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INTERACTIONS BETWEEN LAND SURFACE,
FORESTS AND CLIMATE:
REGIONAL MODELLING STUDIES
IN THE BOREAL ZONE

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Academic dissertation

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Finnish Meteorological Institute
Helsinki, 2016
Interactions between land surface, forests and climate: regional modelling studies in the boreal zone

Abstract

Interactions between the land surface and climate are complex as a range of physical, chemical and biological processes take place. Changes in the land surface or the climate can affect the water, energy and carbon cycles in the Earth system. This thesis discusses a number of critical issues that concern land-atmospheric interactions in the boreal zone, which is characterised by vast areas of peatlands, extensive boreal forests and a long snow cover period. Regional climate modelling and land surface modelling were used as the main tools for this study, in conjunction with observational data for evaluation.

First, to better describe the present-day land cover in the regional climate model, we introduced an up-to-date and high-resolution land cover map to replace the inaccurate and outdated default land cover map for Fennoscandia. Second, in order to provide background information for future forest management actions for climate change mitigation, we studied the biogeophysical effects on the regional climate of peatland forestation, which has been the dominant land cover change in Finland over the last century. Moreover, climate variability can influence the land surface. Although drought is uncommon in northern Europe, an extreme drought occurred in the summer of 2006 in Finland, and induced visible drought symptoms in boreal forests. Thus, we assessed a set of drought indicators with drought impact data in boreal forests in Finland to indicate summer drought in boreal forests. Finally, the impacts of summer drought on water use efficiency of boreal Scots pine forests were studied to gain a deeper understanding of carbon and water dynamics in boreal forest ecosystems.

In summary, the key findings of this thesis include: 1) the updated land cover map led to a slight decrease in biases of the simulated climate conditions. It is expected that the model performance could be improved by further development in model physics. 2) Peatland forestation in Finland can induce a warming effect in the spring of up to 0.43 K and a slight cooling effect in the growing season of less than 0.1 K due to decreased surface albedo and increased evapotranspiration, respectively. Corresponding to spring warming, the snow clearance day was advanced by up to 5 days over a 15-year mean. 3) The soil moisture index SMI was the most capable of the assessed drought indicators in capturing the spatial extent of observed forest damage induced by the extreme drought in 2006 in Finland. Thus, a land surface model capable of reliable predictions of regional soil moisture is important in future drought predictions in the boreal zone. 4) The inherent water use efficiency (IWUE) showed an increase during drought at the ecosystem level, and IWUE was found to be more appropriate than the ecosystem water use efficiency (EWUE) in indicating the impacts of drought on ecosystem functioning. The combined effects of soil moisture drought and atmospheric drought on stomatal conductance have to be taken into account in land surface models at the global scale when simulating the drought effects on plant functioning.
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Helsinki, September 2016

Yao Gao
## Abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CLC</td>
<td>Corine Land Cover</td>
</tr>
<tr>
<td>CMIP</td>
<td>Coupled Model Intercomparison Project</td>
</tr>
<tr>
<td>EC</td>
<td>Eddy Covariance</td>
</tr>
<tr>
<td>EDF</td>
<td>Extreme Drought that affects Forest health</td>
</tr>
<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>EWUE</td>
<td>Ecosystem Water Use Efficiency</td>
</tr>
<tr>
<td>EWUET</td>
<td>Transpiration-based Ecosystem Water Use Efficiency</td>
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<tr>
<td>FNFI1</td>
<td>1\textsuperscript{st} Finnish National Forest Inventory</td>
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<tr>
<td>FNFI10</td>
<td>10\textsuperscript{th} Finnish National Forest Inventory</td>
</tr>
<tr>
<td>GCMs</td>
<td>Global Circulation Models</td>
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<tr>
<td>GHGs</td>
<td>Greenhouse Gases</td>
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<td>GLCCD</td>
<td>Global Land Cover Characteristics Database</td>
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<tr>
<td>GPP</td>
<td>Gross Primary Production</td>
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<tr>
<td>IWUE</td>
<td>Inherent Water Use Efficiency</td>
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<tr>
<td>IWUET</td>
<td>Transpiration-based Inherent Water Use Efficiency</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf Area Index</td>
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<tr>
<td>LSMs</td>
<td>Land Surface Models</td>
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<tr>
<td>LSS</td>
<td>Land Surface Scheme</td>
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<tr>
<td>MPI–ESM</td>
<td>Max Planck Institute for Meteorology Earth System Model</td>
</tr>
<tr>
<td>PFTs</td>
<td>Plant Functional Types</td>
</tr>
<tr>
<td>REW</td>
<td>Relative Extractable Water</td>
</tr>
<tr>
<td>SMA</td>
<td>Soil Moisture Anomaly</td>
</tr>
<tr>
<td>SMI</td>
<td>Soil Moisture Index</td>
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<tr>
<td>SPI</td>
<td>Standardised Precipitation Index</td>
</tr>
<tr>
<td>SPEI</td>
<td>Standardised Precipitation-Evapotranspiration Index</td>
</tr>
<tr>
<td>VPD</td>
<td>Vapour Pressure Deficit</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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<tr>
<td>WUE</td>
<td>Water Use Efficiency</td>
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This thesis consists of an introductory review, followed by four peer-reviewed research articles. In the review, these papers are cited according to their roman numerals.


1. Introduction

The land surface interacts with the climate through physical, chemical and biological processes, which impact on the energy balance and hydrologic cycle of the Earth, as well as on the atmospheric composition (Bonan, 2008). In the context of global climate change induced by anthropogenic emissions of greenhouse gases (GHGs) (IPCC, 2013), detailed analyses of the processes that modulate land-atmosphere interactions are essential for precise future climate predictions and suitable climate change mitigation measures.

Land use and land cover change can have impacts on the climate, and will continue to be an important climate forcing in the future (Feddema et al., 2005). A large body of research has investigated the effects of land use and land cover change on climate over the last decade (Bathiany et al., 2010; Gálos et al., 2011; Göttel et al., 2008; Ge and Zou, 2013; Pielke et al., 2011). In this work, we focused on Finland, where peatland forestation has been intensively conducted (drainage to stimulate forest growth) in naturally treeless or sparsely treed peatlands over the second half of 20th century (Päivänen and Hånell, 2012). The peatland area in Finland in the 1950s was estimated to be 9.7 million ha (Ilvessalo, 1956), of which around 5.5 million ha had been drained for peatland forestation by the beginning of 2000s (Minkkinen et al., 2002; Tomppo et al., 2011). The climatic impacts of peatland forestation have been studied with site-level data and observation-based regional data over Finland (Lohila et al., 2010; Solantie, 1994). However, those studies using observational data were notable to distinguish the effects of peatland forestation on regional climate conditions from global climate changes caused by the increase in concentrations of atmospheric GHGs. In particular, regional scale quantification of the impacts of peatland forestation on the climate from the biogeophysical aspects has not been investigated. Such information is needed for future forest management in regard to climate mitigation.

Moreover, the variability of climate conditions can influence the land surface. Boreal forests have been recognised as a “tipping element” of the Earth system as they are highly sensitive to climate warming (Lenton et al., 2008). Climate extremes such as drought can lead to reductions in forest transpiration and productivity, and even tree mortality in boreal forests
In the summer of 2006, visible drought symptoms on forest appearance were observed in around 30% of forest health observation sites in southern Finland (< 65 °N) (Muukkonen et al., 2015).

Various drought indicators have been proposed in recent years. However, a number of factors lead to difficulties in drought indication, such as the cumulative nature of drought, the temporal and spatial variance during drought development, and the diverse systems that drought could have impacts on (Heim, 2002). Based on meteorological variables, the Standardised Precipitation Index (SPI) and the Standardised Precipitation-Evapotranspiration Index (SPEI) can be calculated at different time scales, and provide a spatially and temporally invariant comparison of drought (McKee et al., 1993; McKee et al., 1995; Vicente-Serrano et al., 2010). Prolonged meteorological drought can initiate shortage in soil moisture, which is closely linked to plant physiology (Mishra and Singh, 2010; Seneviratne et al., 2010). The soil moisture status can be investigated relative to the long-term normal as Soil Moisture Anomaly (SMA), or instantaneously as Soil Moisture Index (SMI) (also referred to as Relative Extractable Water (REW)) (Granier et al., 1999; Lagergren and Lindroth, 2002; Orlowsky and Seneviratne, 2013). Although those drought indicators are globally applicable, their capabilities in indicating specific drought phenomenon at a regional level have rarely been validated in reference to drought impact data (Blauhut et al., 2015). In particular, few drought studies exist in northern Europe because of the low occurrence of drought.

Furthermore, the disturbance of ecosystem functioning has an impact on the water, energy and carbon cycles, for instance, turning an ecosystem from a carbon sink to a carbon source under severe drought (Keenan et al., 2013; Ma et al., 2012; Reichstein et al., 2013). Water Use Efficiency (WUE) is a key metric describing plant functioning. It quantifies the trade-off between photosynthetic carbon assimilation and transpiration at the leaf level (Farquhar et al., 1982). With the widespread application of the eddy covariance (EC) technique, WUE can be calculated at the ecosystem level (EWUE) as the ratio between gross primary production (GPP) and evapotranspiration (ET) (Arneth et al., 2006; Law et al., 2002; Lloyd et al., 2002). The impact of drought on EWUE has been broadly studied; however, there is no agreement
on the changes of EWUE in the forest ecosystem in regard to drought (Ge et al., 2014; Granier et al., 2008; Reichstein et al., 2007; Wolf et al., 2013). In addition, the ecosystem level inherent water use efficiency (IWUE), which can partly counteract the effect of increased vapour pressure deficit (VPD) on ET, has been proposed, and has been shown to increase during a short-term moderate drought (Beer et al., 2009).

Land surface and regional climate models have paved the way for a detailed exploration of the underlying processes that modulate land surface and climate interactions. Regional climate models with high spatial resolution are able to resolve small-scale atmospheric physical and fluid dynamic processes; therefore, they are applicable for the estimation of location, timing and intensity of the climatic influence caused by regional land cover change (Castro et al., 2005; Déqué et al., 2005; Jacob et al., 2007; McGregor, 1997). Land Surface Models (LSMs) focus on land surface processes. LSMs can simulate plant photosynthesis and phenology and the energy, water and carbon exchange between the land surface and the atmosphere (Pitman, 2003). LSMs have also been recognised as a valuable tool to derive spatial distribution of soil moisture, due to the limitations of ground observed soil moisture in space and time and the inability of microwave remote sensing to detect soil moisture in deeper soil layers other than a few centimetres from the surface (Hain et al., 2011; Rebel et al., 2012; Seneviratne et al., 2010). To ensure reliable analyses, model results need to be evaluated with observed datasets and to be interpreted with caution.

This thesis aims to increase our understanding of the interactions between the land surface, forests and climate in the boreal zone. More specifically, the objectives of this thesis are to:

- quantify peatland forestation impacts on the regional climate in Finland from biogeophysical aspects;
- assess the performance of various drought indicators in representing summer drought in boreal forests;
- improve our knowledge of the response of ecosystem functioning to summer drought in boreal Scots pine forests;
- identify the benefits and insufficiencies of modelling approaches in investigating land surface and climate interactions in the boreal zone.
2. Scientific background

2.1 Surface energy and water balance

Land surface, forests and climate are linked through the balance of incoming and outgoing energy, in combination with the water balance at the Earth's surface (Fig. 1). Assuming a layer of horizontally homogenous vegetation exists as an interface between the land surface and the atmosphere, the energy balance equation is:

\[ R_n = LE + H + G + \Delta Q_s \]  

where net surface radiation \((R_n)\) is the total amount of energy absorbed by the Earth's surface. Latent heat flux \((LE)\) is a turbulent flux of energy associated with evaporation from or condensation to the surface and transpiration by vegetation. Sensible heat flux \((H)\) is a turbulent flux of energy induced by the vertical temperature gradient between the air and the surface. Ground heat flux \((G)\) is the heat flux to soil due to temperature gradient within soil. \(\Delta Q_s\) represents the part of energy stored in the assumed interface layer, and it is a sum of several storage terms, such as the energy used for photosynthesis and released in respiration, the heat storages in biomass. \(\Delta Q_s\) is often omitted in climate models, as the amount is very low (Pitman, 2003).

\(R_n\) includes two parts: net shortwave radiation and net longwave radiation. The net shortwave radiation is calculated as the incoming shortwave radiation at the surface \((R_s)\) minus the reflected part \((\alpha R_s)\). Thus, the net shortwave radiation is closely linked to the reflectivity of surface (surface albedo: \(\alpha\)). Different surfaces or vegetation covers have different reflectivities. The net longwave radiation is a balance between incoming longwave radiation at the surface \((R_L)\) and outgoing longwave radiation from the surface. The outgoing longwave radiation is a result of absorbed energy release from the Earth's surface, and can be estimated following Stefan-Boltzmann's Law as \(\varepsilon \sigma T_s^4\), where \(\sigma\) is the Stefan-Boltzmann constant, \(T_s\) is surface temperature and \(\varepsilon\) is surface emissivity. \(R_n\) can be formulated by equation:

\[ R_n = R_s - \alpha R_s + R_L - \varepsilon \sigma T_s^4 \]  

(2.2)
Figure 1: Surface energy and water balance.

The surface energy balance and water balance are coupled through evapotranspiration (ET), which is the outgoing component of the water balance from the Earth's surface and associates with the LE of the energy balance. Precipitation (P) is the source for water in the Earth's surface. Except the amount of precipitation used for ET, precipitation also forms surface runoff (R) and soil water storages (ΔS). After precipitation is infiltrated into a soil column, percolation due to gravity leads to water movements from upper soil to deeper soil. In addition to percolation, diffusion impacts the vertical soil water distribution. Plants may extract water for transpiration from soil using their root. Lateral drainage below the surface can occur when soil gets saturated with water. The surface water balance equation can be written as:

\[ P = ET + R + \Delta S \]  

(2.3)

Land use and land cover change influences surface energy and water balances, thus impacting on climate conditions (Paper I and Paper II) and soil moisture conditions. Changes in surface reflectivity modulate the absorbed shortwave radiation by the surface. For instance, a
snow-covered open area can reflect much more incoming shortwave radiation than a non-snow-covered coniferous forest. Various vegetation types have different ability in transpiration, which is related to leaf area and root depth. Leaf area also determines the precipitation interception capacity. Changes in ET amount can lead to changes in LE. Moreover, the changes in the distribution of root depth can have an impact on soil hydrology. The root zone depth is a surface parameter that describes where plants may extract water for transpiration from soil using their root. Furthermore, the turbulent exchange of momentum, energy and moisture between the surface and the atmosphere is influenced by the roughness of the surface, which can be parameterised as roughness length in models. Forests have larger roughness length compared to other vegetation types. Three components (P, ET, ∆S) of the surface water balance have been used in the calculation of different drought indicators, which are assessed for indicating summer drought in boreal forests (Paper III).

2.2 Photosynthesis, transpiration and stomatal conductance

In the photosynthesis processes, plants assimilate CO₂ from the atmosphere in the environment with light and water (H₂O) to produce carbohydrates (CH₂O) and release O₂ to the atmosphere which can be generally shown as equation below:

\[ CO_2 + H_2O + \text{light} \rightarrow CH_2O + O_2 \] (2.4)

Light, temperature and water are the most important environment conditions that affect photosynthesis. The assimilation rate of a plant can be strongly limited in low light environment and get saturated when there is plenty light. As the activity of enzymes used for photosynthesis is mainly dependent on temperature, the leaf temperature thus has an impact on the assimilation rate. Under an environment with sufficient light and warm temperature, water availability is the limiting factor that most relevant to the photosynthesis capacity, which determines the light-saturated assimilation rate. Visible impacts on forest appearance have been caused by the summer drought in Finland in 2006 (Muukkonen et al., 2015; Paper III).

Transpiration is the process of water movement through plants to the atmosphere. Associating
with the opening of stomata to allow the diffusion of CO$_2$ from the atmosphere into the leaf for photosynthesis, transpiration is considered as an unavoidable cost of photosynthesis. Transpiration transports water and mineral nutrients from roots to leaves, and cool the surface temperature of plants.

The stomatal conductance is defined as the diffusion coefficient of CO$_2$ multiplied with the cross sectional area of the stomata. According to mass conservation, transpired H$_2$O diffuses through stomata 1.6 times faster than CO$_2$. **Paper IV** studies the summer drought impact on ecosystem functioning, which is related to photosynthetic carbon assimilation and transpiration and their connections through stomatal conductance.
3. Material and methods

The regional climate model REMO was used in Paper I and II; and the LSM JSBACH was used in Paper III and IV. The meteorological forcing data for the regional JSBACH simulation in Paper III were adopted from the REMO simulation using the updated land cover map in Paper I. In the sections below, the models and their schemes that are most relevant to this study, as well as various observational data studied in this work are presented.

3.1 Models

3.1.1 REMO regional climate model

REMO is a hydrostatic, three-dimensional atmospheric circulation model that was developed at the Max Planck Institute for Meteorology in Hamburg, Germany (Jacob and Podzun, 1997; Jacob et al., 2001). REMO has showed the ability to represent the basic spatiotemporal patterns of present-day European climate in multi-model intercomparison works, despite the fact that biases exist in the simulations (Hagemann et al., 2004; Jacob et al., 2001; Jacob et al., 2007; Kotlarski et al., 2014). The dynamic core of REMO follows Europa-Modell, which is the former numerical weather prediction model of the German Weather Service (Majewski, 1991). The physical packages (i.e., physical parameterisation scheme) in REMO were originally adopted from the general circulation model ECHAM4 (Roeckner et al., 1996) and many of them have been updated afterwards (see details in section 3.1.1.1). The prognostic variables in REMO include surface pressure, temperature, horizontal wind components, specific humidity and cloud liquid water and ice.

The model uses a rotated spherical Arakawa-C grid horizontally (Arakawa and Lamb, 1977), and a terrain-following hybrid sigma-pressure coordinate system vertically. Temporally, a leap-frog scheme with semi-implicit correction is applied. REMO calculates the fluid dynamics and atmospheric physical processes inside the model domain with the forcing from the boundaries, which contains information in regard to large-scale circulation outside the domain. This is implemented with a relaxation scheme developed by Davies (1976), in which
the large-scale forcing decreases exponentially toward the centre of the domain at the eight outermost gridboxes at each lateral boundary.

The regional model domain in this work covers Fennoscandia and extends from 52 °N to 72 °N and from 4 °E to 40 °E, which is centred around Finland (Fig. 2). The model simulations were performed with a spatial resolution of $0.167^\circ \times 0.167^\circ$ on the rotated model grid and 27 vertical levels. In all the REMO simulations in this thesis, ECWMF ERA-interim reanalysis data was used as the meteorological boundary forcing data (Simmons et al., 2007). Sea surface temperature and sea ice distribution were also prescribed from ERA-Interim data. Prior to the actual REMO simulations, long-term (multi-decades) spin-ups were conducted to obtain equilibrium for the soil water and soil heat budgets.

Figure 2: The model domain and the three sites (Hyytiälä - red, Sodankylä - blue, and Kenttärova - yellow) studied in this thesis. Orography of the model domain is shown as the background. In this study, southern and northern Finland is divided at the 65 °N latitude.
3.1.1.1 The land surface scheme of REMO

The Land Surface Scheme (LSS) of REMO contains a set of surface parameters describing land surface characteristics, which control the surface energy and water balances in REMO. As the impacts of land cover change on climate conditions were studied in Paper I and Paper II, the LSS of REMO is briefly introduced in this section.

In REMO LSS, each model gridbox is composed of fractions of land (vegetation and bare soil), water (ocean and inland lake), and sea ice (Semmler et al., 2004). The biogeophysical characteristics of land cover types (Olson, 1994a, b) in the default land cover map are described by a set of surface parameters (Table 3 in Paper I) (Hagemann et al., 1999; Hagemann, 2002). Those land surface parameters are then averaged according to the fractional coverage of land cover types in a model gridbox (Claussen et al., 1994; Hagemann et al., 1999). Three of the land surface parameters that strongly depend on the vegetation phenology (background surface albedo, leaf area index (LAI), and fractional green vegetation cover) were prescribed with intra-annual cycles using a monthly varying growth factor, which accounts for the seasonal growth of vegetation (Hagemann, 2002; Rechid and Jacob, 2006). Surface albedo is equal to the background surface albedo when there is no snow coverage, while it is a function of snow albedo, background surface albedo and snow depth in the snow-cover period (Kotlarski, 2007). In the REMO LSS used in this work, the intra-annual cycle of background surface albedo has been improved with an advanced parameterisation using global distributions of pure soil and vegetation albedo derived from MODIS satellite data from the period 2001–2004 (Rechid, 2008; Rechid et al., 2009). This updated method for deriving background surface albedo was acceptable for Paper I as it attempted to fit the best descriptions of the present-day land cover into REMO. However, the method is not suitable for historical land-use change studies (such as Paper II) because those albedo maps were not measured during the period with historical land cover. This problem has been recognised by Preuschmann (2012) and a new method has been proposed. Unfortunately, the proposed method was not feasible for high-latitude areas with an extensive snow-cover season, because snow cover hinders the possibility of deriving background albedo values from satellite albedo.
data. Therefore, a simplified method was developed in Paper II to derive the background surface albedo values for the land cover classes in the maps; the parameter values in the snow albedo scheme were also corrected according to Køltzow (2007), Räisänen et al. (2014) and Roesch et al. (2001) (for a more detailed description of the simplified method see Appendix B in Paper II). In addition, small corrections were also made for the surface parameters of coniferous forest and mixed forest in Paper I and Paper II.

The soil temperature is simulated in REMO with heat diffusion equations solved for a five-layer profile (layer thickness: 0.065, 0.254, 0.913, 2.902 and 5.7 m). The heat conductivity and heat capacity required by the heat diffusion equations are dependent on the soil types, for which the FAO/UNESCO soil map of the world is used (FAO/UNESCO, 1971-1981; Kotlarski, 2007). In regard to the soil hydrology, a simple bucket scheme is used (Manabe, 1969) where the maximum water depth corresponds to the root zone depth (Hagemann, 2002). The bucket can be filled with precipitation and snow melt, and depleted through ET (evaporation only occurs in the upper 10 cm of soil) and lateral drainage. The separation of the water supplement into surface runoff and infiltration follows the Arno scheme (Dümenil and Todini, 1992). Hagemann and Gates (2003) improved the Arno scheme to account for the higher resolution subgrid heterogeneity of field capacities within a model gridbox due to the availability of a high resolution land cover map. Three soil hydrology parameters (Beta, Wmin and Wmax) were introduced in the improved Arno scheme to account for the shape of the subgrid distribution of soil water capacities, subgrid minimum and subgrid maximum soil water capacities.

**3.1.2 JSBACH land surface model**

JSBACH is the land surface component of the Max Planck Institute for Meteorology Earth System Model (MPI–ESM) (Roeckner et al., 1996; Stevens et al., 2013). It can be fully coupled with the atmospheric global circulation model, but it can also run offline as a comprehensive process-based terrestrial ecosystem model. Land vegetation cover is described as plant functional types (PFTs) with a set of properties with respect to the processes accounted for by JSBACH. The photosynthesis model of Farquhar et al. (1980) and Collatz et
al. (1992) is used for C3 and C4 plants, respectively.

The land physics of JSBACH were mainly adopted from the physical package of the general circulation model ECHAM5 (Roeckner et al., 2003). The original soil hydrology scheme in JSBACH is the simple bucket scheme used in REMO (described in section 3.1.1.1). It was updated with a 5-layer soil hydrology scheme that has the same vertical distribution as the soil heat profile in the thermal module (Hagemann and Stacke, 2015). Therefore, the active soil depth could be below the root zone until bedrock appears. The soil layers below the root zone can transport water upwards for plant transpiration when the root zone has dried out. Moreover, unlike the bucket scheme where the whole bucket has to be largely saturated, bare soil evaporation in the 5-layer scheme can occur when the uppermost soil layer is wet.

The regional JSBACH simulation in Paper III was performed offline at a temporal resolution of 30 minutes and a spatial resolution of $0.167\degree \times 0.167\degree$ at the Fennoscandian domain. The model was driven by the meteorological data simulated by REMO using the updated land cover map in Paper I, in which the temperature and precipitation were bias corrected with the FMI gridded observational data (Aalto et al., 2013). The PFT distribution over the domain was prescribed based on the more accurate land cover map in Paper I. In addition, in Paper III and Paper IV, site-level simulations with JSBACH at Finnish EC sites (Hyytiälä, Sodankylä, and Kenttärova; shown in Fig. 2) were carried out using the half-hourly local meteorological observations as model forcing. The parameter settings in the JSBACH site-level simulations were mostly based on site-specific information. Prior to the actual regional and site-level JSBACH simulations, long-term spin-up runs were conducted to obtain equilibrium for the soil water and soil heat, as well as for the ecosystem carbon pools.

### 3.1.2.1 Stomatal conductance model in JSBACH

Stomatal conductance ($g_s$) plays an important role in regulating photosynthesis and transpiration, especially under water stress. As Paper IV studies the influence of summer drought on ecosystem functioning in boreal Scots pine forests in Finland, the stomatal conductance model used in the current version of JSBACH is introduced below.
Firstly, the net assimilation rate \( A_n [\text{mol m}^{-2} \text{s}^{-1}] \) and \( g_s [\text{mol m}^{-2} \text{s}^{-1}] \) are calculated for unstressed condition, i.e., nonwater limited condition, as the unstressed net assimilation rate \( A_{n,pot} [\text{mol m}^{-2} \text{s}^{-1}] \) and the unstressed stomatal conductance \( g_{s,pot} [\text{mol m}^{-2} \text{s}^{-1}] \). The \( A_{n,pot} \) is calculated using the photosynthesis model in JSBACH, for which the intercellular CO\(_2\) concentration under unstressed condition \( C_{i,pot} [\text{mol mol}^{-1}] \) is needed. The \( C_{i,pot} \) is prescribed using the atmospheric CO\(_2\) concentration \( C_a [\text{mol mol}^{-1}] \), where \( C_{i,pot} = 0.87C_a \) for C3 plants and \( C_{i,pot} = 0.67C_a \) for C4 plants (Knorr, 2000). After the \( A_{n,pot} \) is determined, the \( g_{s,pot} \) is derived using the following equation:

\[
g_{s,pot} = \frac{1.6A_{n,pot}}{C_a - C_{i,pot}} \tag{3.1}
\]

Then, to derive \( g_s \), \( g_{s,pot} \) is scaled with an empirical water stress factor \( \beta \), which is a function of soil water content:

\[
g_s = \beta g_{s,pot} \tag{3.2}
\]

where

\[
\beta = \begin{cases} 
1 & \theta \geq \theta_{\text{crit}} \\
\frac{\theta - \theta_{\text{wilt}}}{\theta_{\text{crit}} - \theta_{\text{wilt}}} & \theta_{\text{wilt}} < \theta < \theta_{\text{crit}} \\
0 & \theta \leq \theta_{\text{wilt}}
\end{cases} \tag{3.3}
\]

where \( \theta [\text{m}^3 \text{m}^{-3}] \) is the volumetric soil moisture, \( \theta_{\text{crit}} [\text{m}^3 \text{m}^{-3}] \) is the critical soil moisture content, \( \theta_{\text{wilt}} [\text{m}^3 \text{m}^{-3}] \) is the permanent wilting point.

Finally, \( C_i \) and \( A_n \) are computed with \( g_s \). The canopy conductance \( G_c [\text{mol m}^{-2} \text{s}^{-1}] \) and canopy-scale \( A_n \) are integrated over the leaf area.

### 3.2 Observations

#### 3.2.1 Land cover maps

Four land cover maps were adopted for REMO simulations in this study (Table 1). In Paper I,
version 2.0 of Global Land Cover Characteristics Database (GLCCD) was replaced with the 2006 version of the Corine Land Cover (CLC) for the majority of the Fennoscandian domain in REMO, excluding Russia and Belarus where the CLC does not cover. In Paper II, the 1st Finnish National Forest Inventory (FNFI1) and the 10th Finnish National Forest Inventory (FNFI10) were implemented in REMO in order to study the biogeophysical effects of peatland forestation on climate conditions in Finland. The implementation of FNFI maps were based on the work that was done in Paper I.

Table 1: Summary of land cover maps used in this study.

<table>
<thead>
<tr>
<th>Map</th>
<th>Time tag</th>
<th>Spatial Coverage</th>
<th>Spatial Resolution</th>
<th>No. of land cover types</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLC 2006 (CORINE Land Cover)</td>
<td>2006+/-1</td>
<td>Most areas of Europe</td>
<td>100 m</td>
<td>44</td>
<td>European Environment Agency (2007)</td>
</tr>
<tr>
<td>FNFI1 (1st Finnish National Forest Inventory)</td>
<td>1921-1924</td>
<td>Finland</td>
<td>3 km</td>
<td>10</td>
<td>Ilvessalo (1927); Tomppo et al. (2010)</td>
</tr>
<tr>
<td>FNFI10 (10th Finnish National Forest Inventory)</td>
<td>2004-2010</td>
<td>Finland</td>
<td>3 km</td>
<td>10</td>
<td>Korhonen et al. (2013)</td>
</tr>
</tbody>
</table>

The standard land cover map employed in REMO is GLCCD. Based on AVHRR satellite data from April 1992 to March 1993 mainly, the U.S. Geological Survey (1997) constructed GLCCD (version 1.0) to display the global distribution of major ecosystem types (Olson, 1994a, b) at a 1 km horizontal resolution (Loveland et al., 2000). Later, land cover classes that cover 10% of the global land area in GLCCD (version 1.0) were revised and GLCCD (version 2.0) was produced (U.S. Geological Survey, 2001). Similarly, CLC 2006 is a land cover map based on satellite images, which were measured with the HRVIR and LISS-III instruments in 2006 ± 1 year (European Environment Agency, 2007). The horizontal resolution of CLC 2006 is 100 m, and 44 land cover classes were included. The FNFI1 describes the land cover of Finland in the 1920s before peatland forestation (Ilvessalo, 1927; Tomppo et al., 2010), while the FNFI10 represents the present-day land cover in the 2000s (Korhonen et al., 2013). In Paper II, we substituted the CLC with FNFI10 to describe the present-day land cover, in order to avoid uncertainties in comparing land cover maps with different land cover classification methods and different spatial resolutions. The differences between FNFI1 and
FNFI10 show the largest historical changes on land cover in Finland due to peatland forestation, which has started at 1950s. According to the FNFI series, the area of undrained mires was 8.83 million ha at 1951-1953 (FNFI3), 4.32 million ha at 1986-1994 (FNFI8), 4.14 million ha at 1996-2003 (FNFI9) and 4.00 million ha at 2004-2010 (FNFI10) (Päivänen and Hånell, 2012). Both the FNFI land cover maps are at a 3 km resolution and include 10 land cover classes that follow the CLC nomenclature. Both FNFI1 and FNFI10 land cover maps are post-products that were especially prepared for this study from the respective FNFI field measurement data (see detailed description of the procedures in Appendix A in Paper II). The FNFI land cover maps are at a 3 km resolution and include 10 land cover classes that follow the CLC nomenclature, where the land cover type “peat bogs” is defined as naturally treeless peatland and mires where the stocking level is low or the mean height of trees is below 5 m at maturity.

In order to utilise the existing land surface parameters for the default land cover types, translations of the land cover types in the newly introduced land cover maps to the Olson land cover types in GLCCD (version 2.0) have been conducted through comparing the definitions and matching the surface characteristics of land cover types. It is obvious to find appropriate analogues for some land cover types; for instance, matching the coniferous forest, mixed forest and broad-leaved forest in FNFI maps with conifer boreal forest, cool mixed forest and cool broadleaf forest in GLCCD, respectively. However, for some land cover types, such as transitional woodland/shrub in FNFI maps, it is not straightforward to find correspondence land cover types in GLCCD, and GLCCD land cover types with suitable land surface parameters were adopted. All the translations are listed in Table 1 in Paper I and Table B1 in Appendix B in Paper II.

### 3.2.2 Meteorological observations and ecosystem flux data

A number of meteorological observations were used in this work (Table 2). The E-OBS gridded observational data (Haylock et al., 2008) were adopted in Paper I and Paper II for model evaluation. The E-OBS dataset covers the area between 25 °N - 75 °N and 40 °W - 75 °E. It is a daily high-resolution gridded dataset that aims to provide the best estimate of
gridbox values rather than point values to enable direct comparison with the results from regional climate models. The dataset has five elements that include daily mean temperature, daily minimum temperature, daily maximum temperature, daily precipitation sum and daily averaged sea level pressure. It has been found that the uncertainty in E-OBS data is largely dependent on the season and number of observations. Paper I assessed the simulated mean monthly/seasonal maximum and minimum 2-m air temperatures, diurnal temperature range and precipitation with E-OBS data (version 7.0). In Paper II, the temperature trends over 40 years (1959-1998) for March and April were calculated based on monthly mean daily maximum and monthly mean daily minimum surface temperatures over Finland from E-OBS data (version 10.0), so as to compare with the simulated effects on surface temperature in spring from peatland forestation.

Moreover, the gridded meteorological data compiled by the Finnish Meteorological Institute (FMI gridded observational data; Aalto et al. (2013)) from site observations in Finland were used as the baseline climate for the bias correction of JSBACH forcing data, and as inputs for the calculation of observation-based drought indicators (Paper III). The data contain daily mean temperature, daily minimum temperature, daily maximum temperature, precipitation, relative humidity and incoming shortwave radiation on a 0.2° longitude × 0.1° latitude grid over Finland.

Meteorological data at the three sites were used as meteorological forcing for site-level simulations by JSBACH, and in Paper III the site measured soil moisture were compared with the simulated soil moisture. Two of those three sites were also studied in Paper IV with GPP and ET fluxes derived from EC measurements.

In addition, ERA-Interim reanalysis data (Simmons et al., 2007) was used to drive REMO in Paper I and Paper II, and the 10-m wind speed of ECWMF ERA-Interim reanalysis data was used in Paper III to calculate the reference evapotranspiration (ET0) from the Penman-Monteith equation (Allen et al., 1994).
Table 2: Summary of meteorological observations and ecosystem flux data used in this study.

<table>
<thead>
<tr>
<th>Data</th>
<th>Spatial coverage or site</th>
<th>Spatial resolution or time period</th>
<th>Time period</th>
<th>Time resolution</th>
<th>Functionality</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-OBS</td>
<td>Land area of the Fennoscandian domain (Fig. 2)</td>
<td>0.22 rotated grid (Paper I); 0.25 regular grid (Paper II)</td>
<td>2000-2009 (Paper I); March and April of 1959-1998 (Paper II)</td>
<td>Monthly or seasonal</td>
<td>Model evaluation (Paper I and Paper II)</td>
<td>Haylock et al. (2008)</td>
</tr>
<tr>
<td>FMI-gridded observational data</td>
<td>Finland</td>
<td>0.2° lon × 0.1° lat</td>
<td>1981-2010</td>
<td>Daily</td>
<td>Baseline climate for bias correction of REMO simulation (Paper III); Drought indicator calculation (Paper III)</td>
<td>Aalto et al. (2013)</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>The Fennoscandian domain (Fig. 2)</td>
<td>80 km</td>
<td>2000-2009 (Paper I); 1797-1996 (Paper II)</td>
<td>6-hourly</td>
<td>Meteorological forcing for REMO regional simulation (Paper I, Paper II); 10-m wind speed was used for calculating $\text{ET}_0$ for drought indicator (Paper III)</td>
<td>Simmons et al. (2007)</td>
</tr>
<tr>
<td>Site meteorological data</td>
<td>Hyytiälä, Sodankylä, Kenttärova (Fig. 2)</td>
<td>61°51’ N, 24°17’ E; 67°22’ N, 26°38’ E; 67°59’ N, 24°15’ E</td>
<td>Summer (June, July, August) of 1999-2009 for Hyytiälä; Summer of 2001-2008 for Sodankylä; Summer of 2008-2010 for Kenttärova</td>
<td>Half-hourly</td>
<td>Meteorological forcing for JSBACH site-level simulations (Paper III, Paper IV)</td>
<td>Aurela (2005); Aurela et al. (2015); Vesala et al. (2005)</td>
</tr>
<tr>
<td>Site soil moisture data</td>
<td>Hyytiälä, Sodankylä, Kenttärova</td>
<td>The same as above</td>
<td>The same as above</td>
<td>Daily</td>
<td>Drought indicator calculation (Paper III, Paper IV)</td>
<td>The same as above</td>
</tr>
</tbody>
</table>

3.2.3 Forest health observation data

The forest drought damage percentages in Finland of forest health observation data from 2005 to 2008 in Muukkonen et al. (2015) were adopted in Paper IV. The forest health observation data are products of the pan-European monitoring programme ICP Forests (the International Co-operative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests). Forest drought damage symptoms have been identified since 2005 in Finland through visual inspections, following internationally standardized methods (Eichorn et al.,
and national field guidelines (e.g. Lindgren et al., 2005). The inspections have been carried out at forest stands during July and August annually by 10-12 trained observers in Finland. A drought damage site was recognized when a single sample tree in a study site showed drought symptoms. Therefore, uncertainties in the data can rise from subjective interpretations and inappropriate time point of the visual inspections. In the summer of 2006, 24.4% of the 603 forest health observation sites over entire Finland showed drought symptoms, in comparison to 2-4% drought damaged sites in a normal year. Most of the drought damaged sites located in southern Finland, totalling to 30% of the observation sites in southern Finland.

3.3 Studied indicators

3.3.1 Drought indicators

The drought indicators studied in Paper III are summarized in Table 3. The SPI is the most prominent and widely used drought indicator and has been recommended as a standard drought indicator by the World Meteorological Organization (WMO) due to its flexibility for various time scales, simplicity in input parameters and calculation, as well as effectiveness in decision making (Hayes et al., 2011; Sheffield and Wood, 2011). The SPEI was developed based on the SPI. In addition to precipitation, the SPEI accounts for temperature impacts on drought (Vicente-Serrano et al., 2010). The SPI and SPEI can be used to indicate the impacts of drought on various water resources, such as agriculture drought and hydrological drought, when calculated with different time scales (World Meteorological Organization, 2012). The SMA has been adopted in the Coupled Model Intercomparison Project (CMIP) in order to study soil moisture drought under current and future projections in Global Circulation Models (GCMs) (Orlowsky and Seneviratne, 2013). The SMI has been used to investigate soil water related plant physiology issues, as it can represent the relative plant available water in the root zone (Granier et al., 1999; Lagergren and Lindroth, 2002).
Table 3: Summary of drought indicators used in this study.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Definition</th>
<th>Input dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPI</td>
<td>A probabilistic measure of precipitation anomalies over a desired period with respect to the long-term normal (McKee et al., 1993). Similar to SPI, with the improvement that it also accounts for the impact of temperature on drought through PET, in addition to the water supply from precipitation (Vicente-Serrano et al., 2010).</td>
<td>1. FMI gridded meteorological data; 2. JSBACH meteorological forcing data</td>
</tr>
<tr>
<td>SPEI</td>
<td>The normalized deviation of the soil moisture status in a certain period of a year to the soil moisture climatology over this period (Orlowsky and Seneviratne, 2013).</td>
<td>1. Soil moisture from the regional JSBACH simulation</td>
</tr>
<tr>
<td>SMA</td>
<td>A measure of plant available soil water content relative to the maximum plant available water in the soil (Betts, 2004; Granier et al., 2007; Seneviratne et al., 2010).</td>
<td>1. Soil moisture from the regional JSBACH simulation. 2. Soil moisture from the site JSBACH simulations. 3. Observed soil moisture at sites</td>
</tr>
</tbody>
</table>

The SPI, SPEI and SMA are standardized indicators that show a degree of anomalies from the statistical means over a period, while SMI directly presents plant available water. In Paper IV, the standardized indicators were calculated on a time resolution of a 28-day running mean over the 30-year period, and the SMI was calculated daily. The SPI and SPEI were calculated with both the FMI gridded meteorological data and the regional JSBACH forcing data, while SMA and SMI were computed with the soil moisture from the regional JSBACH simulation. Moreover, SMIs at the three measurement sites were derived from site observations and site JSBACH simulations. For descriptions of the calculation methods for those drought indicators see section 3.2 in Paper III or the references listed in Table 3.

3.3.2 Ecosystem functioning metrics

EWUE is calculated as the ratio of GPP and ET (EWUE = GPP/ET), while IWUE is defined as EWUE multiplied by VPD (IWUE = GPP×VPD/ET) according to Beer et al. (2009). For the calculation of EWUE and IWUE, the impacts from interception and soil evaporation can not be excluded when using of ET from ecosystem flux data. However, process-based ecosystem models can simulate plant physiological processes and provide evaporation and transpiration separately. Thus, the transpiration-based ecosystem water use efficiency (EWUET) and inherent water use efficiency (IWUET) can be calculated using simulated
transpiration. In Paper IV, both EWUE and IWUE were calculated at daily time scales with ecosystem flux data and JSBACH site-level simulations at a southern (Hyytiälä) and a northern (Sodankylä) boreal Scots pine (*Pinus sylvestris*) forest sites in Finland, while EWU Et and IWUEt were calculated with JSBACH site-level simulations.
4. Overview of key results

4.1 Effects of land cover on regional climate

4.1.1 Implementing an updated land cover map in the regional climate model REMO

Land surface parameters are typically attributed to land cover types in climate models. Therefore, the best information on land cover that is available should be used in climate models to reduce the uncertainties in simulation results. The default global land cover map in REMO is GLCCD, which has been found to be inaccurate in representing the present-day land cover distribution in Finland. For instance, the fraction of peatlands over land area in Finland estimated by FNFI10 is 7.4% in Korhonen et al. (2013) but 0% in GLCCD, and the large area of deciduous forest in the middle of Finland in GLCCD is deemed unrealistic. Moreover, the use of Narrow Conifers as the dominant vegetation type in the lake area in southern Finland by GLCCD is incorrect. However, those deficiencies are not observed in CLC, which is a more accurate and higher resolution representation of present-day land cover in Europe. In Paper I, CLC was implemented in REMO for the northern European domain, and the impacts of the updated land cover map on regional climate conditions were analysed with the differences between two decadal (2001-2009) model runs.

The REMO simulation using CLC showed similar results to the REMO simulation using GLCCD in terms of surface temperatures and precipitation (Fig. 3). In comparison with the E-OBS observational data, the model biases were only marginally reduced when the CLC was used. The differences in surface temperatures and precipitation between simulations that used CLC and GLCCD were mainly induced by the increased surface albedo in the snow-cover period and the decreased ET in the growing season due to the increase of peatland area and decrease of forests in CLC. In general, REMO underestimated the monthly areal averaged diurnal temperature range by 2 to 3 K in comparison to that in the E-OBS data, mainly due to the underestimation of daily maximum 2-m air temperature and the overestimation of daily minimum 2-m air temperature. The annual areal averaged precipitation over land area was
overestimated by about 27%. Thus, in order to reduce bias in simulated climate by REMO, further developments in model physics are required and are the subject of ongoing research. For example, the 5-layer soil hydrology scheme that was introduced in JSBACH by Hagemann and Stacke (2015) was investigated with its simulated soil moisture over Finland (Paper III). This advanced soil hydrology scheme, which was also implemented in REMO to replace the simple bucket soil hydrology scheme, is under a testing phase. Furthermore, as there are numerous lakes located in our Fennoscandinavian domain, the implementation of a lake model in REMO is an ongoing process (J.-P. Pietikäinen, Finnish Meteorological Institute, personal communication). Moreover, spatially more explicit land cover maps with a parameter set tailored for the study area could reduce the uncertainties in the simulation results of climate models.

Figure 3: a) Differences (REMO – E-OBS) in monthly areal averaged daily maximum 2-m temperature (black) and daily minimum 2-m temperature (red) between the REMO simulation using GLCCD and E-OBS data (solid lines), and between the REMO simulation using CLC and E-OBS data (dashed lines); b) Areal averaged monthly mean diurnal temperature ranges in REMO simulations using GLCCD (solid line) and CLC (dashed line), and in E-OBS (dotted line); c) Monthly mean precipitation averaged over all land grid points in REMO simulations using GLCCD (solid line) and CLC (dashed line), and in E-OBS (dotted line). In those figures, the multi-year monthly means were computed over a 9-year period from 1 January 2001 to 31 December 2009 and the area means were computed over the land area in REMO simulation.

Some deficiencies may influence the results of this study as well. Firstly, the translations of the land cover types between CLC and GLCCD were subjective to a certain extent. Secondly, the freedom for REMO simulations was limited and the modelled results may be constrained because the model domain was relatively small (Køltzow, 2007). Furthermore, as E-OBS are gridded data interpolated from site measurements, the relatively sparse measurement station density in northern Europe, measurement errors and imperfect interpolation methods are
possible reasons for the data biases (Haylock et al., 2008).

4.1.2 Biogeophysical impacts of peatland forestation on regional climate changes in Finland

In Paper II, the biogeophysical impacts of peatland forestation on regional climate conditions in Finland were studied based on the differences in regional climate conditions between the REMO simulations with FNFI10 (post-drainage) and FNFI1 (pre-drainage) land cover maps. The uncertainties related to the model bias were considered to be eliminated by using this “delta change approach” (Gálos et al., 2011).

Results showed that surface albedo decreased strongly during the snow-cover period and slightly in the growing season in peatland forestation area (Fig. 5c in Paper II). The biggest difference in surface albedo occurred in the snow-melt period between the snow-covered open area and the non-snow-covered forest because of advanced snow clearance day (i.e., the first day after that the total number of snow-covered days does not exceed the total number of snow-free days) due to peatland forestation. Other surface parameters describing vegetation characteristics, including LAI, roughness length, fractional green vegetation cover and forest ratio, increased throughout the year after peatland forestation. The strongly decreased surface albedo increases the absorption of the shortwave radiation in the surface, especially in spring when the incoming solar radiation is more sufficient than in winter. In the growing season, the increased LAI and fractional green vegetation cover can lead to an increase in ET, thus more energy were consumed through latent heat flux than gained by the slight decrease in surface albedo. Moreover, the increased roughness length can increase turbulent mixing and consequently the magnitudes of turbulent fluxes.

As a consequence of the changes in land surface characteristics mentioned above, a spring warming effect and a slight cooling effect in the growing season were induced by peatland forestation (Fig. 4). However, there was no clear change in precipitation. More specifically, we found that a warming of up to 0.43 K in monthly averaged daily mean 2-m air temperature in April occurred in the most intensive peatland forestation area, which is located in the
middle west of Finland, whereas the temperature showed a slight cooling of less than 0.1 K in the growing season (from May to October). Also, the snow clearance day was advanced by up to 5 days in an average of 15-year analyses period in this area. Moreover, it is found that a positive feedback induced by peatland forestation occurred between the lower surface albedo and warmer surface air temperature in the snow-melt period. The warming caused by lower surface albedo led to a quicker and earlier snow melting, which induce more decrease in surface albedo and increase in surface air temperature. Furthermore, in a more detailed analysis of the simulated results at the five selected sub-regions (Table 1 in Paper II), which represent a range of peatland forestation intensities, the results showed that the magnitudes of differences in the climate variables were dependent on the intensity of land cover changes, while the timings of the extremes mostly relied on geographical locations that define the radiation balance through the seasonal cycle.

Figure 4: Upper panel: Changes of fractional coverage of the peat bogs and coniferous forest from 1920s to 2000s (FNFI10 - FNFI1). Lower panel: The 15-year (1 December 1982 – 30 November 1996) averaged differences between the model simulation using FNFI10 and using FNFI1 in monthly-averaged daily mean 2-m air temperature in April and June.
To validate the realism of the simulated spring warming effect due to peatland forestation, the 40-year (1958-1998) trends of surface temperatures (monthly mean daily maximum and monthly mean daily minimum) in March and April based on E-OBS data were investigated. The monthly mean daily maximum temperature in both months showed a statistically significant increase in major areas of peatland forestation, but the same increases were not shown in the trends of monthly mean daily minimum temperature. The reason for this is that daily maximum temperature closely depends on the absorption of the shortwave radiation in the surface, while daily minimum temperature is more influenced by the general climate change caused by the increase of GHGs. Nevertheless, it is difficult to compare exact magnitudes and locations of temperature changes in the simulations and observations, as many other factors can impact the temperature change in reality. In addition, we also found that the differences in the regional averaged 11-day running means of the simulated net surface solar radiation of the most intensive peatland forestation area (Fig. 5d in Paper II) agrees well with the observed differences (averaged over 1971 to 2000) in daily mean net surface solar radiation (Fig. 4 in Lohila et al., 2010) between open peatland and forest sites located in southern and northern Finland (more detailed analyses about this can be seen in section 5.2 in Paper II).

Overall, the biogeophysical changes due to peatland forestation can lead to warming in spring and cooling in the growing season of surface. Those impacts on surface air temperature are rather local, and their magnitudes and timings are dependent on the intensity and geographical location of peatland forestation. This study also highlights the potential impacts on climate from the projected increase of woody plants with the earlier onset of the growing season at high latitudes (Falloon et al., 2012; Zhang et al., 2013).

4.2 Indicating summer drought in boreal forests with drought indicators

Paper III investigated the performance of the drought indicators introduced in section 3.3.1 in describing the timing, spatial extent and intensity of drought in summer over a 30-year period (1981-2010) in Finland. In particular, this study assessed the capabilities of those
drought indicators, in conjunction with the forest health observation data described in section 3.2.3, to capture the Extreme Drought affecting Forest health (EDF) in boreal forests in Finland. The EDF is defined in this study according to the extreme drought in Finland in 2006, which caused visible impacts on forest appearance compared to normal years (Muukkonen et al., 2015). In addition, as the JSBACH simulated regional soil moisture was used in the calculation of the soil moisture indicators (SMA and SMI), this study also aimed to provide some insights into the capability of the 5-layer soil hydrology scheme in JSBACH to simulate soil moisture dynamics across Finland.

Firstly, it was found that simulated soil moisture was in good agreement with the observed soil moisture at the three sites (Hyytiälä, Sodankylä, Kenttärova), in regard to the seasonal dynamics of soil moisture and the timing of dry spells (Fig. 2 in Paper III). Nevertheless, differences existed in the rates of change and amplitudes of variations between the simulated and observed soil moisture. Differences in the meteorological forcing data and soil type between the site and the regional grid were the main reasons for the discrepancies between soil moisture of the site-level simulations and site-located grid results from the regional simulation. In regional modelling, effective soil characteristics are chosen to represent the average characteristics of a gridbox due to the large heterogeneity of soil characteristics.

The SPI, SPEI and SMA are standardised indicators that describe the degree of anomalies over a period, while SMI is directly related to plant available water. The results showed that the standardised indicators presented less variability along the latitude transection than was observed with SMI, with the latter indicating drought-prone areas in the shallow soil area along the coastline in southern Finland, and drought-resistant areas in the peat soil area (latitudes 66 °N to 68 °N) in northern Finland. We also found that the buffering effects of soil moisture (i.e. the integrative behaviour of soil moisture) and associated soil moisture memory can delay and extend the drought episodes as indicated by soil moisture indicators, in comparison to those by the meteorological indicators. The SPEI showed higher time correlation coefficients with the soil moisture indicators than SPI, as SPEI takes into account the surface water balance rather than precipitation only. An example of the drought evolution
indicated by those drought indicators in Finland in the summer of 2006 can be seen in Fig. 5.

![Latitude-time transections of SPI, SPEI, SMA, SMI for the summer of 2006.](image)

**Figure 5:** Latitude-time transections of SPI, SPEI, SMA, SMI for the summer of 2006. For SPI, SPEI and SMA, increased drought is indicated with yellow-red shading, and increased wet is indicated with green-blue shading. For SMI, plant available water in the soil increases with the SMI value increased from 0 to 1.

The EDF thresholds for those drought indicators were derived based on the spatially representative statistics of forest health observation in the extremely dry year 2006. The SMI was found to be more capable in spatially representing the EDF in 2006 than other investigated indicators. Moreover, the periods and mean fraction of affected areas of EDF events predicted by the three indicators for the summer months of the 30 years showed large divergences. The SPEI was the most sensitive drought indicator and showed the highest amount of EDF over larger areas, while the SMI showed much less EDF events than the other two indicators. This is reasonable because SPEI is the indicator that is based on the meteorological variables that cause drought, whereas SMI reflects the cumulative results of the meteorological variables.

In conclusion, SMI is considered to be the best of the investigated indicators for indicating summer drought in boreal forests, due to the high initial soil moisture values in the beginning of summer and the broad existence of peat in boreal areas. The selected EDF thresholds for those drought indicators could be calibrated when more forest health observation data from field studies or from satellite measurements are available. This study further indicates that a
land surface model that is capable of reliable prediction of soil moisture is necessary for the evaluation of drought risks in boreal areas in future climate predictions.

4.3 Response of water use efficiency to summer drought in boreal Scots pine forest

Paper IV studied the response of water use efficiency to summer drought at daily time scales at a southern (Hyytiälä) and a northern (Sodankylä) Scots pine forest sites in Finland (site characteristics can be found in Table 1 in Paper IV). The summer period (June-August) from an 11-year dataset for Hyytiälä (1999-2009) and from an 8-year dataset for Sodankylä (2001-2008) were analysed according to data availability. Drought was indicated by the soil moisture indicator SMI, which was studied in Paper III or volumetric soil moisture (θ) when the parameters of the soil properties were not measured e.g. at Sodankylä. In addition, the results based on the JSBACH site-level simulations were evaluated against the observed results, due to the importance of understanding and projecting biosphere-atmosphere feedbacks of terrestrial ecosystems under climate change.

Overall, the coupling between GPP and ET followed a non-linear relationship (Fig. 1 and Fig. S2 in Paper IV). At both sites, GPP and ET increased with increasing incoming solar radiation, air temperature and VPD, but the impact from soil moisture was not clear. It was found that GPP and ET were greatly suppressed, and their relationships to environmental variables changed under a severe soil moisture drought (SMI < 0.2) at Hyytiälä (Fig. 6 shows ET dependence on VPD). Also, the coupling between GPP and ET was disturbed due to soil moisture limitation. No severe soil moisture drought was observed at Sodankylä during the study period, and the GPP and ET groups did not show strong deviations. As a consequence, the EWUE at Hyytiälä from the observed data showed a decrease during a severe soil moisture drought, but no decrease in EWUE was observed due to the soil moisture drought at Sodankylä. However, IWUE increased during a severe soil moisture drought (SMI < 0.2) at Hyytiälä and a moderate drought (0.032 < θ < 0.064) at Sodankylä in the observed data (Fig. 7). The contradictory behaviour of EWUE and IWUE indicates that the decrease in ET was alleviated when VPD increased during drought, and led to a stronger decrease in GPP than in
ET, despite the fact that the decrease in surface conductance at the ecosystem level was stronger than that in GPP. The increase of IWUE presented at different severities of soil moisture drought at the two sites. This indicates a weaker response to soil moisture drought in the southern Scots pine forest site than in the northern site. Therefore, IWUE can be considered a more appropriate metric than EWUE for indicating the impact of soil moisture drought on ecosystem functioning at daily time scales.

Figure 6: Relationship between daily evapotranspiration (ET) and vapour pressure deficit (VPD) from observed data, and relationships between daily ET and VPD, transpiration (T) and VPD from simulated data at Hyytiälä and Sodankylä, categorized by soil moisture conditions. The lines are fitted regression lines for the categorized soil moisture groups.
Figure 7: Relationship between daily ecosystem level water use efficiency (EWUE) and evapotranspiration (ET), and the relationship between gross primary production multiplied by vapour pressure deficit (GPP $\times$ VPD) and ET from observed data at Hyytiälä and Sodankylä; the relationship between daily transpiration-based ecosystem water use efficiency (EWUEt) and transpiration (T), and the relationship between GPP $\times$ VPD and T from simulated data at Hyytiälä and Sodankylä.

In general, the JSBACH simulated GPP and ET demonstrated good correspondences with the observed GPP and ET at daily time scales at the two study sites (Fig. 8), although some deficiencies exist in the modelled results. The modelled daily GPP showed some zero values at Hyytiala because incoming solar radiation were zero in those days in the model driving data derived from site measurements. For the negative daily ET values in the modelled results, a likely reason is that the offline coupling for the JSBACH simulation tends to overestimate night-time condensation, which consequently leads to an underestimation of daily mean latent heat flux (Dalmorech et al., 2015). Nevertheless, the model successfully predicted the strong decrease of GPP and ET under a severe soil moisture drought, and a slight decrease in ET under a moderate drought (0.2 < SMI < 0.4) (Fig. 6). However, the decrease of GPP and ET from simulations under a severe soil moisture drought was smaller than that from observation. The reason for this can be found in Knauer et al. (2015), who concluded that the stomatal conductance in JSBACH is insensitive to air humidity. In global models, simple representations of stomatal regulation have often been applied. Nevertheless, low soil moisture and high VPD are coherent phenomena during a drought. Thus, the comparison
between modelled and observed results indicates that JSBACH needs to be improved with a stomatal conductance model that considers limitations from both soil moisture drought and atmospheric drought on stomatal conductance. Moreover, the inclusion of non-stomatal limitation processes during drought, such as reduced mesophyll conductance or carboxylation capacity (Manzoni et al., 2011; Zhou et al., 2013), may also improve the model results (Keenan et al., 2013). Also, it should be kept in mind that the ecosystem flux data has uncertainties. There is always a random error component in the ecosystem flux data measured with EC technique due to the stochastic nature of the turbulent flow. Systematic errors may also exist in the ecosystem flux data due to imperfect spectral corrections, gap-filling procedures or calibration problems (Richardson et al., 2012; Wilson et al., 2002).

Figure 8: Correlations between the observed and simulated GPP, and correlations between the observed and simulated ET at Hyytiälä and Sodankylä over the study period. All the correlation coefficients are statistical significant (p < 0.01).
4.4 Limitation of our regional modelling studies

Our regional modelling studies can be improved in several aspects. Firstly, as land surface parameters are attributed according to land cover types in those models, accurate land cover maps are always the preconditions for regional simulations. Secondly, tailored land surface parameter values for the study area rather than the default global-wised parameter values are required, for the aim to reduce the inaccuracies in modelling land surface physical processes. Thirdly, high-quality soil type distribution, representative soil parameters, and more sophisticated soil hydrology models have the capability to improve the simulated soil moisture. Then, the meteorological forcing data is of vital importance for LSMs to simulate realistic soil moisture and plant functioning. Moreover, it is expected that further development in model physics could reduce model biases when considering the costs of model efficiency. The simple bucket soil hydrology scheme in REMO is insufficient to represent the complex soil hydrological processes, and the 5-layer soil hydrology scheme has been implemented in REMO and is under a testing phase. The default stomatal conductance model in JSBACH is insensitive to air humidity. This leads to an overestimation of GPP and ET under a severe soil moisture drought. A stomatal conductance model that considers both soil moisture drought and atmospheric drought needs to be implemented in JSBACH. Finally, the modelling studies only used one regional climate model and one land surface model. Ensemble simulations with multi-model intercomparisons will help to reduce model biases and the uncertainties of our understanding on our topics.
5. Review of papers and author's contribution

**Paper I** describes the implementation of an updated and more accurate high-resolution land cover map to replace the standard land cover map in the regional climate model REMO. The impacts of the improved land cover map on the simulated regional climate conditions were analysed with observation-based E-OBS data as a reference. Although the model biases of the simulated climate conditions were only marginally reduced, the newly introduced land cover map provides more realistic reference for future land cover change studies. It is expected that land surface physical processes and land surface parameter values in the model could be developed further to make more improvements. Stefan Weiher made the technical implementation of the maps and simulations. I carried out the data analyses and prepared the manuscript with contributions from the other co-authors.

**Paper II** discusses the biogeophysical impacts of peatland forestation on regional climate changes in Finland. The differences between the climate conditions simulated by REMO using the land cover maps based on pre-drainage (1920s) and after-drainage (2000s) Finnish National Forest Inventories (FNFI) were analysed. Peatland forestation led to a spring warming that was mainly induced by the decreased albedo, whereas a slight cooling was found in the growing season mostly due to the increased evapotranspiration (ET). As a consequence of the spring warming effect, the snow clearance days in peatland forestation areas were advanced. The extents of these climate effects are closely related to the intensity and geological locations of peatland forestation. In addition, the modelled results are qualitatively supported by the observational data. Dr. Henttonen prepared the FNFI land cover maps for this study from the FNFI field measurement data. I implemented the FNFI maps into REMO and performed the simulations. I analysed the results and prepared the manuscript with contribution from the other co-authors.

**Paper III** investigates the performance of a set of drought indicators for their ability in indicating summer drought in boreal forests in Finland. In particular, the forest health observation data, which showed severe drought damage on forest due to the Extreme Drought affecting Forest health (EDF) in 2006 in Finland, were used as a reference to determine the
EDF thresholds of those drought indicators. The soil moisture index SMI was found to be the best in indicating EDF in boreal forests, because of high initial soil moisture values in the beginning of summer and the existence of deep organic soil that less prone to drought. Thus, it is important for the assessment of drought risks in the future, especially in boreal areas, that a land surface model capable of reliable predictions of soil moisture and high-quality soil type distribution are used, in addition to climate data. Dr. Markkanen and Dr. Thum provided the JSBACH simulated soil moisture data for this study. I carried out the calculation of the drought indicators. I analysed the results and prepared the manuscript with contributions from the other co-authors.

**Paper IV** studies the response of water use efficiency to summer drought in boreal Scots pine forests in Finland at daily time scales, mainly using ecosystem flux data measured by EC technique. In addition, the JSBACH simulation results were evaluated against observed results at two Scots pine forest sites in southern and northern Finland. Results showed that the gross primary production (GPP) and ET were greatly decreased during a severe soil moisture drought. The inherent water use efficiency (IWUE) is more appropriate than the ecosystem water use efficiency (EWUE) for indicating the impacts on ecosystem functioning from drought through the exclusion of the vapour pressure deficit (VPD) effect on ET. The JSBACH model successfully captured the soil moisture drought limitation on stomatal conductance. However, in order to adequately simulate the effects of drought on plant functioning, the limitation caused by atmospheric drought has to be incorporated. Ecosystem flux data were provided by Dr. Aurela and Dr. Mammarella. I carried out the data analyses and prepared the manuscript with contributions from the other co-authors.
6. Concluding remarks

The motivation of this thesis was to gain insights into the interactions between the land surface, forests and regional climate in the boreal zone. Specifically, the effect of peatland forestation on regional climate conditions, indication of summer drought that affects boreal forest health, and the response of ecosystem functioning to summer drought in boreal Scots pine forest were studied. Those studies encompassed a wide range of processes related to the energy, water and carbon cycles (Fig. 9).

Figure 9: Relationships between the four articles in this thesis.

This work utilised land surface and regional climate modelling approaches alongside various observational data. The main conclusions of this thesis are the following:

1) For the investigation of the biogeophysical impacts of peatland forestation on regional climate conditions in Finland using the regional climate model REMO (Paper II), it was found that peatland forestation can induce a warming effect in spring due to decreased surface albedo, and a slight cooling effect in the growing season because of increased ET. As a consequence of the warmer temperature in spring, the snow clearance day was advanced. No clear signal was found for precipitation. The extent and timing of those climate effects
depended on the intensity and location of the peatland forestation. In the most intensive peatland forestation area, a warming of up to 0.43 K in spring and a cooling of less than 0.1 K in the growing season in 2-m air temperature were observed, and the snow clearance day was advanced by up to 5 days. In particular, the modelled warming effect in spring was in good agreement qualitatively with the temperature trends of March and April calculated with 40-year observational data.

2) The soil moisture index SMI was the most capable among the assessed drought indicators in capturing the spatial extent of observed forest damage induced by the extreme drought in 2006 in Finland (Paper III). This is because the high initial soil moisture content or the existence of peat in boreal forests in Finland often hinders the standardized indicators (SPI, SPEI and SMA) to capture drought that indicated by the SMI. Thus, in order to assess the drought risks in boreal areas in the future, a land surface model capable of reliable prediction of soil moisture is needed. Unbiased meteorological data are also important as a model forcing.

3) According to ecosystem flux data, GPP and ET were greatly suppressed during a severe soil moisture drought (Paper IV). The decrease of ET was alleviated because of the increased VPD during drought, and led to a decrease of EWUE despite a stronger decrease of surface conductance at the ecosystem level than GPP. IWUE increased during a moderate drought at the northern site and a severe drought at the southern site. This indicates that the southern site had a weaker response to drought than the northern site. From those results, we conclude that IWUE is more appropriate than EWUE in indicating the impacts of drought on ecosystem functioning, through the exclusion of the VPD effect on ET.

4) With the implementation of a more accurate, up-to-date and high resolution land cover map into REMO to replace the inaccurate default land cover map over the Fennoscandian domain (Paper I), we found that biases from REMO simulations of the present-day climate were only slightly reduced. This would indicate that improvements in the model performance could be achieved with better descriptions of the land surface physical processes and more accurate
land surface parameter values. Small-scale spatial climate variability related to historical land cover changes have been investigated using REMO due to its high spatial resolution (Paper II). Regional soil moisture used in the calculation of the soil moisture index SMI was produced by the land surface model JSBACH with its 5-layer soil hydrology scheme in Paper III. In the future, high quality soil type distributions and soil parameters are of vital importance to improve the accuracy of simulated regional soil moisture. The soil hydrology scheme could be further developed by incorporation of soil type heterogeneity in a gridbox and along the soil profile. Furthermore, realistic simulations of plant functioning are needed to understand and project feedbacks between climate change and plant physiological responses. Plant controls of stomatal conductance, photosynthesis and transpiration under water stress in boreal Scots pine forests were simulated by JSBACH in Paper IV, and the modelled results were compared with the EC observations. The results showed that JSBACH successfully reflected the soil moisture drought limitations on stomatal conductance. However, the combined effects from atmospheric drought and soil moisture drought has to be taken into account in the model to adequately simulate the drought effects on plant functioning. In addition, the non-stomatal limitations on photosynthesis during drought, such as reduced carboxylation capacity and mesophyll conductance, may also lead to improvements in model performance.

Information from regional studies is essential for the development of future strategies for climate change mitigation or forest management. The topics that could benefit from this study are diverse. For example, future drought prediction under high resolution climate projections; the relationship between drought impacts on forest health and productivity or bioenergy. Moreover, the feedbacks relevant to this study should be explored. For instance, peatland forestation may lead to changes in soil properties and soil hydrology, which can influence regional soil moisture distribution and also drought; changes in climate can also stimulate land cover change, such as the projected forestation of tundra at high latitudes.
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