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Decomposing sources of uncertainty in climate change projections of boreal forest primary production

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ABSTRACT

We are bound to large uncertainties when considering impacts of climate change on forest productivity. Studies formally acknowledging and determining the relative importance of different sources of this uncertainty are still scarce, although the choice of the climate scenario, and e.g. the assumption of the CO_2 effects on tree water use can easily result in contradicting conclusions of future forest productivity. In a large scale, forest productivity is primarily driven by two large fluxes, gross primary production (GPP), which is the source for all carbon in forest ecosystems, and heterotrophic respiration. Here we show how uncertainty of GPP projections of Finnish boreal forests divides between input, mechanistic and parametric uncertainty. We used the simple semi-empirical stand GPP and water balance model PRELES with an ensemble of downscaled global circulation model (GCM) projections for the 21[st] century under different emissions and forcing scenarios (both RCP and SRES). We also evaluated the sensitivity of assumptions of the relationships between atmospheric CO_2 concentration (C_a), photosynthesis and water use of trees. Even mean changes in climate projections of different meteorological variables for Finland were so high that it is likely that the primary productivity of forests will increase by the end of the century. The scale of productivity change largely depends on the long-term C_a fertilization effect on GPP and transpiration. However, GCM variability was the major source of uncertainty until 2060, after which emission scenario/pathway became the dominant factor. Large uncertainties with a wide range of projections can make it more difficult to draw ecologically meaningful conclusions especially on the local to regional scales, yet a thorough assessment of uncertainties is important for drawing robust conclusions.

1. Introduction

Understanding the development of forest productivity in a changing environment is pivotal for making decisions about forest use in the future. Such understanding is also needed for improving the climate projections themselves, as a large proportion of uncertainty of global warming projections arises from uncertainties in modelling terrestrial phenomena and their biophysical interactions with climate (Bonan, 2008). Boreal forests play a large role in determining the global mean temperature (Snyder et al., 2004; Snyder and Liess, 2014), and are generally assumed to provide climate mitigation potential due to projected increased growth and carbon sequestration under climate change (IPCC et al., 2013), although the biophysical effects like albedo or biogenic volatile organic compounds (BVOCs) may change the net impact (Bright et al., 2014; Unger, 2014). Opposing trends may also emerge as a result of increased utilization of forests for the production of bioenergy and new bio-based products (Ollikainen, 2014). For example in Finland, recent impact studies suggest an increase of 5–27% in productivity of Norway spruce until end of this century (Ge et al., 2013 using SRES A2 scenarios, Reyer et al., 2014 using SRES A1B). However, all impact studies include a lot of uncertainty related to model structure, parameter values, and climate input data, which has not been systematically analysed in boreal forest studies. The lack of including these in the assessment of uncertainty may lead to suboptimal decision-making from the climate change mitigation perspective.

In a large scale comparison, forest productivity is primarily driven by two large fluxes, gross primary production (GPP), which is the source carbon for all carbon in forest ecosystems (Ma et al., 2015), and

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heterotrophic respiration. Correlations can therefore be found along environmental gradients between GPP and Net Primary Production (NPP; Waring et al., 1998; Mäkelä and Valentine, 2001; Dewar et al., 1998), litter fall (Reich et al., 2014; Mäkelä et al., 2016) and carbon accumulation in the soil (Liski et al., 2006). Recent decades have witnessed a profound development of models of canopy GPP, thanks to improved measurements and data from eddy flux networks where carbon and water fluxes are measured globally over different land cover types (e.g.FLUXNET, https://fluxnet.fluxdata.org). This has considerably improved the reliability of GPP predictions under current climate as a function of weather and canopy type (e.g. Novick et al., 2015; Wagle et al., 2016), sometimes also with generic models that do not require site-specific parameterisation (Minunno et al., 2016). Model-data assimilation techniques such as Bayesian model calibration also provide an improved understanding of the uncertainties of model parameters and how they propagate to model predictions (van Oijen et al., 2013; Minunno et al., 2016). The significance of GPP for ecosystem functioning, combined with a sound understanding of the process under the current climate, makes GPP simulatons an appropriate example case for exploring the types of uncertainty we are bound to face in future impact projections in a changing climate.

Uncertainties in model predictions generally originate in input uncertainty and model uncertainty (cf. Uusitalo et al., 2015). In climate change projections, input uncertainty includes uncertainties about climate scenario and climate development under a given scenario, demonstrated in the differences between climate models. In addition, there is uncertainty caused by natural variability of weather. Model uncertainty consists of parametric and structural uncertainty.

An important structural uncertainty for GPP prediction arises from the fact that the interactions of elevated atmospheric CO_2 concentrations (C_a) with changing climate are still poorly understood due to the limited possibilities of theory and model testing in experimental and natural conditions. In modelling studies, even more than half of the projected forest productivity has been attributed to increasing C_a (Bergh et al., 2003; Reyer et al., 2014) while without C_a fertilization, simulated forest productivity has even been predicted to decrease under climate change (Ollinger et al., 2007; Medlyn et al., 2011). While it is generally accepted that elevated C_a increases the water use efficiency of plants (WUE), the extent and mechanisms of this effect are not clear. Analyses of eddy-covariance measurements of the past 15 years have suggested even larger improvements of WUE than predicted by prevailing theories (Keenan et al., 2013). While studies where C_a concentration has been increased in the field (Free-Air Carbon dioxide Enrichment, FACE) have shown that trees increase their photosynthetic rates and still reduce stomatal conductance (Ainsworth and Rogers, 2007), the long-term ecosystem level responses depend on ecosystem type. Direct responses of trees to elevated C_a may become diluted in time, as physiological processes and tree structure acclimate to new conditions (Norby and Zak, 2011). For example, some studies have predicted spruce decline in southern Finland (Kellomäki et al., 2008; Ge et al., 2013), but the result strongly depends on the assumptions of C_a effects on transpiration.

The impact uncertainty arising from uncertainties in global circulation model (GCM) outputs has largely been ignored in (forest productivity in the boreal zone, although it has been investigated in the context of e.g. disturbances (Lehtonen et al., 2016). It is well known that projections of climate models can differ more between each other than projections of one specific climate model between emission scenarios (e.g. van Vuuren et al., 2011; Ahlström et al., 2012; Nishina et al., 2015). In the case of Finland, only few GCMs project mean annual temperature changes below 2 °C between the periods 1971–2000 and 2070–2099, even when assuming a low emission scenario (SRESB1) or a low emission Representative Concentration Pathway (RCP2.6) (Fig. 1). The respective changes in the high-end scenarios reach up to 10 °C (under RCP8.5 forcing, see Jylhä et al., 2009; Rötter et al., 2013; Ruosteenoja et al., 2016). The change in winter temperatures in January may be twice as large as the change in summer temperatures in July. Uncertainties in precipitation changes are much larger, but increases are expected especially in winter (Rötter et al., 2013; Jylhä et al., 2009). The frequent approach of using the ensemble mean of climate model variables as input to ecosystem models (e.g. Peltola et al., 2010; Veijalainen et al., 2010; Sievänen et al., 2014) is questionable since it may violate the coherence between different climate variables.

The objective of this study was to predict gross primary production (P) and plant-water relations of boreal forests in Finland using climate scenarios for the 21st century from ensembles of GCMs with different forcings (both RCP and SRES). By showing both scenario families we acknowledge the fact that SRES scenarios are still used in impact studies, and even more so in policy analyses. Comparing the two sets of scenarios will help us put the SRES scenario results in perspective with those obtained from the RCP scenarios. We calculated P using a simple ecosystem flux model, PRELES, (Peltoniemi et al., 2015) with a generic boreal parameterisation (Minunno et al., 2016). We then quantified and compared the different sources of uncertainty, including the parametric uncertainty obtained from data-model assimilation, the structural uncertainty of C_a fertilization and water use effects, and input uncertainties originating in stochastic variability of weather and uncertainty created by the choice of climate model and forcing scenario. Using our study on GPP as an example, we discuss the implications more broadly in the framework of ecological impact model applications that are subject to large uncertainties.

2. Materials & methods

2.1. The PRELES model

The PRELES model (Peltoniemi et al., 2015) describes P and water exchange (evapotranspiration, E) of forest canopies on the basis of light use efficiency (LUE), expressed as a multiplicative model of potential LUE and environmental modifiers f_i ($0 < f_i < 1$). It inherits its photosynthesis part from Mäkelä et al. (2008a,b) while a simple description of daily soil water balance was made in Peltoniemi et al. (2015). The model has been calibrated to eddy-covariance derived data on P, E, and measurements of soil water in Scots pine stands (Peltoniemi et al., 2015), and a generic, species-independent parameterisation for boreal stands has been prepared (Minunno et al., 2016). While the existing model parameterisation has been carried out in current climate under constant C_a, here we extend the model to be applicable to future environment by incorporating an additional C_a modifier. Here we first outline the structure of the model, then introduce our treatment of the sources of mechanistic and input uncertainty. The details of PRELES are presented in Peltoniemi et al. (2015).

The photosynthetic production P (gC m^{-2} day^{-1}) is predicted in PRELES as:

$$P = f_{\mathrm{aPPFD}}\ P_0 \equiv \beta f_{\mathrm{aPPFD}} \sum_d \Phi_d \prod_i f_{id} \tag{1}$$

where f_{aPPFD} is the fraction of photosynthetic photon flux absorbed by the canopy, P_0 is the potential photosynthetic production when all radiation is absorbed ($f_{\mathrm{aPPFD}} = 1$), β is the potential light use efficiency (gC mol^{-1}, Table 1), Φ_d is photosynthetic photon flux density of day d (PPFD, mol m^{-2} day^{-1}), and f_{id} are values on day d of environmental modifiers related to variable i ($i = L, S, D, W$ representing light, temperature, vapour pressure deficit and soil water, respectively). The product of Φ and the light modifier f_L takes the form of rectangular hyperbola, which describes the saturating light effect on stand P, the temperature modifier f_S calculates the seasonal temperature potential for P. It is calculated using daily mean temperatures and over the course of the year the response typically takes a form resembling a cut sine wave where the peak values during summer are flattened to 1, while during the off-season (currently November-March in southern-most