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Monthly microclimate models in a managed boreal forest landscape

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ABSTRACT

The majority of microclimate studies have been done in topographically complex landscapes to quantify and predict how near-ground temperatures vary as a function of terrain properties. However, in forests understory temperatures can be strongly influenced also by vegetation. We quantified the relative influence of vegetation features and physiography (topography and moisture-related variables) on understory temperatures in managed boreal forests in central Sweden. We used a multivariate regression approach to relate near-ground temperature of 203 loggers over the snow-free seasons in an area of ~16,000 km² to remotely sensed and on-site measured variables of forest structure and physiography. We produced climate grids of monthly minimum and maximum temperatures at 25 m resolution by using only remotely sensed and mapped predictors. The quality and predictions of the models containing only remotely sensed predictors (MAP models) were compared with the models containing also on-site measured predictors (OS models). Our data suggest that during the warm season, where landscape microclimate variability is largest, canopy cover and basal area were the most important microclimatic drivers for both minimum and maximum temperatures, while physiographic drivers (mainly elevation) dominated maximum temperatures during autumn and early winter. The MAP models were able to reproduce findings from the OS models but tended to underestimate high and overestimate low temperatures. Including important microclimatic drivers, particularly soil moisture, that are yet lacking in a mapped form should improve the microclimate maps. Because of the dynamic nature of managed forests, continuous updates of mapped forest structure parameters are needed to accurately predict temperatures. Our results suggest that forest management (e.g. stand size, structure and composition) and conservation may play a key role in amplifying or impeding the effects of climate-forcing factors on near-ground temperature and may locally modify the impact of global warming.

1. Introduction

Forest floor microclimate directly and indirectly influences many biological processes and patterns in forests, such as plant regeneration and growth, species distribution, carbon- and nutrient cycling, soil respiration, and soil development (Bonan and Shugart, 1989; Nilsson and Wardle, 2005). In forests, understory microclimates are created by physiographic features, but also by forest structure and composition, creating conditions of higher humidity, decreased wind speed, lower incoming and outgoing radiation (Geiger et al., 2012). Therefore, understanding and modelling forest microclimate is greatly needed to understand spatial and temporal variation in biological processes. Not least in the context of climate change, this knowledge will help to identify efficient strategies to adapt forest management to important

societal goals, such as wood production, carbon sequestration and biodiversity conservation.

The effects of landscape physiography on near-ground temperatures, in terms of incoming solar radiation modified by slope and aspect, pooling of cold heavy air in depressions, adiabatic decrease in temperature towards higher elevations and the moderating influence of soil moisture, air humidity and water bodies have been well studied (Aalto et al., 2017; Dobrowski, 2011; Geiger et al., 2012; Meineri and Hylander, 2016). Vegetation, on the other hand, can have substantial effects on microclimate by canopy shading, evaporative cooling, reduced wind speed, resulting in reduced lateral transfer of humidity and heat, buffering against heat loss overnight and changes in absorbance of shortwave radiation by differences in albedo (Geiger et al., 2012; Rosenberg, 1974) – referred to as biophysical processes *sensu* Lenoir

et al. (2017). In contrast to physiography, vegetation is influenced by land management, which may have important implications for the microclimate (Frey et al., 2016). Forest management activities, that have the potential to affect the microclimate, include clear-cutting, thinning, green-tree retention, tree planting, choice of tree species as well as the size and distribution of management units (Latimer and Zuckerberg, 2016; Vanwalleghem and Meentemeyer, 2009). Thus, identifying the biophysical processes shaping understory climate (as e.g. in Frey et al., 2016) can enable adaptation to climate change by for example managing the forest in a way that creates favoured microclimates (De Frenne et al., 2013).

The field of microclimate modelling is currently boosted by the upcoming of cheap climate loggers, the increasing quality and availability of remote sensing products (e.g. high-resolution surface mapping with LiDAR producing digital elevation models or canopy maps, see overview in He et al., 2015), the growing computational power and the development of new statistical techniques (Keppel et al., 2012; Lenoir et al., 2017). Up to now, the majority of the predictive models have been done in montane landscapes or other types of complex terrain, accounting for local physiography (Ashcroft and Gollan, 2012; Frey et al., 2016; Fridley, 2009; Lookingbill and Urban, 2003; Vanwalleghem and Meentemeyer, 2009). Only a few studies have included also vegetation features, despite its recognized importance in e.g. buffering temperature extremes (see Table 1. in Lenoir et al., 2017, for a review on microclimate studies including physiographic and biophysical processes). One reason for the lack of vegetation characteristics in microclimate models is the lack of high-resolution maps of vegetation structure. Recent provision of e.g. laser scanning measurements of canopy cover and stand density (Larsson et al., 2016; Means et al., 2000) is now opening up for a move from simple measurements along transects (Chen et al., 1996) to spatial predictions over large areas providing high-resolution maps at a 0.5–100 m grain size (Lenoir et al., 2017). However, microclimate modelling is still in its infancy and there is a need for more work in managed forested landscapes, particularly in areas characterized by minor topographic gradients (e.g. as in George et al., 2015). Boreal forests are still underrepresented in microclimate modelling (but see Chen et al., 1996, 1993; Chen and Franklin, 1997), which is unfortunate since they form the largest global terrestrial carbon storage (Anderson, 1991) and the world's second largest biome (Ruckstuhl et al., 2008) with special characteristics (e.g. a dominance of coniferous trees and dwarf shrubs) making extrapolation from other types of vegetation difficult.

Both spatial patterns of microclimate and influences of different climate-forcing factors are likely to vary over different time scales. For instance, forest floor temperature heterogeneity is larger during the day than at night (Chen and Franklin, 1997) and cold air pooling in topographic depressions can mainly be observed in clear wind-still nights (Dobrowski, 2011). Especially at higher latitudes and in mixed forests

canopy cover, solar angle and their combined effects with topography undergo strong seasonal changes (Lenoir et al., 2013). Temperature extremes during different seasons are limiting for some organisms, when their physiological tolerances are exceeded (Ashcroft et al., 2011; Meineri et al., 2015; Walther et al., 2009; Zimmermann et al., 2009). Additionally, locations with unusual climates (at the extreme ends of temperature gradients) may play a crucial role as future climate refugia (Ashcroft et al., 2012). While many studies have modelled minimum and maximum temperatures (e.g. Fridley, 2009; Geiger et al., 2012; Lookingbill and Urban, 2003; Meineri et al., 2015), only few have considered also seasonal changes in climate-forcing factors and their relative influence on near-ground temperatures (e.g. Ashcroft and Gollan, 2013a).

In this paper, we investigate the relative importance of vegetation versus physiography for maximum and minimum temperatures across different snow-free seasons in a lowland boreal forest landscape, in which we expect forest structure and management to play the dominant role in moderating microclimate. Our aims were: (i) to quantify spatial variation in near-ground temperatures in a managed forest landscape, (ii) to examine the relative importance of physiographic and vegetation drivers across seasons and (iii) to predict monthly minimum and maximum temperatures at a 25 m resolution by using only remotely sensed and mapped predictors.

To achieve this, we analysed temperature data from 203 loggers stratified according to physiographic and vegetation gradients across an area of ~16,000 km². We modelled monthly extreme (minimum and maximum) temperatures in two sets of models. First, we used all available site information, in terms of on-site measured and remotely sensed variables of physiography and forest features, to predict near-ground temperatures. Second, we used only remotely sensed variables available in a mapped form, to produce temperature maps.

2. Methods

2.1. Study area

Our study area stretches 190 km across central Sweden (59 to 61° North and 12.5 to 17° East), covering the majority of the quite sharp transition zone "*Limes Norrlandicus*" (Fig. 1). In this region, the southern boreo-nemoral forest (mixed forest) meets the northern boreal forest (coniferous forest) and many northern or southern forest species have their range limit or change dramatically in abundance in this transition zone (Rydin et al., 1999; Sjörs et. al, 1965). Within this area we focus on forests (16,135 km² of the study area), which are dominated by spruce and pine with some deciduous elements. The field layer is dominated by ericaceous dwarf-shrubs, mosses and lichens. Almost all boreal forest in Sweden is of secondary nature and has been cleared at least once during the past 200 years (Östlund et al., 1997). Sweden's

Table 1

Predictors used to model monthly averages of daily minimum (Tmin) and maximum (Tmax) temperatures. Mean and range are for the observation points, not for the entire study area. OS = model containing on-site measured predictors. MAP = model containing only remotely sensed predictors. log = log-transformed. sqrt = square-root-transformed.

Predictor	unit	abbrev.	min	mean	max	Tmin OS	Tmin MAP	Tmax OS	Tmax MAP
distance to lake Vänern	km	*distvan*	4.68	84.97	173.65	x	x	x	x
distance to water	km	*log_distwat*	0.03	1.13	5.96	x (log)	x (log)	x (log)	x (log)
relative elevation 500 m	m	*log_reel500m*	0.54	25.89	125.23	x (log)	x (log)	–	–
solar radiation example for December (July)	MW	*sr*	0.0001 (0.1210)	0.0001 (0.1487)	0.0003 (0.1623)	–	–	x	x
elevation	m	*alt*	30.58	216.27	477.88	x	x	x	x
soil moisture[a]	m	*soilmoist*	−2.50	−1.49	0.00	x	–	x	–
distance to forest edge[a]	m	*distedge*	0.00	83.45	250.00	x	–	x	–
proportion of conifers[a]	%	*conif*	0.00	85.58	100.00	x	–	x	–
canopy cover[a]	%	*canopy/ canopy2*	0.00	45.96	83.12	x (sqrt)	–	x	–
basal area[a]	m²/ha	*basal_area*	0.00	12.48	40.00	x	–	x	–
topographic wetness index	–	*twi*	4.62	7.20	13.83	–	x	–	x
basal area	m²/ha	*BasAre.R*	0.00	15.48	43.00	–	x	–	x

[a] On-site measurements.