest in areas previously covered by wooded tundra. The shift is applied up to 108  
13 km to represent a slow migration towards higher latitudes in areas that already are covered by  
14 vegetation. This northward shift of dense forest implies an increase in LAI and decrease in  
15 albedo, owing to the denser canopy of the evergreen forest (Table 2). For Ex 1 these two  
16 vegetation changes imply changes in a total area of 563 517 km<sup>2</sup> of shrub expansion/tundra  
17 conversion and a minor area of 181 521 km<sup>2</sup> of northward migrating evergreen forest (Fig. 2,  
18 left panel).

### 19 **2.1.2 Experiment 2**

20 In the second experiment (hereafter Ex 2), the northward migration of the southern edges of  
21 boreal forest is also taken into account by applying a perturbation representing a northward  
22 migration of the southern border of the evergreen forest and its replacement of more  
23 temperate species. To achieve this, in addition to the changes made for Ex 1, also the southern  
24 border of the evergreen needle leaf forest is shifted northward by up to 108 km (similar to the  
25 migration of evergreen forest on the northern border), being replaced by the category of  
26 mixed forest, representing a slow transition towards a more temperate forest type. For the  
27 physical properties of the surface, this implies a decrease in maximum and minimum LAI  
28 values and increase in maximum and minimum albedo (Table 2). These vegetation changes  
29 cover a total area of 392 202 km<sup>2</sup> of northward migrating mixed forest, and represents as such  
30 a substantial shift in vegetation, although consistent with the northern vegetation perturbations  
31 in Ex 1.

32

### 1 3 Results

2 Results are largely presented as differences between experiment simulations as compared to  
3 the control run. To account for inter-seasonal and inter-annual variations, we start by  
4 examining the long term average effects across the full length of the ~~10-year simulation~~  
5 10-year simulation period (excluding the ~~spinup~~spin up-year), largely focusing on regional  
6 means. Time averages are all based on the three hour output frequency, and as such represents  
7 mean day and night values. In addition, average changes over selected areas of specified  
8 vegetation shifts are presented to highlight the effects of individual vegetation changes. The  
9 main emphasis is on alterations in surface fluxes and near-surface atmosphere; however a  
10 short investigation of effects on soil moisture content is also conducted. We investigate the  
11 seasonal variations in Sect. 3.2 and try to further isolate conditional effects with regard to  
12 water deficits in soil and air in Sect. 3.3.

#### 13 3.1 10 year averages: What are the overall effects of vegetation changes?

14 The applied vegetation changes lead to alterations in key surface parameters such as surface  
15 albedo and leaf area index (LAI), corresponding to their new minimum and maximum values  
16 assigned to each vegetation category in the model parameterization (Table 2). The 10 year  
17 average change in albedo due to structural vegetation changes is shown in Fig. 3. Here the  
18 difference between Ex 2 and the control run is shown to account for all applied vegetation  
19 changes. The effect on albedo and LAI ~~changes are not constant throughout the year (Sect.~~  
20 3.2) and across the domain, and is ~~changes are not constant throughout the year (Sect. 3.2) and~~  
21 across the domain, and are a result of the scaling between vegetation dependent prescribed  
22 min. and max. values by the vegetation greenness fraction throughout the year. The annual  
23 average features represented here, show that in areas with a northward migrating evergreen  
24 needle leaf forest, vegetation changes largely leads to a decrease in surface albedo, whereas  
25 areas with simulated shrub expansion do not affect the 10 year average albedo notably~~ye~~. The  
26 southern border change from evergreen needle leaf- to mixed forest leads to ~~a~~ a year-round  
27 increase in surface albedo. A general increase in LAI is seen in areas with a northward  
28 expanding evergreen needle leaf forest, whereas a decrease is seen across the area of mixed  
29 forest migration (Fig. 3, right panel). The areas of shrub expansion do not influence the LAI.  
30 The changes in these surface properties together with the roughness ~~length,~~length are largely  
31 what ~~induces~~induce the changes in the land-atmosphere interactions described below.

1 The 10 year average changes in sensible- and latent surface fluxes as compared to control  
2 simulation are presented in Fig. 4 for both experiments. Only statistically significant results at  
3 the 95% confidence level based on Student's t-test statistics are presented. The overall  
4 average effect of vegetation changes is a decrease in sensible heat flux to the atmosphere (left  
5 panels). Shrub expansion has only a minor influence on the average sensible heat flux. As  
6 seen in the lower left panel, the most pronounced negative effect is a result of the northward  
7 advancement of mixed forest (Ex 2). The northernmost expansion of evergreen trees into  
8 tundra also reduces the sensible heat flux, but not to the same degree. There are large seasonal  
9 variations in the sensible heat response, and these results are largely reflecting the summer  
10 season results (see Sect. 3.2). The reduction in sensible heat flux over the entire 10 year  
11 period for Ex 1 compared to control run, is  $0.7 \text{ W m}^{-2}$  for areas averaged over both shrub  
12 expansion and northward migrating evergreen forest (all numbers refer to averages in areas  
13 with vegetation changes only). The corresponding number for Ex 2, considering all vegetation  
14 changes, is a reduction of  $1.4 \text{ W m}^{-2}$ , mostly a response to the mixed forest northward  
15 migration (Fig. 7).

16 A contrasting pattern is seen in the effect on the latent heat flux (Fig. 4, right panel). The  
17 northward migrating forest and shrub expansion in Ex 1 are both enhancing the latent heat  
18 flux, with areas experiencing a northward migrating evergreen needle leaf forest, dominating  
19 the results (upper panels). The 10 year average response in Ex 1 is an increase in the latent  
20 heat flux by  $1.2 \text{ W m}^{-2}$ . This number also includes areas with tundra shrub expansion, and the  
21 mean change over areas with northward expanding evergreen forest only, is  $4.4 \text{ W m}^{-2}$ . In Ex  
22 2, the mean effect of vegetation migration is a reduction of the latent heat flux by  $0.4 \text{ W m}^{-2}$ ,  
23 mainly influenced by the negative effect of the mixed forest expansion, in which areas the  
24 average latent heat flux is reduced by  $3.5 \text{ W m}^{-2}$ . There are large seasonal variations in the  
25 response of the surface fluxes, as presented in Sect. 3.2.

26 The changing wind speed (Fig. 5) is closely related to the perturbations to the surface  
27 roughness length, and influences the turbulent heat fluxes. The reduced wind speed in the  
28 northern part of the domain contributes to decreases in the sensible heat fluxes, and an  
29 opposite effect is seen along the area of mixed forest perturbation.

30 Figure 6 shows the 10 year average effect of vegetation changes on near surface atmospheric  
31 variables. The 2 m temperature (left panels) is sensitive to surface fluxes of sensible and latent  
32 heat, and to the surface radiative budget. The overall effect on this variable is a good climatic  
33 indicator of the effects of vegetation changes on the atmosphere. In Ex 1 we see the largest



1 effect in the north-eastern part of the domain (upper left panel). The areas with the highest  
2 increase in temperature are dominated by, although not restricted to, areas with a northward  
3 expanding evergreen needle leaf forest. Temperature increase is also seen along areas of shrub  
4 expansion, although with a weaker average response. The 10 year average increase in 2 m  
5 temperature in these areas (total area of changed vegetation in Ex 1) is 0.11 °C. The weak  
6 response in the 2 m temperature is a result of the compensating effect of the lowered surface  
7 albedo by the increase in latent heat flux, yielding small differences in the 2 m temperature.  
8 Also, reduced wind speed and decreases in heat transfer to the near surface atmosphere by  
9 sensible heat flux lowers the near surface temperature response.

10 In Ex 2 (Fig. 6, lower left panel) the dominant feature is the contrasting cooling effect of the  
11 southern border mixed forest northward migration. The annual average effect of this  
12 vegetation change is a cooling of 0.19 °C, which together with the northern vegetation shifts  
13 results in a total average effect of combined vegetation shifts of 0.0 °C, averaged over all grid  
14 cells with vegetation changes. This cooling can be explained by the increase in surface albedo  
15 related to this vegetation perturbation, yielding less radiative warming of the surface and  
16 corresponding weaker heat transfer by turbulent heat fluxes to the atmosphere. Figure 7  
17 summarizes changes in near surface atmospheric variables, given as average effects resulting  
18 from vegetation changes in Ex 1 (left bars), Ex 2- Ex 1 (middle bars) and all of the vegetation  
19 changes, applied in Ex 2 (right bars). Seasonal statistical significance of corresponding  
20 variables is presented in Sect 3.2.

21 10 year average changes in planetary boundary layer height (PBLH) and surface pressure  
22 resulting from vegetation changes is shown in Fig. 8. The PBLH is increased in the areas with  
23 shrub expansion and northward shifts in evergreen needle leaf forest, and decreased in areas  
24 with mixed forest northward expansion, reflecting the results for the turbulent heat fluxes and  
25 temperature changes. A pattern of increased surface pressure along the northern coastline of  
26 the domain is clear, especially over regions of northward expanding evergreen forest.

27 Figure 9 shows the 10 year average percentage change in volumetric liquid soil water content  
28 for Ex 2 compared to control run, for each of the four simulated soil layers. As demonstrated  
29 by the figure, the vegetation change most influential on the water content is the area of  
30 northward expanding evergreen forest into previously tundra covered area in the north of the  
31 domain. The change is larger deeper down in the soil, reflecting the fact that the number of  
32 root layers for the evergreen forest increases to four, as compared to the tundra, which only  
33 influences the three upper layers. The lowering of soil water content is a result of the ability

1 of the evergreen forest to extract more water from the ground compared to the tundra  
2 vegetation, and is reflected in the increase in the latent heat flux in this area. The other  
3 vegetation changes do not significantly affect the soil moisture content. However, the change  
4 of evergreen trees into mixed deciduous forest influences the annual cycle of soil moisture  
5 content by decreasing it in spring and increasing it in late summer and fall (Figure 10).

### 6 **3.2 Seasonal averages; when are various effects largest?**

7 Seasonal variations in surface- and near surface variables as results of the various vegetation  
8 changes are presented in Fig. 10. Each stippled line shows 10 year monthly mean changes for  
9 one type of vegetation change as averages only over the grid cells with the corresponding  
10 vegetation shift. The overall mean effect of all vegetation changes, averaged over the total  
11 area of all vegetation shifts, is shown in the black line marked Ex 2-Ctrl. Black circles  
12 indicate monthly area means passing the 95% confidence interval based on Student's t-  
13 statistics. Confidence intervals are computed from the control simulation monthly means for  
14 each area with changed vegetation, and circled points as such represent months where the  
15 average values for each area are significantly different from the control simulation area mean.

16 For the albedo (Fig. 10, upper left panel), the ~~decrease~~increase due to the northward  
17 migrating mixed forest is most prominent in spring and autumn months, whereas the increase  
18 is less over the summer and smallest during winter. The contrasting negative effect on the  
19 albedo resulting from the evergreen needle leaf tree northward migration is largest in fall and  
20 the mean effect throughout the year is a lowering of the surface albedo. The maximum change  
21 in spring and autumn months, reflect the close dependence on the LAI, which varies  
22 throughout the year. The effect in the winter months is on average small because of snow  
23 covering the vegetation. The spatial variability across the domain is largest in spring and  
24 autumn months (not shown), and smallest in summer, reflecting the fact that LAI changes  
25 occur at an uneven rate across the domain in these transitional periods (the changes in albedo  
26 and LAI results from changing parameter values, and are therefore not ~~stat~~istically tested).

27 The largest effect on the sensible heat flux (Fig. 10, middle left panel); is seen in areas of  
28 evergreen needle leaf forest expansion in summer, on average reducing the heat flux by 11.2  
29  $\text{W m}^{-2}$  in July. In winter and autumn the effect on the sensible heat flux is reversed as result of  
30 this vegetation change, increasing the heat flux in these areas, especially in autumn. The shrub  
31 expansion only has a weak decreasing effect on the sensible heat flux in summer. The mixed  
32 forest migration has a pronounced year-round effect on the sensible heat flux, with the most

1 prominent reduction in spring and early summer. The overall effect of all vegetation changes  
2 (solid line) is close to zero in winter, and a reduction in sensible heat flux to the atmosphere is  
3 seen over the summer.

4 For the latent heat flux (Fig. 10, middle right panel), the effect of the shrub expansion is low,  
5 and the two types of forest expansion dominate the results in contrasting ways. The evergreen  
6 needle leaf forest expansion causes a sharp increase in summer time latent heat fluxes  
7 compared to the control run. Absolute values of the latent heat flux are largest in summer  
8 months, and so are the differences due to vegetation shifts, with a peak increase in July of on  
9 average as much as  $18 \text{ W m}^{-2}$ . The mixed forest expansion on the other hand, acts to decrease  
10 latent heat fluxes all year round, and the decreasing effect is largest in June with an average  
11 reduction of about  $10.3 \text{ W m}^{-2}$ . The net effect is a year- round slight decrease in latent heat  
12 fluxes from the surface to the atmosphere, with largest effect in spring (solid line).

13 The 2 m humidity varies on a monthly basis similar to the latent heat flux, as these two  
14 variables are closely linked. The effect on humidity is dominated by the two types of forest  
15 migration, whereas the effect of shrub expansion is small. The evergreen needle leaf forest  
16 expansion has a prominent positive effect, increasing the humidity especially in summer,  
17 whereas the mixed forest expansion acts to decrease the 2 m humidity in these areas, having  
18 the largest effect over the summer months (not shown). The humidity is dependent on the soil  
19 moisture through transpiration and ground evaporation. The soil moisture content is most  
20 prominently affected by the conversion of tundra to evergreen forest, as the forest subtracts  
21 more soil water from all four layers compared to the tundra vegetation. As a result of the  
22 increased rooting depth, the most prominent effect is on the bottom layer (layer four), as  
23 presented in Fig. 10 (lower left panel).

24 The effects of vegetation changes on the 2 m temperature are complex and vary across the  
25 areas of vegetation shifts and seasons (Fig. 10, lower right panel). However, despite in part  
26 large effects on surface heat fluxes, the overall 2 m temperature response is low, and the area  
27 mean differences are not statistically significant. In areas with shrub expansion there is a  
28 small, yet persistent year-round positive effects on the temperature compared to the control  
29 run, with the largest effects occurring in fall and winter months. In areas with evergreen forest  
30 expansion we see a wintertime heating, whereas the summer time effect is opposite, causing a  
31 cooling of the 2 m temperature in June through August, reflecting the decrease in sensible  
32 heat flux in the same period. The effect of the mixed forest migration is a modest year-round  
33 cooling of the 2 m temperature, and the effect is largest in the spring and autumn months, and

1 lowest in mid-summer. The overall effect is a net increase in 2 m temperatures in winter, and  
2 decreasing 2 m temperatures in summer (solid line). This is accounting for all vegetation  
3 shifts.

### 4 **3.3 Conditional effects; under which conditions are effects largest?**

5 The latent heat flux is mainly the combined effect of soil evaporation, transpiration and  
6 evaporation from interception. The part most closely linked to the specific type of vegetation  
7 cover is the evapotranspiration (i.e. transpiration and evaporation of intercepted water), which  
8 depends on water availability (either as intercepted water or to the plant through the roots),  
9 the efficiency of turbulent transfer and the evaporative power of the ambient atmosphere. As  
10 both the number of soil layers available to the plants roots, and the LAI and thereby the rate of  
11 evapotranspiration, varies across vegetation types, the dependence of latent heat (and thus the  
12 evapotranspiration) on soil moisture as compared to the vapor pressure deficit (VPD) in the  
13 surrounding air, may shift as vegetation category changes. To investigate these effects in more  
14 detail, the effects of selected vegetation changes on the relationship between the latent heat  
15 flux and soil moisture, and latent heat flux and ambient air vapor pressure deficit, are shown  
16 in Fig. 11. The effect of shrub expansion on surface heat fluxes is low, and so we focus here  
17 on areas with forest migration. As fluxes and flux response to vegetation shifts are largest in  
18 summer months, only monthly averages of the summer season (JJA) are used, and correlation  
19 coefficients based on averages in each area are given. Changes averaged over areas with  
20 evergreen forest expansion into tundra is shown in the upper panels, and mixed forest  
21 northward migration in the lower panels. The white circles indicate monthly mean values as  
22 simulated in the control run, and black dots represent monthly mean values averaged over the  
23 same area after vegetation shifts.

24 The correlation coefficient between latent heat flux and soil moisture content is low,  
25 regardless of vegetation type. This indicates that the soil moisture content does not limit the  
26 rate of latent heat, suggesting that the latent heat flux is limited by the available radiative  
27 energy, rather than available water (Seneviratne et al., 2010). The latent heat's correlation to  
28 VPD is increased from 0.68 to 0.74 when changing vegetation from tundra to evergreen  
29 forest, indicating that the evergreen forest latent heat flux is more dependent on the ambient  
30 atmosphere than the tundra vegetation it replaces. Also, the evergreen forest can reach four  
31 root layers rather than three, which is the case for the tundra, making more soil water  
32 available. For the mixed forest northward expansion, the same shifts in correlation occurs,

1 indicating that shifting vegetation type from evergreen forest to mixed forest also acts to  
2 increase the latent heat flux dependence on VPD rather than soil moisture.

3

#### 4 **4 Discussion of results**

5 Perturbations in this study were limited to changing the dominant land category in given  
6 areas, and accordingly to changes in certain physical properties of the surface. The  
7 parameterization of physical processes in the model has not been altered, in order to maintain  
8 a high relevance to other studies. The modified IGBP MODIS vegetation dataset is regarded a  
9 suitable basis for perturbations, although many alternatives do exist with regard to datasets,  
10 and vegetation perturbations that will influence the results. Liess et al. (2011) used the IGBP  
11 MODIS land cover dataset in which no alterations have been made to the land use category of  
12 “open shrub land” as is the case for the modified MODIS dataset (where replaced by various  
13 tundra vegetation classes). They found the open shrub land use class a suitable category for  
14 forest conversion across the ~~arectic~~Arctic and northern boreal domain. This represents a  
15 similar, but somewhat larger land use change than the ones applied in our study, although in  
16 good agreement with observational data and estimates for future changes in the area (Liess et  
17 al., 2011). We have not made any assumptions related to the vegetation coverage after  
18 changing vegetation type, i.e. the greenness vegetation fraction is left unaltered.

19 The perturbations applied here represent simplified estimates of future vegetation distribution,  
20 based on observed trends in vegetation migration in the area. As such, the results are not  
21 possible to validate against time- and site-specific observations. However, some general  
22 features resulting from similar vegetation changes, as observed in large scale, cross-site  
23 measurement studies, may help determine whether modelled results are in line with  
24 expectations or differ substantially. In the following we relate our results to a few such studies  
25 in order to point to possible strengths and weaknesses in model parameterization and  
26 configuration.

27 Changes in albedo are largest in spring and autumn months, reflecting the differences in LAI  
28 in these periods. In summer, the broadleaved deciduous species reach their peak LAI values,  
29 and the difference to the evergreen needle leaf trees is smallest. In winter, the effect of  
30 difference in LAI is at its largest; however its effect on the surface albedo is to a great extent  
31 masked by snow cover. The areas of evergreen needle leaf forest expansion has a profound  
32 impact on summer- and autumn- months albedo, but interestingly a low impact on modelled

1 albedo during winter months. In fact, the effect of the evergreen forest migration on winter  
2 albedo is nearly zero during winter months.

3 It has been suggested that the lowering of surface albedo over snow covered ground, as result  
4 of taller and more complex canopies as compared to snow covered tundra, will greatly affect  
5 wintertime surface heat fluxes and that the lower wintertime albedo would also increase  
6 snowmelt and prolong growing seasons (e.g. Bonan et al., 1992;Betts and Ball, 1997).  
7 However, the parameterization of snow albedo in relation to high latitude vegetation has been  
8 pointed out as a source of uncertainty in high latitude climate modelling (e.g. Qu and Hall,  
9 2006;Loranty et al., 2014). Loranty et al. (2014) found that on average the CMIP5 model tree  
10 cover and albedo do not correlate well. They also point out that the observed general  
11 decreasing albedo with increasing tree cover south of the latitudinal tree line seems badly  
12 represented in coupled climate models.

13 In WRF (Noah), the vegetation-specific surface albedo is weighted against a corresponding  
14 vegetation-specific snow albedo value from Robinson and Kukla (1985). A vegetation-  
15 dependent threshold value with regard to snow water equivalent (SWE) is used to determine if  
16 the ground is fully snow-covered, and for fresh snow, a higher albedo value is estimated to  
17 decay towards the fixed vegetation snow albedo values over a period of a few days. This  
18 parameterization is based on Koren et al. (1999), after revisions by Livneh et al. (2010). The  
19 snow albedo parameterization in WRF-Noah has been subject to a number of studies in recent  
20 years, some revealing weaknesses related to early snowmelt as a result of too low snow  
21 albedo values. However, recent improvements were suggested by Wang et al. (2010), who  
22 found that an increase in the snow cover threshold value for high vegetation, and lowering for  
23 low vegetation, reduced over (under-) estimation of snow albedo over high (low) vegetation.  
24 This alteration, together with other minor improvements, has recently been made available as  
25 an option in Noah and Noah-MP (Noah land surface model with multiparameterization  
26 options) (Yang et al., 2011;Niu et al., 2011), and as such it would be of interest to test this  
27 version in a further study. A verification of estimated snow cover and snow albedo against  
28 observations for the simulated study area is beyond the focus of this study, however, the  
29 results herein suggest that the rather low wintertime warming seen in the evergreen forest  
30 expanding areas, may be somewhat underestimated.

31 Beringer et al. (2005) examined the potential influence of structural vegetation changes by  
32 measuring surface energy exchanges along tundra- to forest transition zone in Alaska during  
33 the summer of 1999. They measured sensible heat fluxes and evapotranspiration in five

1 different sites (tundra, low shrub, tall shrub, woodland and forest) acting as an analogue to  
2 vegetation transitions that might occur under enhanced warming. Despite the fact that  
3 measurement sites in Beringer et al. (2005) and the simulation domain herein differ in both  
4 time and continent, comparing the results points to some general features of summer surface  
5 energy partitioning related to vegetation changes, and may as such be useful. They reported  
6 small differences in latent energy flux between the sites, and a decrease in ground evaporation  
7 was compensated by an increase in evapotranspiration moving from tundra towards more  
8 complex canopies. Sensible heat flux was increased going from tundra to more complex  
9 canopy vegetation, with both shrubs and trees enhancing the sensible heat flux to the  
10 atmosphere. These findings are supported by modeled findings for heat flux changes resulting  
11 from similar vegetation changes (Jeong et al., 2011; Jeong et al., 2014; Snyder and Liess,  
12 2014). Snyder and Liess (2014) found annual mean increases in both sensible and latent heat  
13 fluxes as response to lowered albedo and increased net radiative forcing. For the summer  
14 months, the increased radiative flux was partitioned into sensible rather than latent heat, due  
15 to re-partitioning of evaporative flux, leading to a JJA temperature increase of 0.4 K, and little  
16 or no increase in near surface humidity and precipitation. Jeong et al. (2014) on the other  
17 hand, found increases in both latent and sensible summer season fluxes in response to  
18 ~~arctic~~Arctic greening, leading to relatively large increases in JJA near surface temperatures  
19 (1.95 K).

20 These results stand in contrast to our simulated sensible heat flux, which is reduced in  
21 summertime as result of tree- and shrub expansion into previously tundra covered regions. In  
22 areas with changing tundra (from mixed tundra to wooded tundra), the largest monthly mean  
23 effect is seen in June, with an average reduction of sensible heat of  $1.3 \text{ W m}^{-2}$ , and in areas  
24 with northward expanding evergreen forest the main effect is seen in July, with a mean  
25 reduction of the sensible heat flux by  $11.2 \text{ W m}^{-2}$ . The simulated sensible heat flux is closely  
26 related to wind speed, and in areas where wind speeds are lowered, the turbulent heat fluxes  
27 decrease. Furthermore, the increase in available soil moisture (by increased rooting layers)  
28 going from tundra to evergreen forest acts to increase the transpiration and thereby the latent  
29 heat flux. Also, increased leaf area and corresponding interception and canopy evaporation  
30 serves to increase the latent heat flux and near surface humidity, resulting in increased  
31 summer precipitation. An analysis of the mean JJA rainfall in this area alone shows an  
32 increase in accumulated rainfall of 3,35% over the ten summers. Increased rainfall would  
33 further increase the partitioning of increased absorbed radiation into latent rather than sensible

1 | heat flux, and thereby ~~deere~~decrease heating of the overlying atmosphere. This flux re-  
2 | partitioning leads to an annual 2 m temperature increase of 0.12 °C in areas with evergreen  
3 | forest expansion.

4 | The specifics of vegetation perturbations applied here might have influenced these results.  
5 | Here, we have chosen to only perturb the vegetation type in each area. The greenness fraction  
6 | is not altered, which influences the evapotranspiration and thereby available energy for  
7 | sensible heat, as demonstrated by (Hong et al., 2009). Here, we ~~eoneidered~~considered this  
8 | approach sufficient, as the greenness fraction acts to scale the LAI (and other vegetation  
9 | parameters) values within the vegetation specific range (as indicated in the plotted results for  
10 | the variable), applying the new vegetation category to new areas would not imply a scaling of  
11 | the LAI to values outside the respective category's assigned range. Further investigation of  
12 | the sensitivity of these parameters is beyond the scope of this study, but certainly important  
13 | subjects for further work.

14 | Based on a broad analysis of available observational data from ~~aretie~~Arctic and boreal  
15 | ecosystems, Eugster et al. (2000) found a general increase in latent heat flux in areas with  
16 | deciduous trees replacing evergreen needle leaf forest, due to lower canopy conductance in  
17 | conifer trees. A similar, yet less drastic replacement was made in our Ex 2, where replacement  
18 | of evergreen needle leaf forest by mixed forest (representing a mix of conifer and deciduous  
19 | trees). This shift in vegetation causes a modelled year-round reduction in latent heat. This is a  
20 | result of the model parameterization, which causes a decrease in LAI, but no increase in  
21 | stomatal conductance given the vegetation shift in Ex 2, and thereby acts to decrease the  
22 | latent heat release to the atmosphere. Our experiments suggest a significant increase in latent  
23 | heat flux in summer months in areas with evergreen forest expansion.

24 | Based on summer season observations of flux partitioning over 66 site years within the  
25 | FLUXNET project (Baldocchi et al., 2001), Wilson et al. (2002) found that deciduous forest  
26 | sites in general had a lower summer Bowen ratio (~0.25-0.5) than conifer forest sites (~0.5-  
27 | 1.0), which again were slightly lower than tundra Bowen ratios. In our simulations, areas with  
28 | a northward migrating evergreen forest (northern border) reduce the summer season (JJA)  
29 | Bowen ratio by a factor two, going from wooded tundra to evergreen forest. In areas of  
30 | northward migrating mixed forest (southern boarder), the decrease in both sensible and latent  
31 | heat fluxes results in a slightly decreasing Bowen ratio from 0.51 to 0.49.



1 The modelled increase in evapotranspiration in areas of northward migrating evergreen forest  
2 also affect the soil moisture, with more water being extracted from especially the deeper  
3 layers of soil, owing to the increased number of available soil layers by evergreen forest.  
4 However, the latent heat flux is not highly correlated to the soil moisture content in this  
5 domain, as fluxes are largely energy limited rather than moisture limited. Shifting the  
6 vegetation type towards higher LAI vegetation, acts to reduce correlations for summer months  
7 between latent heat and soil moisture, and increase correlations with VPD. These results are  
8 in agreement with the findings of Kasurinen et al. (2014), who measured latent heat fluxes  
9 over a total 65 different boreal and ~~arectic~~Arctic sites. They found a general increase in latent  
10 heat release and a higher correlation to VPD in observations from forested boreal sites,  
11 compared to tundra ecosystems.

12

## 13 **5 Concluding remarks**

14 In this study, observed trends of boreal forest migration were represented by applying  
15 perturbations to the current boreal vegetation distribution in two separate experiments. The  
16 perturbations were simple enough to extract their separate effects on the overlying  
17 atmosphere, and moderate enough that they induce realistic and relevant information on  
18 atmospheric response to vegetation structural changes.

19 The atmospheric response resulting from the vegetation changes made in Ex 1 and Ex 2  
20 largely points in different directions. The Ex 1 high north shrub- and evergreen forest  
21 expansion largely leads to a decreasing albedo and larger latent heat fluxes, which  
22 subsequently lead to enhanced near surface temperatures and deeper and wetter planetary  
23 boundary layer. Increased summer precipitation and reduced wind speed leads to lower  
24 sensible heat flux, causing a lowering of the Bowen ratio changing from tundra to conifer  
25 forest. On the other hand, the Ex 2 replacement of evergreen forest by more broadleaved  
26 species along the southern border of the boreal forest, leads to lower LAI, higher albedo and  
27 lower surface fluxes, resulting in lower heating of the boundary layer and lower near surface  
28 temperatures and humidity. The differing response of the various vegetation changes results in  
29 that the overall effect on the domain is a near zero temperature response on a 10 year average.  
30 However, there are large seasonal differences in atmospheric response for the individual  
31 vegetation shifts.

1 The study has been successful in uncovering some special features of model parameterization  
2 that might yield unexpected results relative to physical observations of vegetation changes,  
3 such as the masking of albedo changes by snow cover, reducing the expected warming in  
4 winter and spring, and the lowering instead of increase in sensible heat for more complex  
5 canopies. Although latent heat and soil moisture content are closely linked variables, the low  
6 correlations found between the two prove that the high latitude study domain is energy, rather  
7 than water- limited throughout the year.

8 In our simulations the perturbations are kept moderate enough to be achieved within this  
9 century, and although a result of large climatic average changes in the area, the mean response  
10 of the present day atmosphere is not regarded very different from what can be expected as  
11 feedbacks from the one accompanying such vegetation changes. We have mainly focused on  
12 long term average effects and seasonal mean variations. Many feedback processes are not  
13 possible to study in this time resolution, and shorter, more specific time periods might be  
14 advantageous in this respect. For the purpose of more detailed investigation on finer temporal  
15 and spatial scale, future work include the use of these long term simulations as framework for  
16 nested, finer resolution simulations, focusing on more specific processes in vegetation  
17 atmosphere feedbacks.

18

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23

## 24 **References**

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28

1 Table 1. Key parameterizations chosen for the model setup.

Parameterization scheme	Reference
Mellor-Yamada-Janjic planetary boundary layer	(Janjić, 1994)
Morrison two moment microphysics	(Morrison et al., 2009)
RRTMG short- and long wave radiation options	(Iacono et al., 2008)
Kain-Fritsch cumulus scheme	(Kain, 2004)

2

3 Table 2. Key parameters for the dominant vegetation categories used in Ex 1 and Ex 2.

Vegetation category	Min LAI	Max LAI	Roughness length	Min albedo	Max albedo	Rs	Max snow albedo
Mixed Tundra	0.41	3.35	0.15	0.15	0.2	150	60
Wooded tundra	0.41	3.35	0.3	0.15	0.2	150	55
Evergreen needle leaf forest	5	6.4	0.5	0.12	0.12	125	52
Mixed forest	2.8	5.5	0.5	0.17	0.25	125	53

4

5

Landuse efficiency, Evergreen needle leaf forest  
(fraction per gridbox)

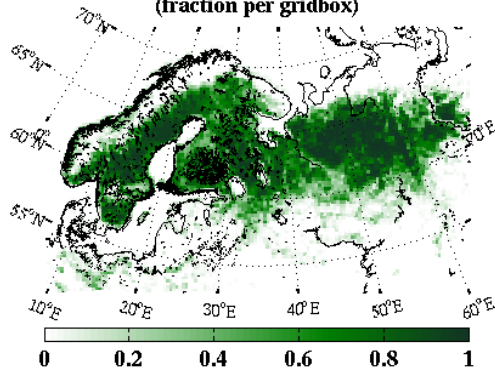
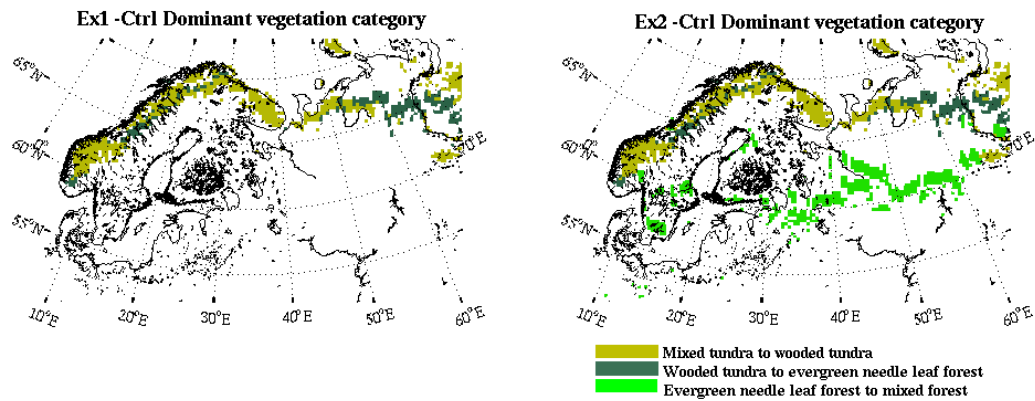


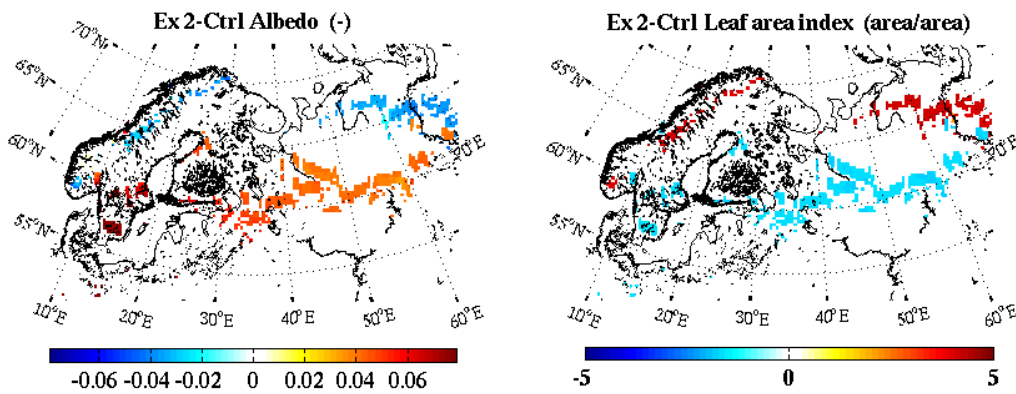
Figure 1. The northern European boreal forest domain, represented here by evergreen needle leaf forest as fraction of grid cell, remapped from the modified IGBP MODIS data to 27x27 km resolution.



1

2 Figure 2. Changes in dominant vegetation category as compared to control simulation for Ex  
 3 1 (left panel) and Ex 2 (right panel). Beige color represents areas where the dominant  
 4 category is changed from mixed tundra to wooded tundra to represent shrub expansion. Dark  
 5 green color indicates areas where the dominant land use category of wooded tundra has been  
 6 replaced by evergreen needle leaf forest. Light green color represents areas where mixed  
 7 forest has taken over for evergreen needle leaf forest (only Ex 2).

8

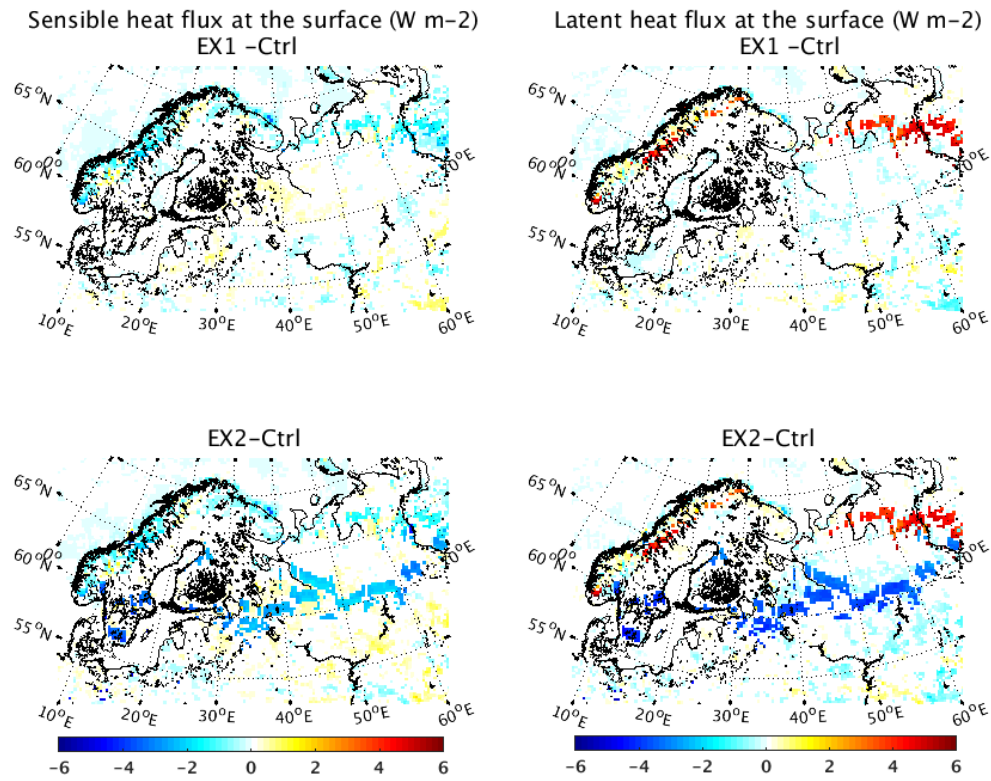


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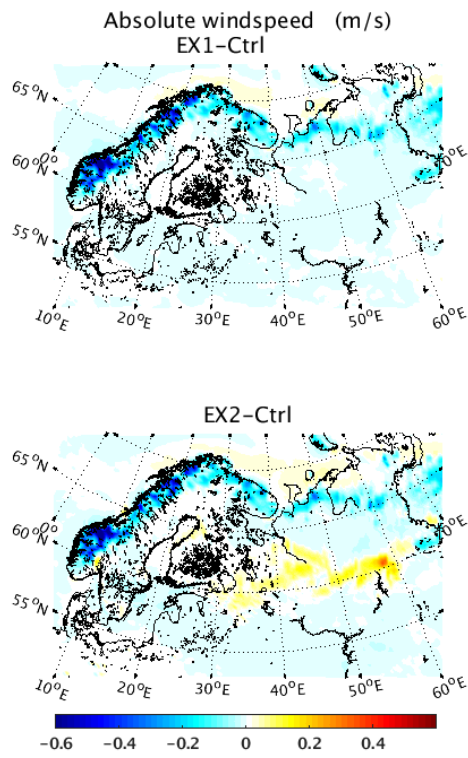
11 Figure 3. Changes in 10 year average albedo (left panel) and LAI (right panel) for Ex 2  
 12 (including all vegetation changes), as compared to control simulation.

13



1  
 2 Figure 4. Changes in 10 year average surface sensible heat flux (left panels) and latent heat  
 3 flux (right panels), as compared to control simulation. Ex 1 in upper panels, Ex 2 in lower  
 4 panels (Only showing significant results at the 95% confidence level).

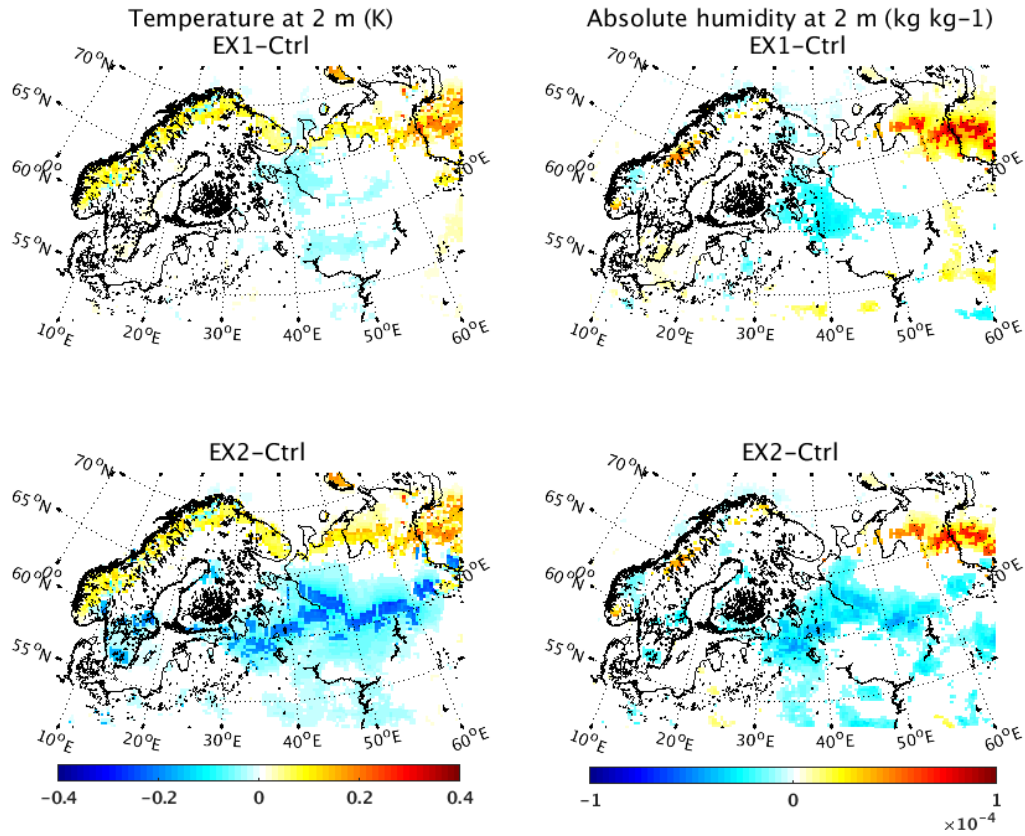
1



2

3 Figure 5. Changes in 10 year average absolute wind speed (m/s) for Ex 1 (upper panel) and  
4 Ex 2 (lower panel) as compared to control run.

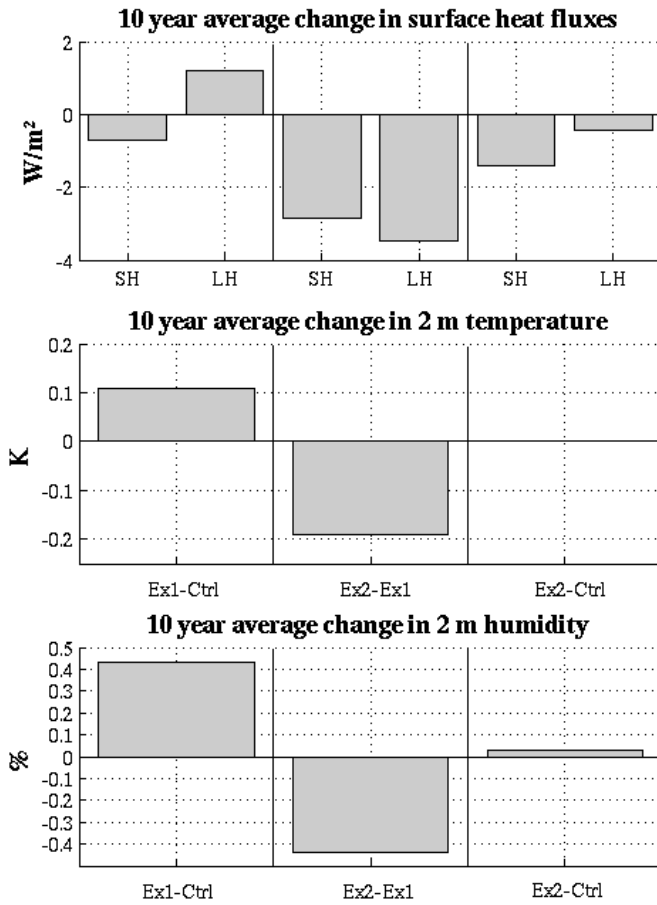
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Figure 6. Changes in 10 year average near-surface variables as compared to control run. 2 m temperature change (left panels) and change in 2 m absolute humidity (right panels). Ex 1 in upper panels, Ex 2 -in lower panels (Only showing significant results at the 95% confidence level).

1

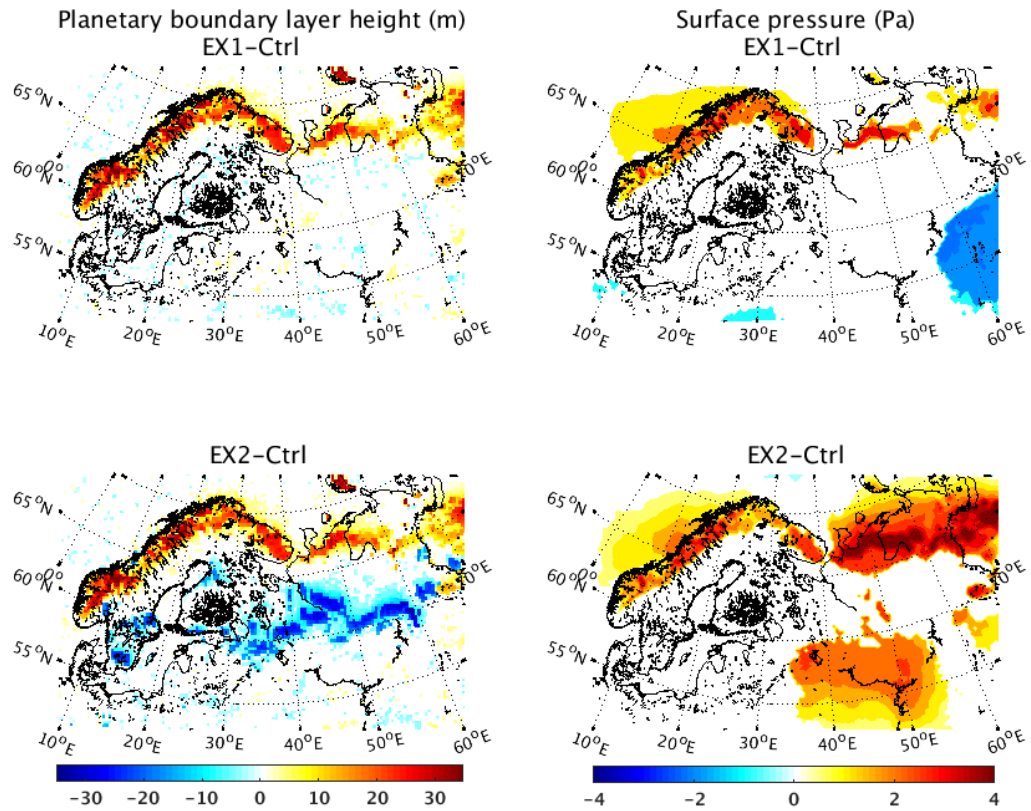


2

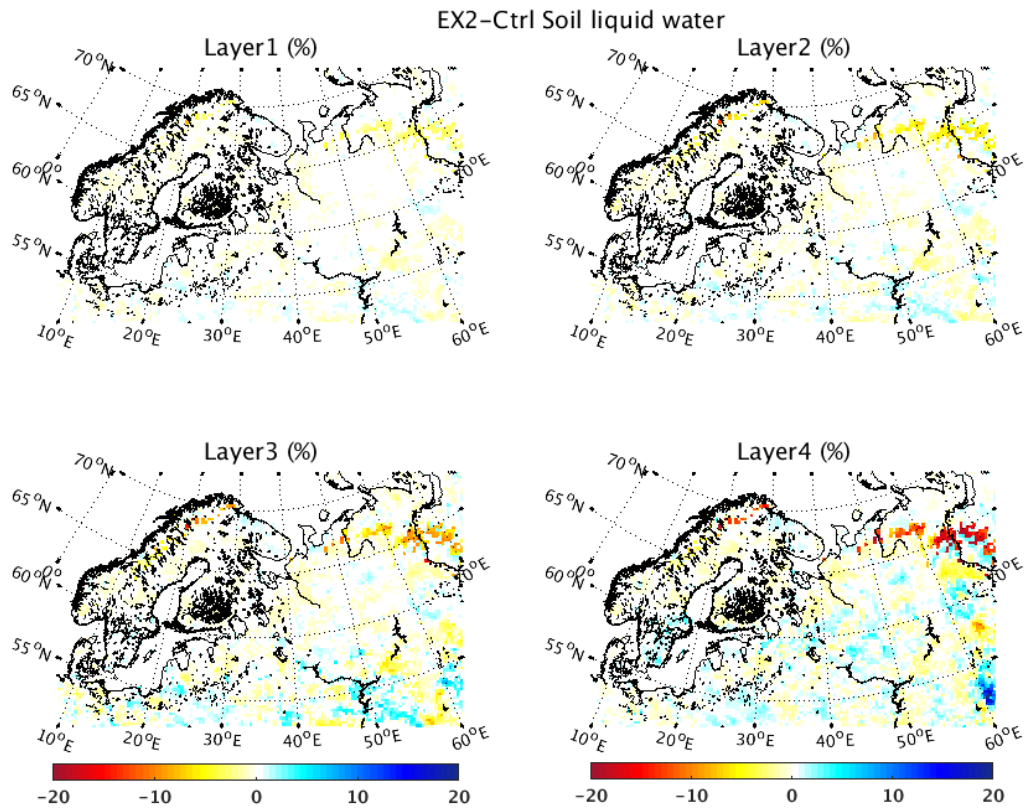
3 Figure 7. Changes in 10 year averages in surface variables, as averages per area of vegetation  
4 change only. Left side bar(s) shows vegetation shift effects of Ex 1 compared to control run  
5 (northward migration of evergreen forest and shrub expansion combined). Middle bar(s)  
6 shows effect of mixed forest migration only, given as difference between Ex 2 and Ex 1.  
7 Right bar(s) show the effect of all vegetation changes together, averaged over all areas with  
8 vegetation changes. Note that areas of different vegetation shifts are not equal in size, and  
9 therefore averages are not additive.

10

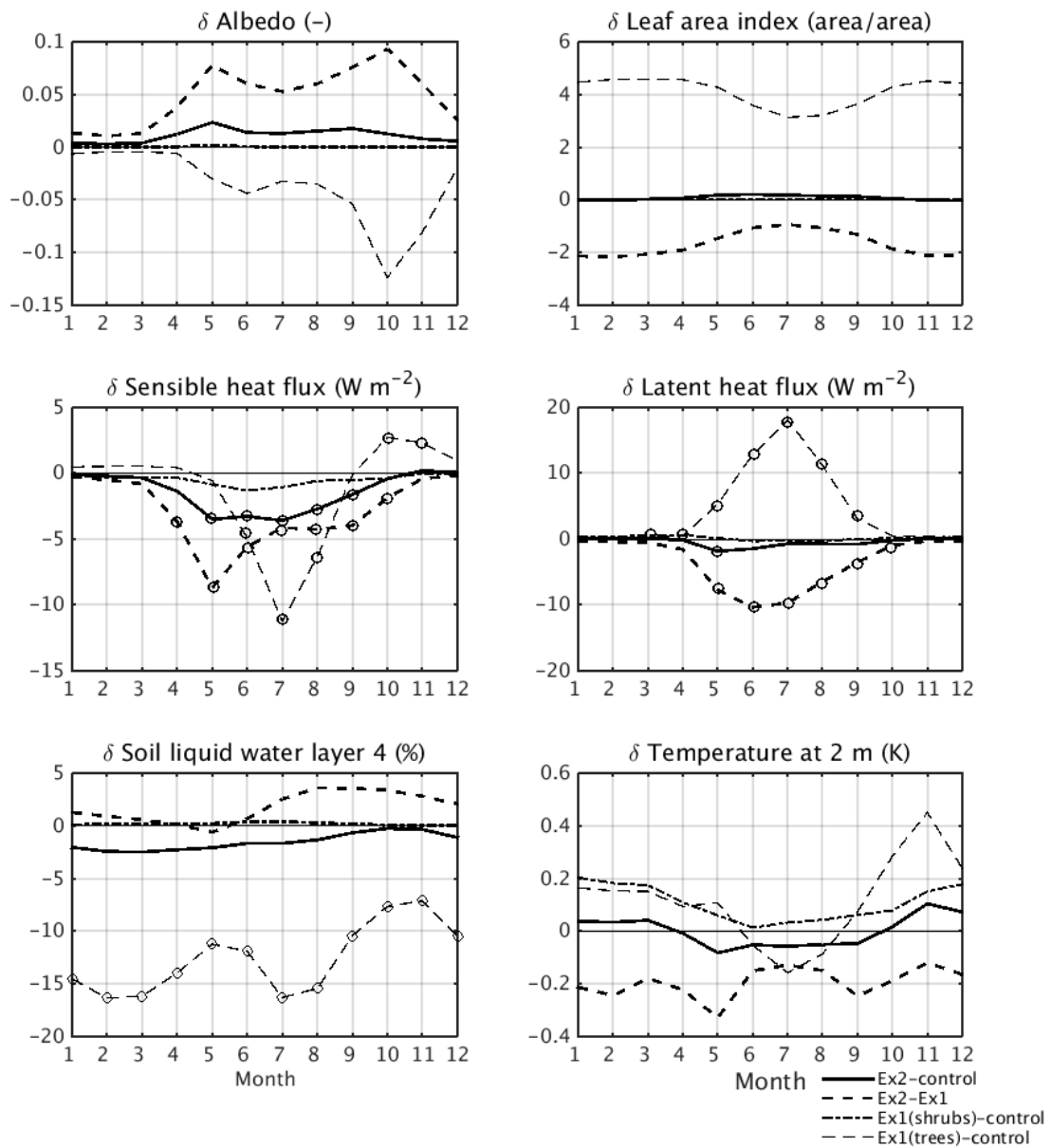




1  
 2 Figure 8. Changes in 10 year average planetary boundary layer height (left panels) and surface  
 3 pressure (right panels) for Ex1 (upper) and Ex2 (lower) compared to control run (only  
 4 showing results significant at the 95% confidence level).  
 5



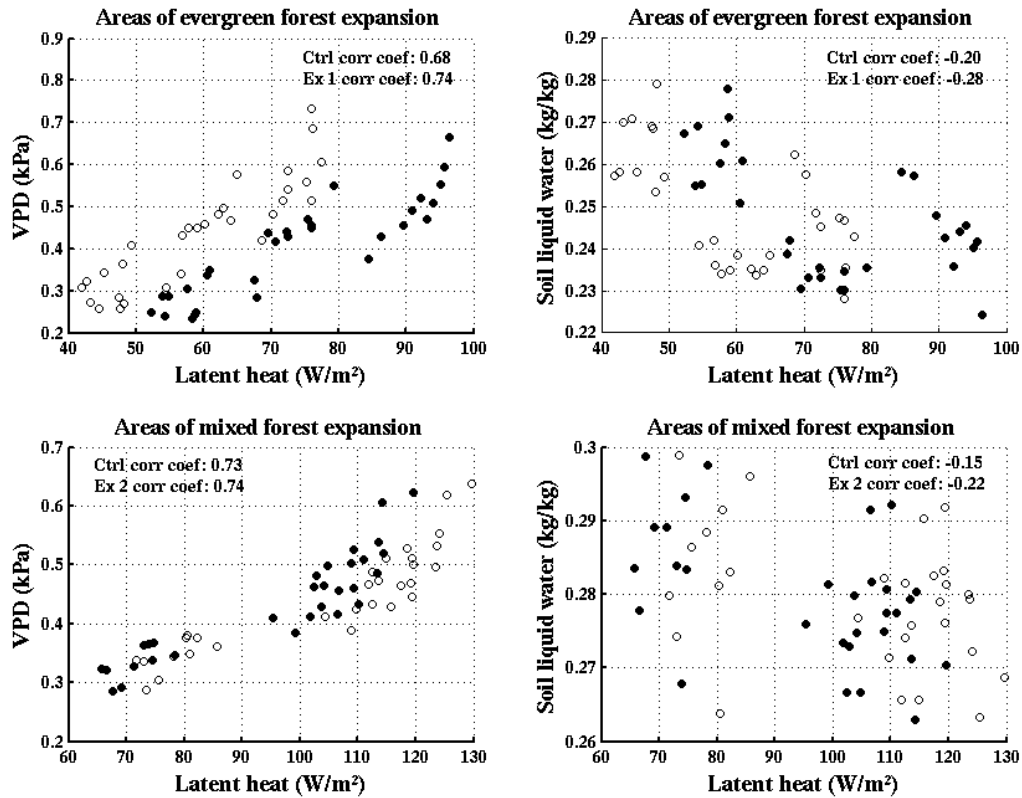
1  
 2 Figure 9. Percentage change in 10 year average volumetric liquid water soil content for each  
 3 soil layer, as the difference between Ex 2 and the control run. Note that red colors indicate  
 4 dryer-, and blue wetter conditions as compared to control run (Only showing significant  
 5 results at the 95% confidence level).



1

2 Figure 10. Seasonal changes in 10 year monthly average surface- and near-surface variables  
 3 for each area with changed vegetation. Average of all vegetation changes shown in thick,  
 4 black line (Ex 2 -Ctrl), black circles indicate significant results at the 95% confidence level.

5



1  
 2 Figure 11. Effect of change in vegetation cover on the relationship between the monthly mean  
 3 latent heat flux and VPD at 2 m (left panels), and latent heat and liquid soil moisture content  
 4 in the top soil layer (right panels). The data are based on summer season (JJA) monthly  
 5 means, averaged over areas with northward expanding evergreen forest (upper panels) and  
 6 areas with northward migrating mixed forest (bottom panels).