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Review and synthesis

Tamm Review: Observed and projected climate change impacts on Russia's forests and its carbon balance

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ABSTRACT

Russia's boreal forests provide numerous important ecosystem functions and services, but they are being increasingly affected by climate change. This review presents an overview of observed and potential future climate change impacts on those forests with an emphasis on their aggregate carbon balance and processes driving changes therein. We summarize recent findings highlighting that radiation increases, temperature-driven longer growing seasons and increasing atmospheric CO_2 concentrations generally enhance vegetation productivity, while heat waves and droughts tend to decrease it. Estimates of major carbon fluxes such as net biome production agree that the Russian forests as a whole currently act as a carbon sink, but these estimates differ in terms of the magnitude of the sink due to different methods and time periods used. Moreover, models project substantial distributional shifts of forest biomes, but they may overestimate the extent to which the boreal forest will shift poleward as past migration rates have been slow. While other impacts of current climate change are already substantial, and projected impacts could be both large-scale and disastrous, the likelihood for a tipping point behavior of Russia's boreal forest is still unquantified. Other substantial research gaps include the large-scale effect of (climate-driven) disturbances such as fires and insect outbreaks, which are expected to increase in the future. We conclude that the impacts of climate change on Russia's boreal forest are often superimposed by other environmental and societal changes in a complex way, and the interaction of these developments could exacerbate both existing and projected future challenges. Hence, development of adaptation and mitigation strategies for Russia's forests is strongly advised.

Contents

Abbreviations: LB, live biomass; RWI, ring width increment; NBP, net biome production; NPP, net primary production; HR, heterotrophic respiration; DGVM, Dynamic Global Vegetation Model; CI, confidential interval; T, temperature; CWD, coarse woody debris.

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1. Introduction

Global climate change mitigation discussions need to focus more on boreal forests (Gauthier et al., 2015). Such a focus is necessary because of the significant importance of these forests for the climate system itself, mediated through biosphere–atmosphere exchanges of water, carbon and energy. The two dominating feedbacks are changes in reflectance and energy exchange that result from the loss or gain of evergreen coniferous vegetation at high latitudes and changes in carbon cycling (Betts, 2000; Bonan, 2008; O'Halloran et al., 2012). The latter is particularly relevant for Russia's boreal forests because they cover a huge and widely pristine area (>90% of the total Russian forest cover, i.e. ~900 Mha; Shvidenko et al., 2013), storing huge amounts of carbon. Actually, about half of the terrestrial global carbon sink (i.e. ~0.6 PgC yr^{-1} out of 1.3 ± 0.15 PgC yr^{-1} in the period 2000–2009, after subtraction of land use change emissions) is estimated to be located in Russia's forests (Dolman et al., 2012; Schaphoff et al., 2013). Yet, compared to the many existing studies of climate change impacts on Canada's (e.g. Peng et al., 2011; Price et al., 2013) and Fennoscandia's (e.g. Ge et al., 2013) boreal forests, proportionally little is known for Russia's boreal forests specifically, despite their great importance locally, regionally and globally – hence our present review.

Warming in the boreal region in Russia has been stronger than in the global mean, while precipitation changes are regionally specific (Hansen et al., 2006, 2010). These ongoing changes in climate alter Russia's boreal forests in various ways. Climate change induces manifold physiological and structural responses of the vegetation cover of Russia's boreal forest, which are basically governed by processes that limit tree growth, i.e. primarily low growing season temperature, low solar radiation, and low nitrogen availability (Boisvenue and Running, 2006). Droughts and heat waves associated with a long-term change in background climate can accelerate or intensify forest diseases, insect outbreaks and fire activity, leading to increased tree mortality. Different feedbacks of boreal forests to change in climate and environment were already observed in Russian forests. Statistically significant change of ratio between live biomass of stems, roots and foliage was reported for the country's forests during 1961–2002 (Lapenis et al., 2005). A widespread increase of tree mortality over the entire Russian boreal belt has been confirmed (Allen et al., 2010), although drought—i.e. increasing water demand of plants induced by higher temperatures in vast continental regions—is not the only driver of this phenomenon (Shvidenko et al., 2013; Steinkamp and Hickler, 2015). With continuing and accelerating climate change, there is a risk that the boreal forest may even cross a tipping point and shift to an alternative state (Chapin et al., 2005; Lenton et al., 2008; Scheffer et al., 2012). Other prospective impacts of future climate change on forest ecosystems in Russia, as documented in Russian-language literature, have been reviewed by Sharmina et al. (2013). They found that the key anticipated impacts are potential shifts of vegetation zones, more frequent and intensive wildfires, and increased plant productivity through CO_2 fertilization. These potential changes would substantially reduce the carbon sink capacity of the boreal zone (Koven et al., 2011; Schaphoff et al., 2006, 2013), accelerated by warming-induced permafrost melting (Romanovsky et al., 2010). The latter is a crucial process as the Russian boreal forest zone stores a massive amount of carbon in permafrost soils and wetlands (Zimov et al., 2006; Tarnocai et al., 2009; Schepaschenko et al., 2013).

The objective of this paper is to present an overview of observed and potential future climate change impacts on Russia's boreal forests based on a comprehensive review of the recent scientific literature and to synthesize existing knowledge for assessing the regional distribution of impacts and key underlying mechanisms. We streamline the review toward an assessment of Russia's carbon budget and balance because of its global importance, which has been emphasized in many studies (Gauthier et al., 2015; Malhi et al., 1999). We do so by first discussing observed changes in those key processes that dominate the Russian carbon balance and that are particularly affected by climate change, namely forest productivity, forest distribution and disturbances. Then we summarize the recent literature on observed changes in the carbon balance. In order to provide future perspectives, we finally summarize projected changes in the key processes and the future carbon balance. We close by briefly discussing the likelihood of a tipping of Russia's boreal forest. We rely on regional studies within the boreal forest of Russia and on global studies that have sufficient granularity to single out Russian forests. For more general process descriptions we also consider scientific literature on boreal forests outside Russian territory.

2. Key processes dominating the carbon balance

2.1. Forest productivity

Forest productivity in the northern latitudes depends on a variety of interacting climatic and non-climatic factors (Table 1). Among the governing climatic factors are solar radiation, temperature, direct effects of atmospheric CO_2 concentration and nitrogen deposition (Chapin et al., 2005; Ciais et al., 2005) as well as water availability and the seasonality of precipitation (Berner et al., 2013). Other factors relevant for forest productivity—impacts of which may be modulated by climatic conditions—are fires, insect outbreaks, and diseases that have been shown to counteract forest growth stimulation by increased temperature (Zamolodchikov et al., 2013).

Recent analyses of Normalized Differenced Vegetation Index (NDVI) data, used as a proxy for terrestrial Gross Primary Production (GPP), explored the spatial and temporal variability of 'greening' (enhanced productivity) and 'browning' patterns (lower productivity) in the boreal zone (Beck et al., 2011; Bunn and Goetz, 2006; Goetz et al., 2007; de Jong et al., 2011). Furthermore, tree ring studies have identified complex patterns of tree growth in response to past climate variability (Lloyd and Bunn, 2007). Table 1