ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

A review of and perspectives on global change modeling for Northern Eurasia

To cite this article: Erwan Monier *et al* 2017 *Environ. Res. Lett.* **12** 083001

View the article online for updates and enhancements.

You may also like

- Siberia Integrated Regional Study: multidisciplinary investigations of the dynamic relationship between the Siberian environment and global climate change
E P Gordov and E A Vaganov

- Regional adaptation of a dynamic global vegetation model using a remote sensing data derived land cover map of Russia
S Khvostikov, S Venevsky and S Bartalev

- Probabilistic projections of 21st century climate change over Northern Eurasia
Erwan Monier, Andrei Sokolov, Adam Schlosser et al.

This content was downloaded from IP address 137.75.80.24 on 23/09/2022 at 17:22

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
16 February 2017

REVISED
5 June 2017

ACCEPTED FOR PUBLICATION
21 June 2017

PUBLISHED
8 August 2017

Original content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

TOPICAL REVIEW

A review of and perspectives on global change modeling for Northern Eurasia

Erwan Monier[1,9], David W Kicklighter[2], Andrei P Sokolov[1], Qianlai Zhuang[3], Irina N Sokolik[4], Richard Lawford[5], Martin Kappas[6], Sergey V Paltsev[1] and Pavel Ya Groisman[7,8]

1 Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, United States of America
2 The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA, United States of America
3 Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN, United States of America
4 School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, United States of America
5 Morgan State University, Baltimore, MD, United States of America
6 Department of Cartography, GIS and Remote Sensing, Georg-August-Universität Göttingen, Göttingen, Germany
7 North Carolina State University at National Centers for Environment Information, NOAA, Asheville, NC, United States of America
8 P. P. Shirshov Institute for Oceanology, RAS, Moscow, Russia
9 Author to whom any correspondence should be addressed.

E-mail: emonier@mit.edu

Keywords: global change, Northern Eurasia, NEESPI, Earth system model, integrated assessment model, coupled human–Earth system

Abstract

Northern Eurasia is made up of a complex and diverse set of physical, ecological, climatic and human systems, which provide important ecosystem services including the storage of substantial stocks of carbon in its terrestrial ecosystems. At the same time, the region has experienced dramatic climate change, natural disturbances and changes in land management practices over the past century. For these reasons, Northern Eurasia is both a critical region to understand and a complex system with substantial challenges for the modeling community. This review is designed to highlight the state of past and ongoing efforts of the research community to understand and model these environmental, socioeconomic, and climatic changes. We further aim to provide perspectives on the future direction of global change modeling to improve our understanding of the role of Northern Eurasia in the coupled human–Earth system. Modeling efforts have shown that environmental and socioeconomic changes in Northern Eurasia can have major impacts on biodiversity, ecosystems services, environmental sustainability, and the carbon cycle of the region, and beyond. These impacts have the potential to feedback onto and alter the global Earth system. We find that past and ongoing studies have largely focused on specific components of Earth system dynamics and have not systematically examined their feedbacks to the global Earth system and to society. We identify the crucial role of Earth system models in advancing our understanding of feedbacks within the region and with the global system. We further argue for the need for integrated assessment models (IAMs), a suite of models that couple human activity models to Earth system models, which are key to address many emerging issues that require a representation of the coupled human–Earth system.

1. Introduction

Northern Eurasia consists of a diverse set of ecosystems, both natural and managed, across a wide range of climatic conditions, including subarctic, humid continental, semi-arid and desert climates. The region is host to a variety of the Earth's biomes like tundra, taiga, broadleaved forest, steppe and desert, as well as significant areas of cropland, pasture, rangeland, managed forests and urban areas. Northern Eurasia includes roughly 70% of the Earth's boreal forest and is underlain by more than two-thirds of the Earth's permafrost (Groisman *et al* 2009). Frozen soils within the northern Arctic and subarctic regions store large quantities of organic carbon, whether in the top soil layer or in deposits deeper than 3 m (McGuire *et al* 2009,

© 2017 IOP Publishing Ltd

Schuur *et al* 2015). For example, large amounts of carbon are believed to be sequestered in the deep permafrost carbon pool of the Yedoma region in Siberia, in typical Yedoma deposits (late Pleistocene ice- and organic-rich silty sediments) in Alaska, and in deposits formed in thaw-lake basins (generalized as thermokarst deposits). Similarly, significant stocks of carbon are stored in boreal forests, both in their soil, live biomass, deadwood and litter (Pan *et al* 2011, Thurner *et al* 2014). As a result, Northern Eurasia is a major player in the global carbon budget. Furthermore, the region has experienced major environmental and socioeconomic changes over the past century. These include increases in temperature, growing season length, floods and droughts (Groisman and Soja 2009, Soja and Groisman 2012, Groisman *et al* 2009), permafrost thaw (Romanovsky *et al* 2007), and forest fires (Groisman *et al* 2007); changes in snow characteristics and icing conditions (Bulygina *et al* 2011, 2015); and extensive disturbance from land-use change and water management projects (Groisman *et al* 2009). These past and ongoing environmental and socioeconomic changes can have major impacts on biodiversity, environmental sustainability, ecosystem services, and the carbon cycle in the region that can potentially feedback to alter the global Earth system. These studies also suggest the region is poised to be further impacted by future climate change. For these reasons, Northern Eurasia represents a critical and complex region to understand with substantial challenges for the modeling community.

To better understand this region, which extends from 15°E in the west to the Pacific coast in the east and from 40°N in the south to the Arctic Ocean coast in the north, a group of international scientists, including US, European, Asian and Russian scientists have been motivated to work together and developed a program of research called the Northern Eurasia Earth Science Partnership Initiative (NEESPI). As a result of the first formal NEESPI workshop, which took place in 2002, and other subsequent workshops, the mission of NEESPI was defined as follows: '. . . identify the critical science questions and establish a program of coordinated research on the state and dynamics of terrestrial ecosystems in Northern Eurasia and their interactions with the Earth's climate system to enhance scientific knowledge and develop predictive capabilities to support informed decision-making and practical applications.' An overview of the NEESPI science plan is given in Groisman and Bartalev (2007). Since then, a substantial effort has been directed to the development of a variety of models to organize and improve our knowledge of Earth system processes in Northern Eurasia, especially focusing on their future responses to climate change and changes in socioeconomic drivers. Through NEESPI, a large body of interdisciplinary and dynamic research has been produced, highlighting major implications of environmental, socioeconomic and climatic change for natural and managed ecosystems and investigating the potential future states of the region to support informed decision-making for society. Many of these results were published in three completed Focus Issues in *Environmental Research Letters* (Groisman and Soja 2007, 2009, Soja and Groisman 2012), an ongoing Focus Issue (which will be the last NEESPI Focus Issue), one completed Special Issue in *Global and Planetary Change* (Groisman 2007) and a large number of books (Groisman *et al* 2014).

In this review paper, we assess the state of recent and ongoing efforts to model specific aspects of the Earth system relevant to Northern Eurasia. Specifically, we survey articles from the various NEESPI special issues, other NEESPI-supporting articles and articles selected based on the authors' experience and knowledge with the relevant literature on Northern Eurasia. We further select the articles describing the development and application of models or modeling frameworks to investigate issues specific to the region. We underscore the few studies that have aimed to integrate multiple components of the Earth system and frame the NEESPI modeling efforts in the context of more global and general modeling exercises. We then discuss new approaches to global change modeling for Northern Eurasia. We draw attention to the usefulness of Earth system models to examine the potential importance of feedbacks among Earth system components on the evolution of global change and the responses of ecosystems, including those in Northern Eurasia, to that change. We further emphasize the need to incorporate human dimensions with environment dynamics and the emergence of integrated assessment models as important tools to model the coupled human–Earth system. A wide spectrum of model integration exists, ranging in complexity from representing the impact of climate change on a single component of the Earth system to a fully integrated coupled human–Earth system modeling framework (see figure 1). However, issues still exist, consequently NEESPI researchers need to develop a new paradigm of integrated global change modeling for Northern Eurasia. Finally, we discuss how new modeling efforts may help to provide insights into emerging issues unique to the region and address questions of uncertainty in future projections.

2. Recent and ongoing modeling studies over Northern Eurasia

A large number of models have been developed to represent the complex and diverse set of physical, ecological, climatic and human systems that make up Northern Eurasia. These include models focusing on the many ecological and geophysical processes comprising Earth system dynamics of interest in the region, such as the hydrological cycle, soil thermal dynamics, wildfires, dust emissions, carbon cycle, terrestrial ecosystem characteristics, climate and

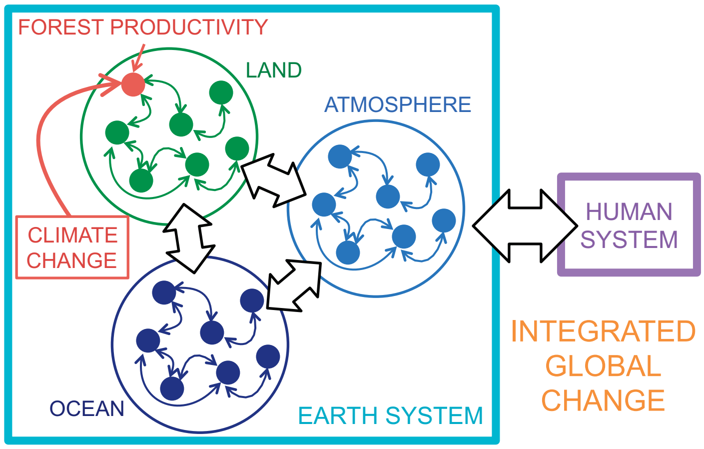

Figure 1. Schematic showing an example of a current study that focuses on the climate impacts on a single component of the Earth system, here imposing climate change on forest productivity (shown in red), compared to an example of a framework that links the Earth system (cyan), including the land (green), atmosphere (light blue) and ocean (dark blue) and their individual components, to the human system (purple). The resulting coupled human–Earth system modeling framework allows for a complete investigation of integrated global change. There is a spectrum of integrated modeling studies, and most studies fall in between these two drastic examples (i.e. representing the impact of climate change on land processes, including both red and green colors).

weather, or sea ice. Modeling efforts also focus on human dimensions, like demographic models, risk management models, and models that link the human system and the Earth system, such as models representing agriculture, forestry and water management. Because Northern Eurasia accounts for 60% of the land area north of 40°N, includes roughly 70% of the Earth's boreal forest and more than two-thirds of the Earth's permafrost, most of the past and ongoing research on modeling of Earth system dynamics over Northern Eurasia have put a large emphasis on the land system, whether the focus is on physical processes (e.g. land and water carbon cycle, energy balance) or the fate of the land system under climate change (permafrost thawing, agriculture, wildfire, dust storms). Table 1 shows a non-exhaustive list of modeling studies with a focus on Northern Eurasia sorted by specific aspects of the Earth and human systems.

These models also vary widely in their characteristics, approaches, applications and focus, from *empirical models* that are based on statistical relationships using observed data to *process-based models* that focus on simulating detailed processes that explicitly describe the behavior of a system, and from *agent-based models* that simulate individual agents of a system in order to assess the behavior of the system as a whole to *systems models* that focus on the interactions among the various components of a system. Depending on the particular scope of the research question, models are developed to take advantage of the various model classes and approaches, as summarized in figure 2.

Empirical models can be expertly calibrated to reproduce past and current behavior of the system when observational data is available, but they can suffer from unimpressive out-of-sample performance, such as for future climate change studies, in different geographical regions, or for components with different properties. Process-based models are well-suited for examining a system's responses to evolving conditions, or when observational datasets are scarce or non-existent (i.e. gap-filling or re-analysis datasets), but they can suffer from biases, overfitting of parameters due to data scarcity, and a lack of consensus on the underlying theory to describe a specific process. For these reasons, empirical models are mainly used when sufficient observational datasets are available to derive robust statistical relationships, such as empirical crop models in the United States (Lobell and Asner 2003, Schlenker and Roberts 2009, Sue Wing *et al* 2015), but are not as commonly used over Northern Eurasia. Process-based models can be used in global studies, such as process-based crop models simulating yields over the entire globe, even in regions where crops are not currently growing (Rosenzweig *et al* 2014).

Agent-based models focus on a single agent, represented with a high level of detail, but at the cost of not representing interactions and feedbacks among the various components of the Earth system. These models are particularly common in ecology, such as modeling individual trees in a forest (Shuman *et al* 2013b). At the other end of the spectrum, systems models are generally designed to study feedback processes, with a simplified representation of each component, often assumed to be homogeneous in scale and properties, and thus are more commonly used at larger scales when computational demand is high and data is lacking. For example, micro-scale land surface models can use a multilayer structure to represent the canopy, even distinguishing leaf angle classes in each canopy layer to represent differential illumination of canopy surfaces (Xu *et al* 2014); meanwhile global land surface models generally assume a single layer 'big leaf' model (Friend 2001).

Table 1. Non-exhaustive list of modeling studies with a focus on Northern Eurasia sorted by specific aspects of the Earth and human systems. Note that some studies are listed under several aspects of the Earth and human systems.

Agriculture (crop modeling, economics)	Dronin and Kirilenko 2010, Gelfan *et al* 2012, Iizumi and Ramankutty 2016, Magliocca *et al* 2013, Peng *et al* 2013, Schierhorn *et al* 2014a, 2014b, Tchebakova *et al* 2011
Air quality (aerosols, ozone, pollen . . .)	Baklanov *et al* 2013, Darmenova *et al* 2009, Lu *et al* 2010, Siljamo *et al* 2013, Sofiev *et al* 2013, Soja *et al* 2004, Sokolik *et al* 2013, Xi and Sokolik 2015, 2016
Carbon (in land and water)	Bohn *et al* 2013 2015, Cresto-Aleina *et al* 2015, Dargaville *et al* 2002a, 2002b, Dass *et al* 2016, Dolman *et al* 2012, Gao *et al* 2013, Glagolev *et al* 2011, Gustafson *et al* 2011, Hayes *et al* 2011a, 2011b, 2014, John *et al* 2013, Kicklighter *et al* 2013, 2014, Kim *et al* 2011, Koven *et al* 2011, Kuemmerle *et al* 2011, 2011b, Lu *et al* 2009, McGuire *et al* 2010, Mukhortova *et al* 2015, Narayan *et al* 2007, Olchev *et al* 2009a, 2013, Rawlins *et al* 2015, Rossini *et al* 2014, Sabrekov *et al* 2014, 2016, Saeki *et al* 2013, Schaphoff *et al* 2015, Schierhorn *et al* 2013, Schulze *et al* 2012, Shakhova *et al* 2013, 2015, Shuman and Shugart 2009, Shuman *et al* 2013a, Yue *et al* 2016, Zhang *et al* 2012, Zhu *et al* 2013, 2014, Zhu and Zhuang 2013, Zhuang *et al* 2013
Climate	Anisimov *et al* 2013, Arzhanov *et al* 2012a, 2012b, Miao *et al* 2014, Monier *et al* 2013, Onuchin *et al* 2014, Shahgedanova *et al* 2010, Shkolnik and Efimov 2013, Volodin 2013, Volodin *et al* 2013, Zuev *et al* 2012
Cryosphere (snow, glaciers, sea ice . . .)	Callaghan *et al* 2011a, 2011b, Farinotti *et al* 2015, Hagg *et al* 2006, Klehmet *et al* 2013, Loranty *et al* 2014, Pieczonka and Bolch 2015, Shahgedanova *et al* 2010, Shakhova *et al* 2015, Sorg *et al* 2012
Demography	Heleniak 2015
Energy balance	Brovkin *et al* 2006, Gálos *et al* 2013, Loranty *et al* 2014, Olchev *et al* 2009b, Oltchev *et al* 2002b, Tchebakova *et al* 2012
Hydrological cycle	Bowling and Lettenmaier 2010, Cresto-Aleina *et al* 2015, Gelfan 2011, Georgiadi *et al* 2010, 2014, Hagg *et al* 2006, Karthe *et al* 2015, Khon and Mokhov 2012, Klehmet *et al* 2013, Kuchment *et al* 2011, Liu *et al* 2013, 2014, 2015, McClelland *et al* 2004, Motovilov and Gelfan 2013, Novenko and Olchev 2015, Olchev *et al* 2009a, 2013, Oltchev *et al* 2002a, 2002b, Osadchiev 2015, Rawlins *et al* 2010, Serreze *et al* 2006, Shiklomanov *et al* 2013, Shiklomanov and Lammers 2013, Sorg *et al* 2012, Streletskiy *et al* 2015, Troy *et al* 2012, Zhang *et al* 2011
Land-use change	Blyakharchuk *et al* 2014, Griffiths *et al* 2013, Gustafson *et al* 2011, Hayes *et al* 2011a, Hitztaler and Bergen 2013, Kicklighter *et al* 2014, Kraemer *et al* 2015, Kuemmerle *et al* 2009, Meyfroidt *et al* 2016, Robinson *et al* 2013, Schierhorn *et al* 2013, Schierhorn *et al* 2014, 2014b, Smaliychuk *et al* 2016, Zhang *et al* 2015
Infrastructure	Shiklomanov and Streletskiy 2013, Shiklomanov *et al* 2017, Stephenson *et al* 2011, Streletskiy *et al* 2012
Nitrogen	Kopáček *et al* 2012, Kopáček and Posch 2011, Oulehle *et al* 2012, Zhu and Zhuang 2013, Zhuang *et al* 2013
Permafrost	Euskirchen *et al* 2006, Gao *et al* 2013, Gouttevin *et al* 2012, Hayes *et al* 2014, MacDougall and Knutti 2016, Marchenko *et al* 2007, Shakhova *et al* 2013, 2015, Streletskiy *et al* 2012, 2015, Zhang *et al* 2011
Terrestrial ecosystems characteristics	Cresto-Aleina *et al* 2013, Kopačková *et al* 2014, 2015, Lapenis *et al* 2005, Lebed *et al* 2012, Li *et al* 2016, Shuman *et al* 2013, 2013b, Shuman and Shugart 2012, Ziółkowska *et al* 2014
Vegetation shifts	Gustafson *et al* 2011, Jiang *et al* 2012, 2016, Khvostikov *et al* 2015, Kicklighter *et al* 2014, Li *et al* 2014, Macias-Fauria *et al* 2012, Novenko *et al* 2014, Schaphoff *et al* 2015, Shuman *et al* 2015, Soja *et al* 2007, Tchebakova *et al* 2009, 2010, 2016a, 2016b, Tchebakova and Parfenova 2012, Velichko *et al* 2004
Weather (i.e. extreme events)	Barriopedro *et al* 2011, Meredith *et al* 2015, Mokhov *et al* 2013, Schubert *et al* 2014, Shkolnik *et al* 2012
Wildfire	Balshi *et al* 2007, Dubinin *et al* 2011, Gustafson *et al* 2011, Kantzas *et al* 2013, Loboda and Csiszar 2007, Malevsky-Malevich *et al* 2008, Narayan *et al* 2007, Park and Sokolik 2016, Schulze *et al* 2012, Soja *et al* 2004, Tchebakova *et al* 2009, 2012, Vasileva and Moiseenko 2013
Zoology	Kuemmerle *et al* 2011a, 2014, Ziółkowska *et al* 2014

Process-based models have been used most frequently by the NEESPI community, most likely because Northern Eurasia is not as data rich as other regions of the world. However, in practice, most process-based models include some form of empirical modeling to inform parameterizations of processes that are not precisely known or processes taking place at scales too small to be fully represented. Meanwhile many models fall in-between agent-based models and systems models, with a compromise made between the detailed representation of systems and their interactions. Furthermore, because of the trade-off between model complexity, scale and observational data availability, methodologies have been developed to combine models with observational datasets, whether they are based on inventories (Dolman *et al* 2012) or remote sensing (John *et al* 2013).

While most modeling studies focus on a specific component of the Earth system, a few studies have integrated various aspects of the Earth system, in terms of scale (Gouttevin *et al* 2012, Zhu *et al* 2014), teleconnection or global feedbacks (Dargaville *et al* 2002b, Macias-Fauria *et al* 2012) and processes (Euskirchen *et al* 2006, Callaghan *et al* 2011b, Sokolik

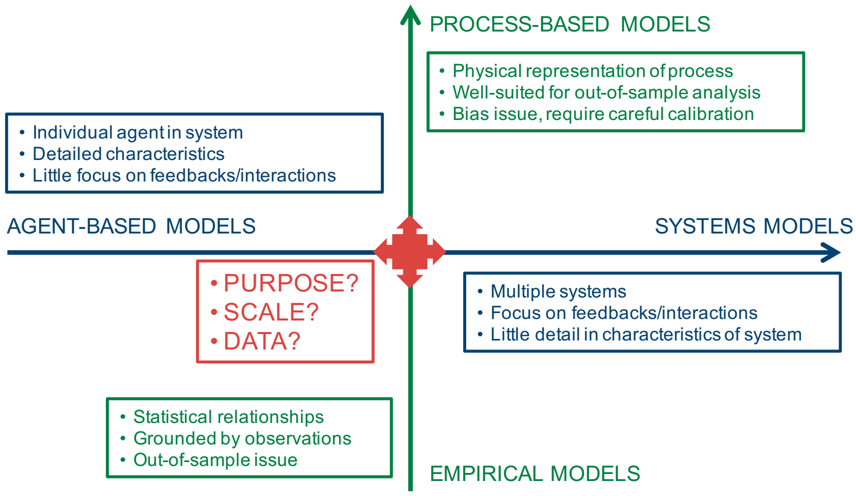

Figure 2. Schematic summarizing the strength and limitations of models based on the class of model (empirical models to process-based models) and modeling approaches (from agent-based models to systems models). The choice of model characteristics generally depends on the purpose, scale and data availability.

et al 2013). Other studies focus on integrated systems where multiple disciplines overlap, such as modeling studies of water management (Shiklomanov *et al* 2013), land management (Gustafson *et al* 2011, Kuemmerle *et al* 2011b, Lebed *et al* 2012, Robinson *et al* 2013, Shuman *et al* 2013a, Blyakharchuk *et al* 2014) or climate and infrastructure (Shiklomanov and Streletskiy 2013, Shiklomanov *et al* 2017). This growing effort to integrate existing models, through scale, processes and feedback has translated in more coordinated and multidisciplinary research projects. For example, NEESPI scientists have integrated models that can interact with each other, e.g. weather and aerosol physics, including dust and smoke aerosols (Darmenova *et al* 2009, Xi and Sokolik 2015, 2016, Park and Sokolik 2016); permafrost and terrestrial hydrology with water management (e.g. Zhang *et al* 2011, Shiklomanov and Lammers 2013); the carbon and water cycles (e.g. Bohn *et al* 2015); land carbon and atmospheric transport modeling (Dargaville *et al* 2002a, 2002b); and biospheric and climate information (Tchebakova *et al* 2009, 2016a, 2016b, Shuman *et al* 2015).

These modeling studies generally fall into two categories: (1) diagnostic modeling studies that identify key mechanisms and processes that control the behavior of a system, assess the present relationships among critical components of the environment and evaluate models based on experimental and observational datasets (e.g. Gouttevin *et al* 2012, Anisimov *et al* 2013, Zhu *et al* 2014, Rawlins *et al* 2015); and (2) prognostic modeling studies that focuses on the response of Earth system components to global change (Gao *et al* 2013, Zhu *et al* 2013, Kicklighter *et al* 2014).

Diagnostic modeling studies have improved our understanding of the Earth system. These studies are important as they ground the modeling efforts to reality and provide a critical sanity check. They also guarantee that models pass rigorous tests before being used to enhance our understanding of mechanisms and processes controlling the system of interest. For this purpose, there is a growing need for close collaborations between modeling groups and observational studies (Liu *et al* 2013, 2014, Loranty *et al* 2014, Rawlins *et al* 2015). Many approaches exist to evaluate models at different temporal and spatial scales. Focusing on the example of terrestrial carbon and water fluxes, eddy-covariance is used for local high temporal resolution (Liu *et al* 2014, 2015, Rawlins *et al* 2015); dissolved organic carbon (DOC) export and discharge at the mouth of a river allows for the assessment of the integrated response of a watershed (Kicklighter *et al* 2013); inventory of forest carbon stocks and biomass increment at the regional-to-global scale evaluation (Pan *et al* 2011); or satellite measurements for spatially explicit regional-to-global scale evaluation (Liu *et al* 2013, 2014, Mehran *et al* 2014, Rawlins *et al* 2015).

At the same time, if a model is assessed as performing realistically when simulating past or present day conditions, it does not guarantee that the response to different environmental conditions, like future climate change, is sensible. For this reason, suitable formalisms and standard experimental protocols that allow comparison between models are getting more traction. The number of Model Intercomparison Projects (MIPs) has grown substantially in the past decade. With the inception of the Atmospheric Model Intercomparison Project (AMIP) in 1990, more than 30 MIPs are now in existence, including the Snow Models Intercomparison Project (SnowMIP), the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP), or the Arctic Regional Climate Model Intercomparison Project (ARMIP) to name a few. A list of MIPs can be found at www.wcrp-climate.org/wgcm/projects.shtml. Most MIPs usually include models that are structurally similar and that

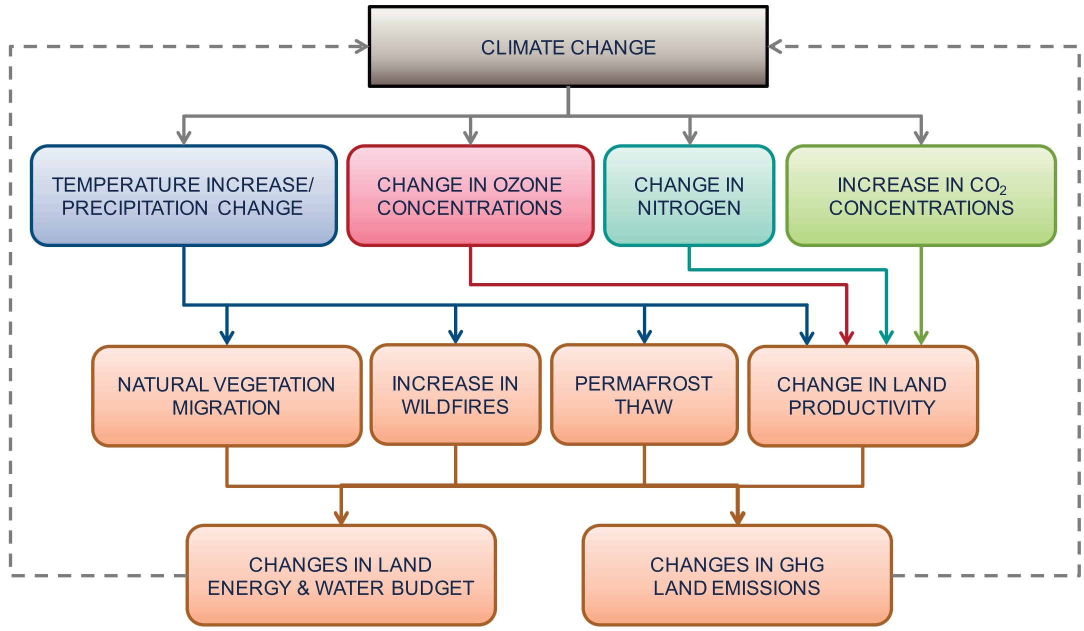

Figure 3. Schematic of a detailed, but non-exhaustive, accounting of climate change impacts on land biogeochemistry and biogeophysics. Dashed lines represent the potential feedback of terrestrial ecosystem responses to the climate system.

focus on the same component of the Earth system (Sea-Ice Model Intercomparison Project, SIMIP), phenomenon (Tropical Cyclone Climate Model, TCMIP), process (Cloud Feedback Model Intercomparison Project, CFMIP), time period of focus (Paleo Model Intercomparison Project, PMIP) or on the interaction among specific components of the Earth system (Atmospheric Chemistry and Climate Model Intercomparison Project, ACC-MIP). Because of large inconsistencies in input datasets, model output, or experimental design of simulations between different classes of models, most models within a MIP have the same structure and generally fall in the category of process-based models. Little effort has been devoted to comparing different classes of models (process-based versus empirical; agent-based versus system models). Similarly, few MIPs have focused on a region of interest, especially on Northern Eurasia.

Prognostic modeling studies focus on projections of climate change over Northern Eurasia (Arzhanov *et al* 2012a, 2012b, Shkolnik *et al* 2012, Monier *et al* 2013, Volodin *et al* 2013) and its associated impacts over the 21st century. These studies build upon the model development and evaluation discussed previously and they investigate the response of the Earth system to global change. They often focus on specific processes, such as permafrost thaw (Gao *et al* 2013) or natural plant migration (Jiang *et al* 2012, 2016), or specific elements of the Earth system, like agriculture (Schierhorn *et al* 2014a, 2014b) or forests (Tchebakova and Parfenova 2012, Olchev *et al* 2013). While highly focused modeling studies can greatly enhance our understanding of the response of a key process or element of the Earth system, they usually make it difficult to assess the behavior of a system as a whole. For example, there are many processes through which climate change can impact the emissions of greenhouse gases from the land system (see figure 3), including: (1) climate-induced vegetation shifts; (2) changes in the frequency and severity of wildfires; (3) permafrost thaw; and (4) changes in land productivity caused by changes in temperature and precipitation, ozone damage, nitrogen deposition, CO_2 fertilization, and land management. Individually, a study focusing on a single process can enhance our understanding of the land biogeochemistry under future climate change, such as the work of Felzer *et al* (2005), which focuses on the role of ozone damage on forestry and crop productivity. But unless such studies are well coordinated (e.g. using the same climate change scenarios) and integrated (using the same modeling framework), these studies would not permit a detailed accounting and an attribution of the relative role of each process in the overall system.

Furthermore, if interactions and feedbacks exist among the different processes of climate change impacts, individual studies could be misleading. For example, changes in land emissions of greenhouse gases (GHGs) can lead to potentially significant feedbacks to the climate system, adding to the anthropogenic emissions, and leading to even greater concentrations of greenhouse gases in the atmosphere. While our example focuses on land biogeochemistry, the impact of climate changes in the characteristics of the land, including albedo, surface roughness and soil moisture (biogeophysical impact) plays an equally important role in how the Earth's energy budget may evolve (Brovkin *et al* 2006, 2013). As a result, we argue that a greater understanding and comprehensive representation of feedbacks and interactions within the Earth system are required and should be a major emphasis of future model development efforts.

Most studies of climate change impacts rely on standard scenarios of climate change, such as climate model projections archived from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor *et al* 2012) that use the Representative Concentration Pathway (RCP) scenarios (van Vuuren *et al* 2011a). These climate scenarios are part of the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) and have the advantage of being the result of an international coordinated effort to create multi-model ensembles of climate simulations under a set of standard scenarios of greenhouse gas concentrations. Such ensembles of climate simulations sample the model structural uncertainty that arise from differences in the parameterizations of climate processes, the climate system response and resolution; however, they are only an ensemble of opportunity and do not sample the full range of projections. Nonetheless, multi-model ensembles based on coordinated scenarios have become the standard for the climate impacts research community, and have resulted in major advances in the understanding of many components of the Earth system, including ocean ecosystems, agriculture, the global climate system response, climate extremes, the Asian monsoon, Arctic sea ice, or soil carbon (Bopp *et al* 2013, Kharin *et al* 2013, Knutti and Sedláček 2013, Rosenzweig *et al* 2014, Sperber *et al* 2013, Stroeve *et al* 2012, Todd-Brown *et al* 2013). A common experimental design for studies modeling climate impacts is to prescribe climate change using the CMIP5 multi-model ensembles, either the full ensemble including all models that provide the relevant climate information or simply a subset of models, and to examine the varied response of a particular component of the Earth system. A limitation of such a modeling framework is that because climate change is prescribed, little attention is placed on potential feedbacks, such as the regional and global land feedbacks described in figure 3, which are largely absent from the CMIP5 multi-model ensembles. The reliance of standardized climate scenarios can often result in a lack of systematic analysis of the various feedbacks in the climate system. As a result, it is still unclear which feedbacks are important and need to be considered. The alternative is to use modeling frameworks that are able to represent the many feedbacks in the Earth system, both at the global and regional scales. Such models, known as Earth system models, are expected to be important tools for future modeling studies focusing on Northern Eurasia.

3. New approaches to global change modeling for Northern Eurasia

While many studies focus on the impact of climate change on various ecosystems and components of the Earth system, climate change impacts cannot be examined without considering the role of human activity. For this reason, we argue that the term 'climate change' should be replaced by the more accurate terminology of 'global change'. To examine how global change influences the Earth system, two related approaches are being developed based on an integrated modeling framework, Earth system models and integrated assessment models. Below, we first describe these two integrated modeling frameworks in general and the motivations behind them. We then describe the potential benefits of applying these approaches to Northern Eurasia along with the data needed and available to support such modeling activities.

3.1. Earth system models

The Earth system has complex interactions among various physical, biological and chemical processes in its different components such as the land, the atmosphere and the ocean. An exact definition of the Earth system is not formally agreed upon. In this review, we offer the following definition: coupled atmosphere, ocean, land (including rivers and lakes) and cryosphere (sea ice, land ice, permafrost) components with a representation of dynamical and physical processes (e.g. river flow, ocean eddies, cloud processes, erosion), chemical processes (chemical gases and aerosols), biogeochemical processes (life-mediated carbon-nutrient dynamics) and biogeophysical processes (life-mediated water and energy balance) in all components.

Earth system models (ESMs) have long been used to gain insight into the complex interactions and feedbacks within the Earth system that cannot be directly studied in laboratories or through observational datasets. They are particularly useful tools to investigate the response of the system to changes in external forcings, such as changes in the concentrations of greenhouse gases, that not only affect each of the components individually but also the interactions among the components. More recent Earth system model development efforts have focused on the representation of the interactive climate-chemistry system, with efforts like the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP, Friedlingstein *et al* 2006) or the estimation of the climate–carbon feedbacks using Earth system models of intermediate complexity (EMICs, Eby *et al* 2013).

ESMs have both advantages and limitations over detailed single component models. ESMs are computationally expensive. Because they simulate the global Earth system, they have not been the preferred modeling framework for targeted studies focusing on specific regions like Northern Eurasia when feedbacks are not considered. In addition, because ESMs represent the entire Earth system, with numerous interactions and feedbacks among components, simplifications in the representation of each component are necessary to keep the computational burden at reasonable levels. Thus, the representation of any particular component of the Earth system is rarely at the cutting edge. While their development relies heavily on detailed single-component models, the strength of ESMs is their capability to integrate a vast number of components. As a result, ESMs are well suited to investigate the complex feedbacks among processes and components of the Earth system at the local, regional and global scales. ESMs can also be used to investigate regional-to-global scale connections. An example of complex interactions and feedbacks that require an ESM is the effect of land-use change on climate.

Land-use change has been shown to have large impacts on the climate system, especially at local and regional scales (Brovkin *et al* 2006, 2013). Land-use change can affect the climate system via two pathways. First, land-use change impacts GHG concentrations in the atmosphere by changing land-atmosphere fluxes of carbon dioxide (CO_2), through land clearing mainly associated with deforestation, and nitrous oxide (N_2O), through changes in fertilizer application associated with the expansion and abandonment of cropland areas. This 'biogeochemical pathway' has a global fingerprint since GHGs are well-mixed in the atmosphere. Second, land-use change affects the physical characteristics of the land surface, including albedo, roughness and hydrology (e.g. evapotranspiration, soil moisture), and thus influence the exchange of heat and water between the land and the atmosphere. This 'biogeophysical pathway' has mainly a local and regional fingerprint, although it can affect regions away from land-use change through teleconnections in the climate system. An Earth system model, with its representation of the land, ocean and atmosphere components, including chemistry, aerosols and carbon cycle, is necessary to represent both feedback pathways (Hallgren *et al* 2013).

While many ESMs have recently incorporated the influence of land-use change on earth system processes in their simulations (Brovkin *et al* 2013, Eby *et al* 2013), the timing and locations of these land-use changes have been prescribed based on assumed economic decisions that were not affected by the simulated changes in environmental conditions. To better incorporate feedbacks of changing environmental conditions (particularly climate change) on future economic decisions, another suite of models are being developed, known as integrated assessment models, to represent the impacts of global change on the Earth system.

3.2. Integrated assessment models

The 21st century will bring unprecedented challenges including rapid population and economic growth, increasing demand for food, fiber, construction materials, energy and water at a time when emissions abatement targets, agreed to at the 21st Conference of the Parties (or 'COP21') to the United Nations Framework Convention on Climate Change (UNFCCC), will induce changes in the energy system away from fossil fuels and towards low-carbon alternatives, including biofuels and bioelectricity. Competition for land to meet these increased human demands will have major implications for land management practices, including water resources management, land-use change and land-use emissions (Melillo *et al* 2009, 2016, Reilly *et al* 2012), with potentially significant feedbacks to the climate system (Hallgren *et al* 2013, Jones *et al* 2013, DeLucia 2015). At the same time, GHG emissions will drive changes in temperature and precipitation patterns that will alter crop yields (Rosenzweig *et al* 2014, Sue Wing *et al* 2015), productivity of managed forests and natural terrestrial ecosystems, as well as the need for irrigation, and its costs and capacities. These changes will not only affect the food and water systems, but also the energy system (i.e. the Food-Energy-Water nexus) through impacts on the cost of growing biomass and water availability. The influence of growing populations, abating GHG emissions and climate change will differ regionally, and international trade in food and energy commodities can smooth impacts across regions.

A detailed representation of the human system, including the global economy, demography, technologies and user preferences, is essential to study potential impacts of future global change. While original climate change scenarios relied on $2\times CO_2$ concentrations idealized scenarios (first IPCC Assessment reports), future emissions of greenhouse gases and aerosols are now projected using integrated assessment models (IAMs). These models combine scientific and socio-economic modeling of climate change primarily for the purpose of examining the implications of climate mitigation and, to a lesser degree, potential pathways of adaption to climate change. IAMs generally include a model of the global economy that simulates anthropogenic emissions of greenhouse gas and a model of the physical climate system (e.g. Integrated Model to Assess the Greenhouse Effect or IMAGE, van Vuuren *et al* 2011b, MIT Integrated Global System Model or IGSM, Sokolov *et al* 2005, Reilly *et al* 2013, Global Change Assessment Model or GCAM, Thomson *et al* 2011, Model for Energy Supply Strategy Alternatives and their General Environmental Impact or MESSAGE, Riahi *et al* 2011, Asia Pacific Integrated Model or AIM, Fujimori *et al* 2014). Weyant *et al* (1996) identify three major goals of integrated assessment modeling: (1) to coordinate the exploration of the possible fate of both natural and human systems; (2) to support the development of climate policies; and (3) to identify research needs to improve our ability to design robust policy options. As highlighted in Weyant *et al* (1996), integrated assessment models are no stronger than the underlying natural and economic science that supports them. In addition, major inconsistencies exist in the different

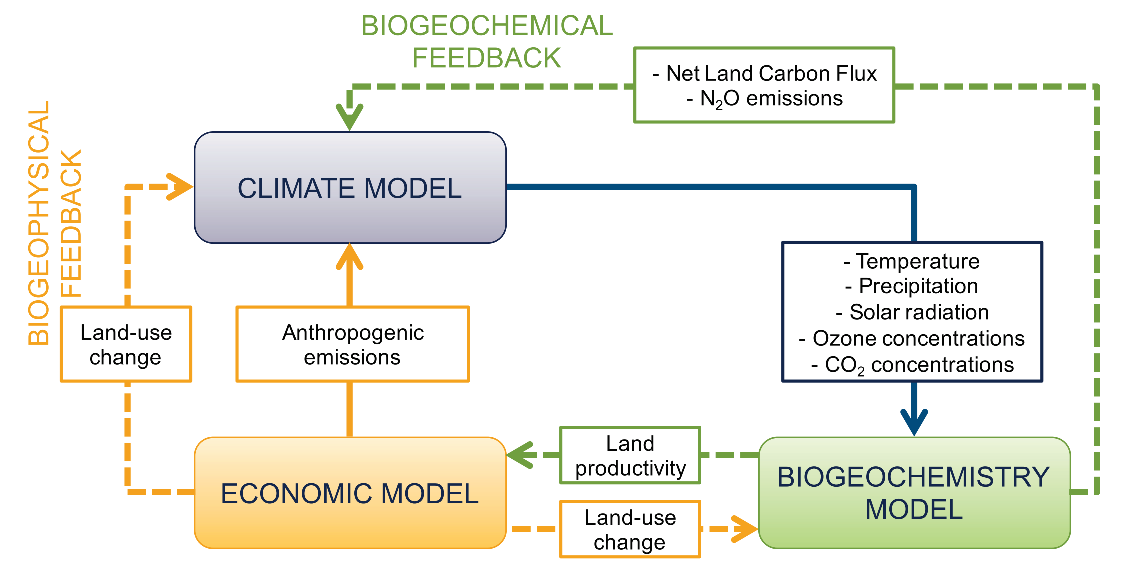

Figure 4. Schematic of modeling framework to investigate the biogeochemical and biogeophysical impacts of human-driven land-use change, similar to that used in Reilly *et al* (2012) and Hallgren *et al* (2013).

disciplines so the underlying science is often not in a form suitable for immediate use in IAMs. As a result, IAMs often lag the latest model development in an individual discipline. For example, the widely-used RCP scenarios, the underlying scenarios used as part of the latest IPCC Assessment Report, provide scenarios of anthropogenic emissions and concentrations as well as land-use change. However, the land-use change scenarios are driven only by economic considerations, assuming fixed land productivity, and thus do not account for climate change impacts on crop yields, natural terrestrial ecosystem productivity, or water availability for irrigation (Hurtt *et al* 2011).

Reilly *et al* (2013) suggest a different strategy for investigating the impacts of climate change on Earth's physical, biological and human resources and links to their socio-economic consequences in IAMs. The strategy relates changes in climate variables and human activities to changes in other physical and biological variables that affect human activities and well-being such as crop yield, food prices, premature death, flooding or drought events, and land-use change. Based on this strategy, various targeted studies have investigated land-use change using more detailed IAM frameworks. For example, Melillo *et al* (2009) use an IAM that accounts for the climate change impacts on management and natural terrestrial ecosystems to examine direct and indirect effects of possible land-use changes from an expanded global biofuel program on greenhouse gas emissions over the 21st century. Hallgren *et al* (2013) followed that work by investigating the climate impacts of a large-scale biofuels expansion, identifying the contributions of the biogeochemical and biogeophysical pathways (figure 4). Reilly *et al* (2012) use the same detailed IAM to explore the role of land-use change on global mitigation strategies to stabilize global warming to within 2 °C of the preindustrial level. While these modeling efforts highlight the potential capability of IAMs to enhance our representation of the coupled human–Earth system, here with a focus on land-use change, they represent state-of-the-art IAM modeling and, unfortunately, do not represent the general state of land-use change modeling in current IAMs. In addition, little information on Northern Eurasia can be gleaned from most IAM studies and IAMs are seldom used with a focus on Northern Eurasia. An exception is Kicklighter *et al* (2014), who extend the same detailed IAM model to include climate-induced vegetation shifts and investigate their potential influence on future land-use change and the associated land carbon fluxes in Northern Eurasia.

3.3. Global change modeling for Northern Eurasia

As the Northern Eurasia modeling community moves toward global change modeling studies with a major focus on the coupled human–Earth system, ESMs and IAMs can become valuable tools that quantify the relative importance of the responses of Northern Eurasian ecosystems and their feedbacks to the evolution of future global change. By examining interactions and feedbacks among Earth system and economic components, these models can expand upon existing research topics and open up new research avenues. We identify three different strategies revolving around these new approaches to global change modeling for Northern Eurasia that can benefit the NEESPI community:

- *Taking advantage of existing global change modeling efforts at the global level.* The ESM and IAM communities regularly participate in international coordinated modeling exercises to investigate varied global change research questions. For example, Nelson *et al* (2014a) examine the impact of climate change on agricultural production, cropland area, trade, and prices by climate, crop, and economic models. While these models are able to conduct simulations for various sized regions across the globe, these coordinated exercises generally lack a regional focus when publishing results, and usually do not identify Northern Eurasia as a key region of interest. Similarly, many global studies of the food–energy–water (FEW) system lack a focus on specific regions other than the United States, Europe, or China. Tighter collaborations of the NEESPI community with international coordinated exercises (e.g. AgMIP) could lead to major benefits for our understanding of FEW in Northern Eurasia and help identify any gaps in the representation of Northern Eurasia and its unique characteristics in ESMs and IAMs.

- *Developing coupled human–Earth system models specific to Northern Eurasia.* Various efforts to integrate the human system and the Earth system with a focus on Northern Eurasia already exist and must be continued and expanded upon. For example, a new coupled model, called WRF-Chem-DusMo (dust module), has recently been developed to explore the linkages among dust, climate and land-use change dynamics in Central Asia (Xi and Sokolik 2015, 2016). As indicated earlier, Earth system processes and economic activities tend to be represented rather simply in current ESMs and IAMs. Collaborations of the NEESPI community with coupled human–Earth system modelers could lead to improvements in the representation of Earth system processes and economic activities in Northern Eurasia in these models to the benefit of everyone.
- *Investigating tipping points specific to Northern Eurasia.* Major focus should be put toward identifying potential tipping points specific to the region, with implications for the global Earth system, such as permafrost degradation, the associated methane emissions and potential runaway climate change (Gao *et al* 2013); dieback of boreal forests from increasing heat and drought stress (Goetz *et al* 2007, Buermann *et al* 2014) and 'green desertification' caused by single or repeated catastrophic wildfires (Shvidenko *et al* 2011) and their potential to alter the global climate system through changes in greenhouse gases emissions and surface albedo. In addition, we argue that future research projects need to put a greater focus on understanding the varied and complex interactions among Northern Eurasia, surrounding regions and the rest of the world and identify how important these interactions are. Again, this can be achieved by relying on ESMs and IAMs, given that the appropriate improvements in the representation of key processes are made through collaborations between Earth system modelers and modeling experts from Northern Eurasia (e.g. improving the representation of permafrost or wildfires in ESMs).

Finally, we argue for a strong synergy between investigating the impact of global change on Northern Eurasia and better identifying the role of Northern Eurasia in the global system. To do so, strong collaborations between global and regional modeling teams are necessary and should be encouraged. We believe that ESMs and IAMs are particularly suited to investigate these regional interactions.

3.4. Data in support of global change modeling for Northern Eurasia

Similar to other modeling activities, the value of ESMs and IAMs to advance the understanding of key Earth system or economic processes in Northern Eurasia depends on the quality of data used to: 1) develop or update model algorithms and parameterizations; 2) provide inputs to drive model simulations; and 3) test model results. Useful data may be collected over a range of spatial and temporal scales such as site-level field observations and experiments, water quality data collected at the mouth of rivers that integrate information at a watershed scale, forest and soil inventories that integrate information at regional to country scales, economic data that integrate information at regional to country scales, and atmospheric chemistry flask data that integrate information at hemispheric to global scales (e.g. Krankina *et al* 2004, Houghton *et al* 2007, Prinn *et al* 2011, Kicklighter *et al* 2013, Liu *et al* 2013, 2014). In addition, gridded time-series data, based on either satellite and airborne remote imagery or interpolations among networks of site data, also provide useful information to evaluate how well ESM and IAM simulations capture spatial and temporal patterns (e.g. Liu *et al* 2013, 2014). However, there is still much uncertainty among gridded data sets representing an Earth system variable based on differing assumptions in interpolation procedures or interpretation of satellite imagery (e.g. Liu *et al* 2015). Additional efforts are needed to better understand and reduce these data uncertainties in the future.

It should come as no surprise that considerable amounts of data are required for evaluating the strengths and limitations of ESMs and IAMs for investigating global change over the Northern Eurasia as these models simulate a large number of components of the coupled human–Earth system. Due to the multidisciplinary aspect of the coupled human–Earth system, these datasets can be difficult to acquire, process and maintain in formats easily accessible to the whole research community. For Northern Eurasia, many satellite data products are publicly available (i.e. NASA and NOAA or the ESA

Living Planet Programme and the COPERNICUS programme https://earth.esa.int/web/guest/data-access), and have been used by the NEESPI research community to study, among others, the carbon cycle, land cover, land use, and forest fire monitoring. In addition, diverse datasets have been developed over the last decade to support the NEESPI domain modeling. These include, but are not limited to:

- Meteorological data (observations and some model products) for Northern Eurasia are available (with data overlaps) from three national data centers. While these data centers are 'national', each center carries a suite of information for either the entire NEESPI domain or most of the domain as well as for the Globe. These are the Russian Center for Hydrometeorological Information-World Data Center, RIHMI-WDC (http://meteo.ru/english/data/), the Beijing Climate Center (http://bcc.cma.gov.cn), the US National Center for Environmental Information (www.ncei.noaa.gov/access) and the European Climate Research Unit (e.g. CRU TS Version 3.22 and TS 4.0; www.cru.uea.ac.uk/data).
- Hydrological and geomorphological information for Northern Eurasia is stored and updated at the NEESPI Focus Research Center for Water System Studies at the Department of Geography of the University of New Hampshire (www.wsag.unh.edu/neespi.html). Examples of products available from this Center can be seen at: http://neespi.sr.unh.edu/maps/.
- Land cover information for the NEESPI domain became a part of the GOFC-GOLD data holdings www.gofcgold.wur.nl/sites/neespi.php. For Northern Eurasia, these data holdings serve as a depository for the needs of the forest monitoring and full carbon budget accounting of the region. The NASA data holding for satellite products (https://mirador.gsfc.nasa.gov/) also includes Northern Eurasia. The ESA Living Planet Programme with COPERNICUS offers also freely available satellite data over Northern Eurasia (e.g. Sentinel data; www.esa.int/Our_Activities/Observing_the_Earth/Copernicus).

Furthermore, many information systems have been developed over the years by the NEESPI community (e.g. Leptoukh *et al* 2007, Titov *et al* 2009, Gordov *et al* 2013). These tools include storage and processing models for climate datasets (Okladnikov *et al* 2016), an online instrument for multidisciplinary data visualization, analysis and manipulation with a focus on hydrological application (Shiklomanov *et al* 2016), and a hardware and software platform prototype for monitoring and projecting environmental changes in the northern extratropical areas (Gordov *et al* 2016). These powerful interactive visualization and analysis tools provide access to climate datasets to researchers and users without requiring expert knowledge in data processing and plotting. As such, they serve an important mission to broaden the Northern Eurasia research community.

Similarly, socio-economic data are available for many countries within Northern Eurasia and the globe. In particular, the Global Trade Analysis Project (GTAP) dataset (Aguiar *et al* 2016) contains the consistent representation of economic output, trade, consumption and government expenditures that cover the entire economies of the following countries: Norway, Sweden, Finland, Russia, Mongolia, China, Kazakhstan, Azerbaijan, Georgia, Armenia, Ukraine, Bulgaria, Romania, Hungary, Czech Republic, Slovakia, Poland, Belarus, Lithuania, Latvia, and Estonia. Land-use data and energy data are available from the major agencies like the International Energy Agency (IEA) and Food and Agriculture Organization (FAO). For many of these countries, regional representation is also available. For example, Tarr *et al* (2001) provide the social accounting matrices for 88 regions of Russia with data for production, consumption and intermediate use of commodities and services, and for bilateral trade with other regions and the rest of the world. The economy in each Russian region is represented by 30 industrial sectors producing commodities and services.

At the same time, there is a need for improvement in the availability and quality of both Earth system and socio-economic data. Networks of Earth system observing stations, such as meteorological stations, are quite dense in the populated regions of Northern Eurasia but they are scarce over the desert regions to the south, the mountains of western China and northern Siberia. Since the availability and quality of observational data from these networks varies dramatically, and since international archives are updated only intermittently over these regions, it is advisable to collaborate with local scientists, especially in China and the Central Asian newly independent states. Furthermore, while most country-level economic transactions are available for analysis, the disaggregation of the data at a finer spatial scale is limited. Even more limited are data for socio-economic characteristics like level of education, health services, employment numbers by industry, income by different age, gender or location, population migration, etc.

For these reasons, the global change modeling community must be an essential driver to help identify the crucial data gaps and to provide guidance to research agencies about the type of data needed to support global change modeling. Those include statistical agencies, who would benefit from information on the data required for the analysis of the economic and welfare implications of global change at a level that is useful for decision-making. They also include science agencies, who need to know what data would be required, for example, to improve models of permafrost degradation and its associated methane emissions.

4. Emerging issues in the coupled human–Earth system of Northern Eurasia

At the frontier of Earth system and integrated assessment modeling, many issues and research foci have recently emerged and driven further development of coupled human–Earth system models. In this section, we highlight a few important emerging issues in the coupled human–Earth system of Northern Eurasia.

While modeling of the FEW nexus has gained substantial momentum in recent years, it is still arguably an emerging issue for most research groups, even when not focusing on Northern Eurasia. Major innovations at the nexus of the FEW system are still needed, with improved integrations of the various components of the coupled human–Earth system. Currently, well-recognized studies of the FEW system (Elliott *et al* 2014, Nelson *et al* 2014a, 2014b, Schmitz *et al* 2014, Valin *et al* 2014, von Lampe *et al* 2014) have common limitations: they impose climate change without considering potential feedbacks of the FEW system to the regional and global climate through either biogeochemical and biogeophysical pathways; they fail to fully integrate all three components of the FEW system and their interactions, such as not accounting for the impact of water scarcity on irrigation availability and its impact on irrigated crop yields or on water availability for power plant cooling and its impact on energy production; and they fail to account for even simple adaptive management practices, such as improvements in conveyance efficiency, field efficiency and water storage for irrigation. Certainly, improving the integration of the FEW system within IAMs is underway but these modeling development efforts have not yet focused on Northern Eurasia and its unique environmental and socioeconomic background. While the FEW nexus is a global issue, it has unique characteristics in different regions (Lawford *et al* 2013). For the NEESPI region, unique characteristics include thermokarst dynamics, permafrost degradation, scarcity of human infrastructure, varied levels of agriculture development and management practices, locally diverse hydrological conditions associated with complex biomes and climate interactions. These characteristics need to be understood and modeled at appropriate scales. Better data and information are urgently needed to improve the effective use of information and models in support of better planning and decision-making in the region.

With air pollution identified as the world's largest environmental health risk (Lim *et al* 2012), many research groups have developed modeling frameworks that link climate change, air pollution and human health (West *et al* 2007, Jacobson 2008, Selin *et al* 2009). These modeling frameworks have been used to estimate the economic implications of changes in air quality (Fann *et al* 2014) as well as to evaluate the air quality co-benefits of climate policies and improve climate change policymaking (Nemet *et al* 2010). However, such studies have largely focused on countries like the United States (Thompson *et al* 2014, Saari *et al* 2014, Garcia-Menendez *et al* 2015), despite the importance of the air pollution and health nexus in Northern Eurasia and its unique characteristics. Aside from the traditional anthropogenic precursor emissions associated with the industry, energy and transportation sectors, or biogenic emissions of precursors, Northern Eurasia experiences varied and complex sources of air pollution, including wildfires, crop residue burning and dust. With Russia expected to experience the largest increase in burned forest area in the world (Kim *et al* 2017), the resulting emissions of particulate matter are likely to play a considerable role in future changes in air pollution and health. Meanwhile, the Russian Federation accounted for 31%–36% of all cropland burning across the globe between 2001 and 2003 (Korontzi *et al* 2006), with crop residues being burned to clear fields, fertilize the soil, and eliminate pests and weeds. Finally, the drylands of Central Asia, which is the largest dry area in the extratropics, is a major source of dust storms and a powerful source of atmospheric pollution (Issanova and Abuduwaili 2017). In addition to these pollution sources, complex transport of air pollutants to and from Northern Eurasia need to be better understood. Quantifying the economic impact of future changes in air pollution in the region, especially taking into account these unique sources of pollutants and the transport of pollutants to and from surrounding countries, can prove key to accurately inform policy responses for Northern Eurasia.

Beyond existing issues like the fate of FEW system or the air quality and health nexus, Northern Eurasia could experience climate-induced changes in coming years that may well reshape the region. As the Arctic sea ice extent shrinks, Arctic trade routes will remain open for longer periods of time, and new routes will likely open. Investigating the fate of Northern Eurasia as these new trade routes emerge will require complex coupled human–Earth system models that account for the many potential impacts, interactions and feedbacks on the system. Combined with increasing demand for natural resources from neighboring regions like India, China and other Southeast Asian countries, these new trade routes could result in the ability of the timber industry and energy exploration to reach remote areas like Siberia. At the same time, warmer temperatures could cause the disappearance of temporary roads constructed over frozen lakes and rivers, thus requiring major developments in infrastructures, including highways and communications (Stephenson *et al* 2011). As these changes create new

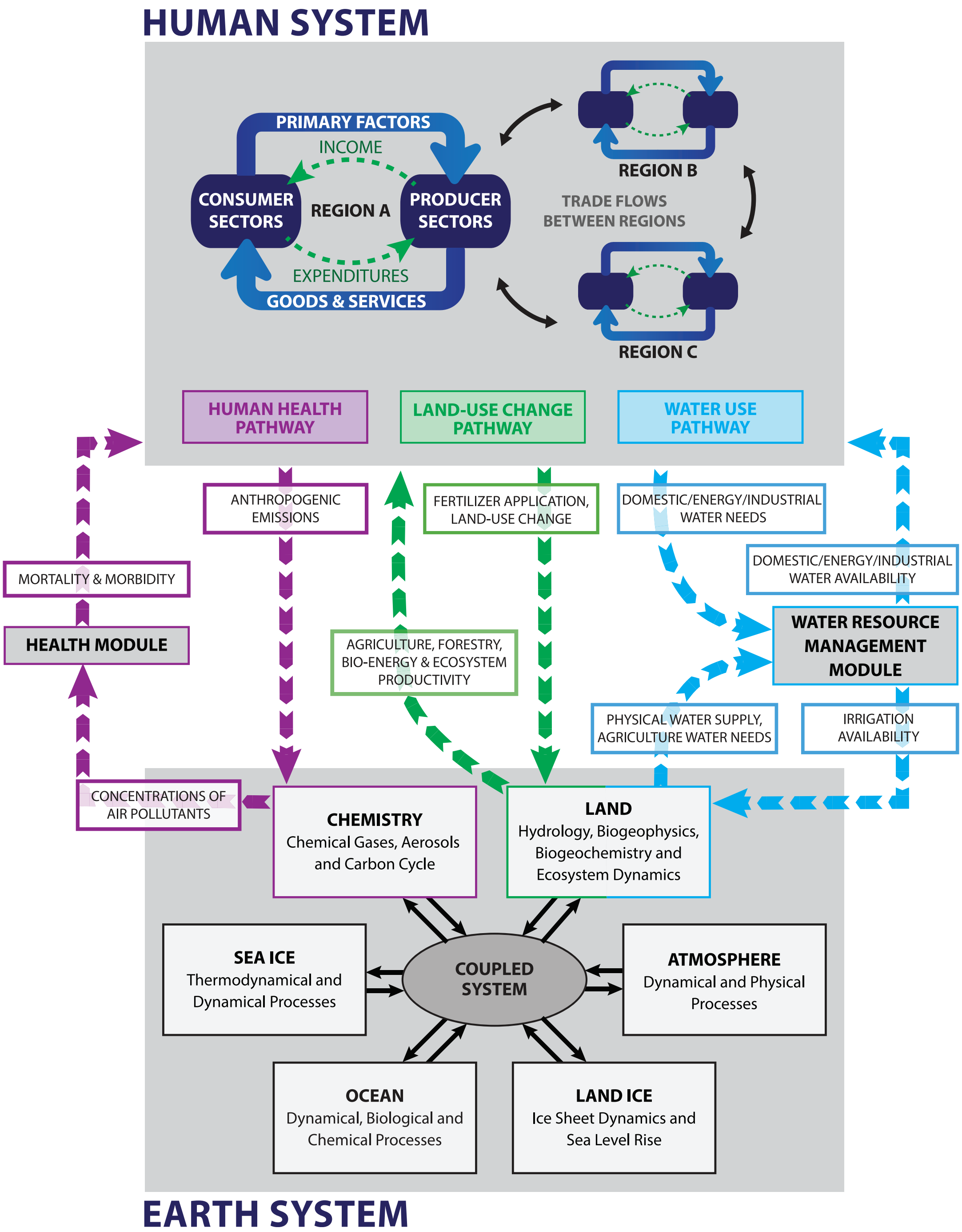

Figure 5. Schematic of an integrated assessment model (IAM) that couples a human activity model and an Earth system model with a focus on three feedback pathways: health, land-use change, and water resources.

economic opportunities, significant population migration within Northern Eurasia and from neighboring regions could create new socio-economic stressors. Furthermore, with increasing population and demand for energy, along with permafrost degradation that impacts buildings in many communities in Siberia, major changes in urbanization, both expansion and abandonment (including 'boom and bust'), and infrastructure (oil and gas) can be expected. The implications for land-use change in Northern Eurasia could be substantial.

There are many other examples of complex pathways of interactions and feedbacks between the human system and the Earth system that are yet to be investigated and that could prove very important for Northern Eurasia. Models that include a detailed representation of all components of the human–Earth coupled system, while accounting for the exhaustive number of feedbacks among these components, can certainly provide tremendous and novel insights into the complex issue of global change. An example of such a model, with a focus on three feedback pathways, water resources, health, and land-use change, is shown in figure 5.

Given the imperfect nature of models, large uncertainties in future projections of major driving forces of change (i.e. demography, economic growth, the implementation of climate policies, and the development of new technologies to name a few), and our limited knowledge of various processes (i.e. climate system response, natural climate variability, ecosystem dynamics), studies need to be placed in the context of uncertainty (Sokolov *et al* 2009, Webster *et al* 2012, Monier *et al* 2013). Large model intercomparison exercises are growing steadily to better understand model structural uncertainty, although few have a focus on Northern Eurasia (Rawlins *et al* 2015). The implementation of large ensembles of model simulations is fast becoming the norm and studies using only a single model have been slowly marginalized. At the same time, the reliance of the community on standard scenarios and model simulations, such as the RCPs and the CMIP5, can lead to a false sense of confidence in the full distribution of future global change. For this reason, coordination of research efforts and explicit guidelines for modeling global change can be beneficial to the community, but only if they do not preclude the diversity of models, approaches, and focus studies.

5. Final words

Since the beginning of the NEESPI project over a decade ago, scientists from multiple disciplines and nations have provided a truly interdisciplinary and dynamic body of research. They highlighted major past and ongoing environmental, socioeconomic and climatic changes over Northern Eurasia and investigate their impacts to natural ecosystems and society. To support their research, they developed a large number of models to organize and improve our understanding of the state and dynamics of terrestrial ecosystems in northern Eurasia and their interactions with the Earth system. These models have been important tools to enhance our scientific knowledge and predictive capabilities to support informed decision-making.

Many of the new international programs are emphasizing resilience and transformation of human/environmental systems in the face of environmental change. NEESPI has great reason to be proud of its success. This review provides but a glimpse of what has been accomplished in observing, understanding and modeling a region undergoing significant environmental, socioeconomic and climatic changes. Nonetheless significant work remains to be done in the continued improvement of our modeling capability to represent the coupled human–Earth system in Northern Eurasia in the face of global change. In this review, we argue that Earth system models and integrated assessment models exemplify new approaches to accomplish that objective. At the same time, we recognize that to succeed in making ESMs and IAMs valuable tools for Northern Eurasia, their representations of the unique characteristics of Northern Eurasia need to improve. This can only be achieved through tight collaborations between the Northern Eurasia modeling community and the ESM and IAM communities.

The International Geosphere Biosphere Programme (IGBP) officially ended in December 2015 after 30 years of success and many of its components transformed into the 'Future Earth' Secretariat. As a result, the NEESPI project is moving to establish a new program, '*Northern Eurasia Future Initiative*' (NEFI), with the goal to better represent the coupled human–Earth system to model global change for Northern Eurasia. The future program strongly depends on building an understanding of how human populations will be affected by environmental changes across the region, what management practices can be developed to help mitigate or allow adaptation to these changes, and how we can bridge the considerable gaps in research procedures, national scale policy intervention, capacity for prediction, and time- and space- scales that can plague the incorporation of human dynamics with environment dynamics. Thus, NEFI is a logical consequence of the accomplishments of NEESPI.

Acknowledgments

We thank the Northern Eurasian Earth Science Partnership Initiative (NEESPI) for providing the background that made this study possible. We also acknowledge the funding from the US National Aeronautics and Space Administration (NASA) Land-Cover and Land-Use Change (LCLUC) Program, which provided support for Erwan Monier, David Kicklighter, Andrei Sokolov, Qianlai Zhuang and Sergey Paltsev under grant NNX14AD91G and Irina Sokolik under grant NNX14AD88G. Support for Pavel Groisman was provided by Grant 14. B25.31.0026 of the Ministry of Education and Science of the Russian Federation to P. P. Shirshov Institute for Oceanology and by Project 'Arctic Climate Change and its Impact on Environment, Infrastructures, and Resource Availability' sponsored by ANR (France), RFBR (Russia), and NSF (USA) in response to Belmont Forum Collaborative Research Action on Arctic Observing and Research for Sustainability. The Joint Program on the Science and Policy of Global Change is funded by a number of federal agencies and a consortium of 40 industrial and foundation sponsors (for the complete list see http://globalchange.mit.edu/sponsors).

ORCID iDS

Erwan Monier https://orcid.org/0000-0001-5533-6570

References

Aguiar A, Narayanan B and McDougall R 2016 An overview of the GTAP 9 data base *J. Glob. Econ. Anal.* **1** 181–208

Anisimov O, Kokorev V and Zhil'tsova Y 2013 Temporal and spatial patterns of modern climatic warming: case study of Northern Eurasia *Clim. Change* **118** 871–83

Arzhanov M M, Eliseev A V and Mokhov I I 2012a A global climate model based, Bayesian climate projection for northern extra-tropical land areas *Glob. Planet. Change* **86** 57–65

Arzhanov M M, Eliseev A V, Klimenko V V, Mokhov I I and Tereshin A G 2012b Estimating climate changes in the Northern Hemisphere in the 21st century under alternative scenarios of anthropogenic forcing *Izvestiya, Atmos. Ocean. Phys.* **48** 573–84

Baklanov A A *et al* 2013 Aspects of atmospheric pollution in Siberia *Environmental Changes in Siberia: Regional Changes and their Global Consequences* ed P Groisman and G Gutman (Berlin: Springer) ch 8 pp 303–46 (http://doi.org/10.1007/978-94-007-4569-8_8)

Balshi M S *et al* 2007 The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: a process-based analysis *J. Geophys. Res.* **112** G02029

Barriopedro D, Fischer E M, Luterbacher J, Trigo R M and Garcia-Herrera R 2011 The hot summer of 2010: redrawing the temperature record map of Europe *Science* **332** 220–4

Blyakharchuk T A, Tchebakova N M, Parfenova E I and Soja A J 2014 Potential influence of the late Holocene climate on settled farming versus nomadic cattle herding in the Minusinsk Hollow, south-central Siberia *Environ. Res. Lett.* **9** 065004

Bohn T J *et al* 2013 Modeling the large-scale effects of surface moisture heterogeneity on wetland carbon fluxes in the West Siberian Lowland *Biogeosciences* **10** 6559–76

Bohn T J *et al* 2015 WETCHIMP-WSL: intercomparison of wetland methane emissions models over West Siberia *Biogeosciences* **12** 3321–49

Bopp L *et al* 2013 Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models *Biogeosciences* **10** 6225–45

Bowling L C and Lettenmaier D P 2010 Modeling the effects of lakes and wetlands on the water balance of Arctic environments *J. Hydrometeorol.* **11** 276–95

Brovkin V, Claussen M, Driesschaert E, Fichefet T, Kicklighter D, Loutre M F, Matthews H D, Ramankutty N, Schaeffer M and Sokolov A 2006 Biogeophysical effects of historical land cover changes simulated by six earth system models of intermediate complexity *Clim. Dyn.* **26** 587–600

Brovkin V *et al* 2013 Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century *J. Clim.* **26** 6859–81

Buermann W, Parida B, Jung M, MacDonald G M, Tucker C J and Reichstein M 2014 Recent shift in Eurasian boreal forest greening response may be associated with warmer and drier summers *Geophys. Res. Lett.* **41** 1995–2002

Bulygina O N, Groisman P Ya, Razuvaev V N and Korshunova N N 2011 Changes in snow cover characteristics over Northern Eurasia since 1966 *Environ. Res. Lett.* **6** 045204

Bulygina O N, Arzhanova N M and Groisman P Ya 2015 Icing conditions over Northern Eurasia in changing climate *Environ. Res. Lett.* **10** 025003

Callaghan T V *et al* 2011a The changing face of Arctic snow cover: a synthesis of observed and projected changes *Ambio* **40** 17–31

Callaghan T V *et al* 2011b Multiple effects of changes in Arctic snow cover *Ambio* **40** 32–45

Cresto-Aleina F, Brovkin V, Muster S, Boike J, Kutzbach L, Sachs T and Zuyev S 2013 A stochastic model for the polygonal tundra based on Poisson-Voronoi diagrams *Earth Syst. Dyn.* **4** 187–98

Cresto-Aleina F, Runkle B R K, Kleinen T, Kutzbach L, Schneider J and Brovkin V 2015 Modeling micro-topographic controls on boreal peatland hydrology and methane fluxes *Biogeosciences* **12** 5689–704

Dargaville R, McGuire A D and Rayner P 2002a Estimates of large-scale fluxes in high latitudes from terrestrial biosphere models and an inversion of atmospheric CO_2 measurements *Clim. Change* **55** 273–85

Dargaville R J *et al* 2002b Evaluation of terrestrial carbon cycle models with atmospheric CO_2 measurements: results from transient simulations considering increasing CO_2, climate and land-use effects *Glob. Biogeochem. Cycles* **16** 1092

Darmenova K, Sokolik I N, Shao Y, Marticorena B and Bergametti G 2009 Development of a physically-based dust emission module within the Weather Research and Forecasting (WRF) model: assessment of dust emission parameterizations and input parameters for source regions in Central and East Asia *J. Geophys. Res.* **114** D14201

Dass P, Rawlins M A, Kimball J S and Kim Y 2016 Environmental controls on the increasing GPP of terrestrial vegetation across northern Eurasia *Biogeosciences* **13** 45–62

DeLucia E H 2015 How biofuels can cool our climate and strengthen our ecosystems *Eos* **96** 14–9

Dolman A J *et al* 2012 An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion methods *Biogeosciences* **9** 5323–40

Dronin N and Kirilenko A 2010 Climate change, food stress, and security in Russia *Reg. Environ. Change* **11** 167–78

Dubinin M, Lushchekina A and Radeloff V C 2011 Climate, livestock and vegetation: what drives fire increase in the arid ecosystems of Southern Russia? *Ecosystems* **14** 547–62

Eby M *et al* 2013 Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity *Clim. Past* **9** 1111–40

Elliott J *et al* 2014 Constraints and potentials of future irrigation water availability on agricultural production under climate change *Proc. Natl Acad. Sci. USA* **111** 3239–44

Euskirchen E S *et al* 2006 Importance of recent shifts in soil thermal dynamics on growing season length, productivity and carbon sequestration in terrestrial high-latitude ecosystems *Glob. Change Biol.* **12** 731–50

Fann N, Nolte C G, Dolwick P, Spero T L, Brown A C, Phillips S and Anenberg S 2014 The geographic distribution and economic value of climate change-related ozone health impacts in the United States in 2030 *J. Air Waste Manage. Assoc.* **65** 570–80

Farinotti D, Longuevergne L, Moholdt G, Duethmann D, Mölg T, Bolch T, Vorogushyn S and Güntner A 2015 Substantial glacier mass loss in the Tien Shan over the past 50 years *Nat. Geosci.* **8** 716–22

Felzer B, Reilly J, Melillo J, Kicklighter D, Sarofim M, Wang C, Prinn R and Zhuang Q 2005 Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model *Clim. Change* **73** 345–73

Friedlingstein P *et al* 2006 Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison *J. Clim.* **19** 3337–53

Friend A D 2001 Modelling canopy CO_2 fluxes: are 'big-leaf' simplifications justified? *Glob. Ecol. Biogeogr.* **10** 603–19

Fujimori S, Masui T and Matsuoka Y 2014 Development of a global computable general equilibrium model coupled with detailed energy end-use technology *Appl. Energ.* **128** 296–306

Gálos B, Hagemann S, Hänsler A, Kindermann G, Rechid D, Sieck K, Teichmann C and Jacob D 2013 Case study for the assessment of the biogeophysical effects of a potential afforestation in Europe *Carbon Balance Manage.* **8** 3

Gao X, Schlosser C A, Sokolov A, Anthony K W, Zhuang Q and Kicklighter D 2013 Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback *Environ. Res. Lett.* **8** 035014

Garcia-Menendez F, Saari R K, Monier E and Selin N E 2015 US air quality and health benefits from avoided climate change under greenhouse gas mitigation *Environ. Sci. Technol.* **49** 7580–8
Gelfan A N 2011 Modelling hydrological consequences of climate change in the permafrost region and assessment of their uncertainty *Cold Region Hydrology in a Changing Climate: Proc. Symp. H02 (IUGG2011) (Melbourne, Australia, July 2011)* vol 346 ed D Yang, D Marsh and A Gelfan (Wallingford: IAHS Publications) pp 92–97
Gelfan A, Muzylev E, Uspensky A, Startseva Z and Romanov P 2012 Remote sensing based modeling of water and heat regimes in a vast agricultural region *Remote Sensing—Applications* ed B Escalante-Ramirez (Rijeka: InTech) pp 141–76 ch 6 (https://doi.org/10.5772/37076)
Georgiadi A G, Milyukova I P and Kashutina E A 2010 Response of river runoff in the cryolithic zone of eastern Siberia (Lena River Basin) to future climate warming *Environmental Change in Siberia: Earth Observation, Field Studies and Modelling* ed H Balzter (Dordrecht: Springer) pp 157–69 (https://doi.org/10.1007/978-90-481-8641-9_10)
Georgiadi A G, Koronkevich N, Milyukova I P and Barabanova E A 2014 The ensemble scenarios projecting runoff changes in large Russian river basins in the 21st century *Proc. IAHS* **364** 210–5
Glagolev M, Kleptsova I, Filippov I, Maksyutov S and Machida T 2011 Regional methane emission from West Siberia mire landscapes *Environ. Res. Lett.* **6** 045214
Goetz S J, Mack M C, Gurney K R, Randerson J T and Houghton R A 2007 Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America *Environ. Res. Lett* **2** 045031
Gordov E K *et al* 2013 Development of information-computational infrastructure for environmental research in Siberia as a baseline component of the Northern Eurasia Earth Science Partnership Initiative (NEESPI) Studies *Regional Environmental Changes in Siberia and their Global Consequences* ed P Groisman and G Gutman (Dordrecht: Springer) ch 2 pp 19–55 (http://doi.org/10.1007/978-94-007-4569-8_2)
Gordov E, Shiklomanov A, Okladnikov I, Prusevich A and Titov A 2016 Development of distributed research center for analysis of regional climatic and environmental changes *IOP Conf. Ser.: Earth Environ. Sci.* **48** 012033
Gouttevin I, Krinner G, Ciais P, Polcher J and Legout C 2012 Multi-scale validation of a new soil freezing scheme for a land-surface model with physically-based hydrology *Cryosphere* **6** 407–30
Griffiths P, Müller D, Kuemmerle T and Hostert P 2013 Agricultural land change in the carpathian ecoregion after the breakdown of socialism and expansion of the European Union *Environ. Res. Lett.* **8** 045024
Groisman P Ya 2007 Preface to special issue on Northern Eurasia regional climate and environmental change *Glob. Planet. Change* **56** v–vii
Groisman P Ya and Bartalev S A 2007 Northern Eurasia Earth Science Partnership Initiative (NEESPI): science plan overview *Glob. Planet. Change* **56** 215–34
Groisman P Ya and Soja A J 2007 Northern Hemisphere high latitude climate and environmental change *Environ. Res. Lett.* **2** 045008
Groisman P Ya and Soja A J 2009 Ongoing climatic change in Northern Eurasia: justification for expedient research *Environ. Res. Lett.* **4** 045002
Groisman P Ya *et al* 2007 Potential forest fire danger over Northern Eurasia: changes during the 20th century *Glob. Planet. Change* **56** 371–86
Groisman P Ya *et al* 2009 The Northern Eurasia earth science partnership: an example of science applied to societal needs *Bull. Am. Meteorol. Soc.* **90** 671–88
Groisman P Ya, Gulev S and Maksyutov S 2014 Current status and future Earth system studies in northern Eurasia *Eos. Trans. AGU* **95** 133–40
Gustafson E J, Shvidenko A Z and Scheller R M 2011 Effectiveness of forest management strategies to mitigate effects of global change in south-central Siberia *Can. J. Forest Res.* **41** 1405–21
Hagg W, Braun L N, Weber M and Becht M 2006 Runoff modelling in glacierized Central Asian catchments for present-day and future climate *Hydrol. Res.* **37** 93–105
Hallgren W, Schlosser C A, Monier E, Kicklighter D, Sokolov A and Melillo J 2013 Climate impacts of a large-scale biofuels expansion *Geophys. Res. Lett.* **40** 1624–30
Hayes D J, McGuire A D, Kicklighter D W, Burnside T J and Melillo J M 2011a The effects of land cover and land use change on the contemporary carbon balance of the arctic and boreal terrestrial ecosystems in northern Eurasia *Eurasian Arctic Land Cover and Land Use in a Changing Climate* ed G Gutman and A Reissell (Dordrecht: Springer) pp 109–36 (https://doi.org/10.1007/978-90-481-9118-5_6)
Hayes D J *et al* 2011b Is the northern high-latitude land-based CO_2 sink weakening? *Glob. Biogeochem. Cycles* **25** GB3018
Hayes D J, Kicklighter D W, McGuire A D, Chen M, Zhuang Q, Yuan F, Melillo J M and Wullschleger S D 2014 The impacts of recent permafrost thaw on land-atmosphere greenhouse gas exchange *Environ. Res. Lett.* **9** 045005
Heleniak T 2015 Population change in the former communist states of Europe and Asia *International Encyclopedia of the Social and Behavioral Sciences* ed J D Wright (Burlington, MA: Elsevier) pp 545–52 (https://doi.org/10.1016/B978-0-08-097086-8.31037-6)
Hitztaler S K and Bergen K M 2013 Mapping resource use over a Russian landscape: an integrated look at harvesting of a non-timber forest product in Central Kamchatka *Environ. Res. Lett.* **8** 045020
Houghton R A, Butman D, Bunn A G, Krankina O N, Schlesinger P and Stone T A 2007 Mapping Russian forest biomass with data from satellites and forest inventories *Environ. Res. Lett.* **2** 045032
Hurtt G C 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land use transitions wood harvest resulting secondary lands *Clim. Change* **109** 117–61
Issanova G and Abuduwaili J 2017 *Aeolian Proceses as Dust Storms in the Deserts of Central Asia and Kazakhstan* (Singapore: Springer) (https://doi.org/10.1007/978-981-10-3190-8)
Iizumi T and Ramankutty N 2016 Changes in yield variability of major crops for 1981–2010 explained by climate change *Environ. Res. Lett.* **11** 034003
Jacobson M Z 2008 On the causal link between carbon dioxide and air pollution mortality *Geophys. Res. Lett.* **35** L03809
Jiang Y, Zhuang Q, Schaphoff S, Sitch S, Sokolov A, Kicklighter D and Melillo J 2012 Uncertainty analysis of vegetation distribution in the northern high latitudes during the 21st century with a dynamic vegetation model *Ecol. Evol.* **2** 593–614
Jiang Y, Zhuang Q, Sitch S, O'Donnell J A, Kicklighter D, Sokolov A and Melillo J 2016 Importance of soil thermal regime in terrestrial ecosystem carbon dynamics in the circumpolar north *Glob. Planet. Change* **142** 28–40
John R, Chen J, Noormets A, Xiao X, Xu J, Lu N and Chen S 2013 Modeling gross primary production in semi-arid Inner Mongolia using MODIS imagery and eddy covariance data *Intern. J. Remote Sensing* **34** 2829–285
Jones A D 2013 Greenhouse gas policy influences climate via direct effects of land-use change *J. Clim.* **26** 3657–70
Kantzas E, Lomas M and Quegan S 2013 Fire at high latitudes: data-model comparisons and their consequences *Glob. Biogeochem. Cycles* **27** 677–91
Karthe D, Chalov S R and Borchardt D 2015 Water resources and their management in central Asia in the early twenty first century: status, challenges and future prospects *Environ. Earth Sci.* **73** 487–99
Kharin V V, Zwiers F W, Zhang X and Wehner M 2013 Changes in temperature and precipitation extremes in the CMIP5 ensemble *Clim. Change* **119** 345–57

Khon V Ch and Mokhov I I 2012 The hydrological regime of large river Basins in Northern Eurasia in the XX-XXI centuries *Water Resour.* **39** 1–10
Khvostikov S, Venevsky S and Bartalev S 2015 Regional adaptation of a dynamic global vegetation model using a remote sensing data derived land cover map of Russia *Environ. Res. Lett.* **10** 125007
Kicklighter D W, Hayes D J, McClelland J W, Peterson B J, McGuire A D and Melillo J M 2013 Insights and issues with simulating terrestrial DOC loading of Arctic river networks *Ecol. Appl.* **23** 1817–36
Kicklighter D W, Cai Y, Zhuang Q, Parfenova E I, Paltsev S, Sokolov A P, Melillo J M, Reilly J M, Tchebakova N M and Lu X 2014 Potential influence of climate-induced vegetation shifts on future land use and associated land carbon fluxes in Northern Eurasia *Environ. Res. Lett.* **9** 035004
Kim H-S, Maksyutov S, Glagolev M V, Machida T, Patra P K, Sudo K and Inoue G 2011 Evaluation of methane emissions from West Siberian wetlands based on inverse modeling *Environ. Res. Lett.* **6** 035201
Kim J B, Monier E, Sohngen B, Pitts G, Drapek R, McFarland J, Ohrel S and Cole J 2017 Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios *Environ. Res. Lett.* **12** 045001
Klehmet K, Geyer B and Rockel B 2013 A regional climate model hindcast for Siberia: analysis of snow water equivalent *Cryosphere* **7** 1017–34
Knutti R and Sedláček J 2013 Robustness and uncertainties in the new CMIP5 climate model projections *Nat. Clim. Change* **3** 369–73
Kopáček J and Posch M 2011 Anthropogenic nitrogen emissions during the holocene and their possible effects on remote ecosystems *Glob. Biogeochem. Cycles* **25** GB2017
Kopáček J, Posch M, Hejzlar J, Oulehle F and Volková A 2012 An elevation-based regional model for interpolating sulphur and nitrogen deposition *Atmos. Environ.* **50** 287–96
Kopačková V, Misurec J, Lhotakova Z, Oulehle F and Albrechtová J 2014 Using multi-date high spectral resolution data to assess physiological status of macroscopically undamaged foliage on a regional scale *Int. J. Appl. Earth Obs. Geoinform* **27** 169–86
Kopačková V, Lhotáková Z, Oulehle F and Albrechtová J 2015 Assessing forest health via linking the geochemical properties of soil profile with the biochemical parameters of vegetation *Int. J. Environ. Sci. Technol.* **12** 1987–2002
Korontzi S, McCarty J, Loboda T, Kumar S and Justice C 2006 Global distribution of agricultural fires in croplands from 3 years of Moderate Resolution Imaging Spectroradiometer MODIS data *Glob. Biogeochem. Cycles* **20** GB2021
Koven C D, Ringeval B, Friedlingstein P, Ciais P, Cadule P, Khvorostyanov D, Krinner G and Tarnocai C 2011 Permafrost carbon-climate feedbacks accelerate global warming *Proc. Natl Acad. Sci. USA* **108** 14769–74
Kraemer R, Prishchepov A V, Müller D, Kuemmerle T, Radeloff V C, Dara A and Frühauf M 2015 Long-term agricultural land-cover change and potential for cropland expansion in the former Virgin Lands area of Kazakhstan *Environ. Res. Lett.* **10** 054012
Krankina O N, Harmon M E, Cohen W B, Oetter D R, Olga Z and Duane M V 2004 Carbon stores, sinks and sources in forests of northwestern Russia: can we reconcile forest inventories with remote sensing results? *Clim. Change* **67** 257–72
Kuchment L S, Gelfan A N and Demidov V N 2011 Modeling of the hydrological cycle of a forest river basin and hydrological consequences of forest cutting *Open Hydrol. J.* **5** 9–18
Kuemmerle T, Chaskovskyy O, Knorn J, Radeloff V C, Kruhlov I, Keeton W S and Hostert P 2009 Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007 *Remote Sens. Environ.* **113** 1194–207
Kuemmerle T, Perzanowski K, Akcakaya H R, Beaudry F, van Deelen T R, Parnikoza I, Khoyetskyy P, Waller D M and Radeloff V C 2011a Cost-effectiveness of different conservation strategies to establish a European bison metapopulation in the Carpathians *J. Appl. Ecol.* **48** 317–29
Kuemmerle T, Olofsson P, Chaskovskyy O, Baumann M, Ostapowicz K, Woodcock C, Hougton R A, Hostert P, Keeton W and Radeloff V C 2011b Post-Soviet farmland abandonment, forest recovery, and carbon sequestration in western Ukraine *Glob. Change Biol.* **17** 1335–49
Kuemmerle T, Baskin L, Leitão P, Prishchepov A V, Thonicke K and Radeloff V C 2014 Potential impacts of oil and gas development and climate change on migratory reindeer calving grounds across the Russian Arctic *Divers. Distrib.* **20** 416–29
Lapenis A, Shvidenko A, Schepaschenko D, Nilsson S and Aiyyer A 2005 Acclimation of Russian forests to recent change in climate *Glob. Change Biol.* **11** 2090–102
Lawford R, Bogardi J, Marx S, Jain S, Pahl Wostl C, Knüppe K, Ringler C, Lansigan F and Meza F 2013 Basin perspectives on the water-energy-food security nexus *Curr. Opin. Environ. Sustainability* **5** 607–16
Lebed L, Qi J and Heilman P 2012 An ecological assessment of pasturelands in the Balkhash area of Kazakhstan with remote sensing and models *Environ. Res. Lett.* **7** 025203
Leptoukh G, Csiszar I, Romanov P, Shen S, Loboda T and Gerasimov I 2007 NASA NEESPI data and services center for satellite remote sensing information *Environ. Res. Lett.* **2** 045009
Li C, Qi J, Yang L, Wang S, Yang W, Zhu G, Zou S and Zhang F 2014 Regional vegetation dynamics and its response to climate change—a case study in the Tao River Basin in Northwestern China *Environ. Res. Lett.* **9** 125003
Li Q, Xu L, Pan X, Zhang L, Li C, Yang N and Qi J 2016 Modeling phenological responses of Inner Mongolia grassland species to regional climate change *Environ. Res. Lett.* **11** 015002
Lim S S *et al* 2012 A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010 *Lancet* **380** 2224–60
Liu Y *et al* 2013 Response of evapotranspiration and water availability to changing climate and land cover on the Mongolian Plateau during the 21st century *Glob. Planet. Change* **108** 88–95
Liu Y, Zhuang Q, Pan Z, Tchebakova N, Kicklighter D, Miralles D, Chen J, Sirin A, He Y and Melillo J 2014 Response of evapotranspiration and water availability to the changing climate in Northern Eurasia *Clim. Change* **126** 413–27
Liu Y *et al* 2015 Evapotranspiration in Northern Eurasia: impact of forcing uncertainties on terrestrial ecosystem model estimates *J. Geophys. Res.-Atmos.* **120** 2647–60
Lobell D B and Asner G P 2003 Climate and management contributions to recent trends in US agricultural yields *Science* **299** 1032–2
Loboda T V and Csiszar I A 2007 Assessing the risk of ignition in the Russian Far East within a modeling framework of fire threat *Ecol. Appl.* **17** 791–805
Loranty M M, Berner L T, Goetz S J, Jin Y and Randerson J T 2014 Vegetation controls on northern high latitude snow-albedo feedback: observations and CMIP5 model simulations *Glob. Change Biol.* **20** 594–606
Lu Y, Zhuang Q, Zhou G, Sirin A, Melillo J and Kicklighter D 2009 Possible decline of the carbon sink in the Mongolian Plateau during the 21st century *Environ. Res. Lett.* **4** 045023
Lu Z, Streets D G, Zhang Q, Wang S, Carmichael G R, Cheng Y F, Wei C, Chin M, Diehl T and Tan Q 2010 Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000 *Atmos. Chem. Phys.* **10** 6311–31
MacDougall A H and Knutti R 2016 Projecting the release of carbon from permafrost soils using a perturbed parameter ensemble modelling approach *Biogeosciences* **13** 2123–36

Macias-Fauria M, Forbes B C, Zetterberg P and Kumpula T 2012 Eurasian Arctic greening reveals teleconnections and the potential for novel ecosystems *Nat. Clim. Change* **2** 613–8
Magliocca N R, Brown D G and Ellis E C 2013 Exploring agricultural livelihood transitions with an agent-based virtual laboratory: global forces to local decision-making *PLoS One* **8** e73241
Malevsky-Malevich S P, Molkentin E K, Nadyozhina E D and Shklyarevich O B 2008 An assessment of potential change in wildfire activity in the Russian boreal forest zone induced by climate warming during the twenty-first century *Clim. Change* **86** 463–74
Marchenko S S, Gorbunov A P and Romanovsky V E 2007 Permafrost warming in the Tien Shan Mountains, Central Asia *Glob. Planet. Change* **56** 311–27
McClelland J W, Holmes R M, Peterson B J and Stieglitz M 2004 Increasing river discharge in the Eurasian Arctic: consideration of dams, permafrost thaw, and fires as potential agents of change *J. Geophys. Res.* **109** D18102
McGuire A D, Anderson L G, Christensen T R, Dallimore S, Guo L, Hayes D J, Heimann M, Lorenson T D, Macdonald R W and Roulet N 2009 Sensitivity of the carbon cycle in the Arctic to climate change *Ecol. Monogr.* **79** 523–55
McGuire A D 2010 An analysis of the carbon balance of the Arctic Basin from 1997 to 2006 *Tellus B* **62** 455–74
Mehran A, AghaKouchak A and Phillips T J 2014 Evaluation of CMIP5 continental precipitation simulations relative to satellite-based gauge-adjusted observations *J. Geophys. Res. Atmos.* **119** 1695–707
Melillo J M, Reilly J M, Kicklighter D W, Gurgel A C, Cronin T W, Paltsev S, Felzer B S, Wang X, Sokolov A P and Schlosser C A 2009 Indirect emissions from biofuels: how important? *Science* **326** 1397–9
Melillo J M, Lu X, Kicklighter D W, Reilly J M, Cai Y and Sokolov A P 2016 Protected areas' role in climate-change mitigation *Ambio* **45** 133–45
Meredith E P, Semenov V A, Maraun D, Park W and Chernokulsky A V 2015 Crucial role of Black Sea warming in amplifying the 2012 Krymsk precipitation extreme *Nat. Geosci.* **8** 615–9
Meyfroidt P, Schierhorn F, Prishchepov A V, Müller D and Kuemmerle T 2016 Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia Ukraine and Kazakhstan *Glob. Environ. Change* **37** 1–15
Miao C, Duan Q, Sun Q, Huang Y, Kong D, Yang T, Ye A, Di Z and Gong W 2014 Assessment of CMIP5 climate models and projected temperature changes over Northern Eurasia *Environ. Res. Lett.* **9** 055007
Mokhov I I, Akperov M G, Prokofyeva M A, Timazhev A V, Lupo A R and Le Treut H 2013 Blockings in the Northern Hemisphere and Euro-Atlantic Region: estimates of changes from reanalysis data and model simulations *Doklady Earth Sci.* **449** 430–3
Monier E, Sokolov A, Schlosser A, Scott J and Gao X 2013 Probabilistic projections of 21st century climate change over Northern Eurasia *Environ. Res. Lett.* **8** 045008
Motovilov Yu G and Gelfan A N 2013 Assessing runoff sensitivity to climate change in the Arctic basin: empirical and modelling approaches *Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections: Proc. H02, IAHS-IAPSO-IASPEI Assembly (Gothenburg, Sweden, July 2013)* vol 360 ed A Gelfan, D Yang, E Gusev and H Kunstmann (Wallingford: IAHS Publications) pp 105–12
Mukhortova L, Schepaschenko D, Shvidenko A, McCallum I and Kraxner F 2015 Soil contribution to carbon budget of Russian forests *Agric. Forest Meteorol.* **200** 97–108
Narayan C, Fernandes P M, van Brusselen J and Schuck A 2007 Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol *Forest Ecol. Manage.* **251** 164–73
Nelson G C *et al* 2014a Climate change effects on agriculture: economic responses to biophysical shocks *Proc. Natl Acad. Sci. USA* **111** 3274–9
Nelson G C *et al* 2014b Agriculture and climate change in global scenarios: why don't the models agree *Agric. Econ.* **45** 85–101
Nemet G F, Holloway T and Meier P 2010 Implications of incorporating air-quality co-benefits into climate change policymaking *Environ. Res. Lett.* **5** 014007
Novenko E Yu, Zyuganova I S and Olchev A V 2014 Application of the paleoanalog method for prediction of vegetation dynamics under climate changes *Dokl. Biol. Sci.* **457** 228–32
Novenko E Yu and Olchev A V 2015 Early holocene vegetation and climate dynamics in the central part of the East European Plain (Russia) *Quat. Int.* **388** 12–22
Okladnikov I G, Gordov E P and Titov A G 2016 Development of climate data storage and processing model *IOP Conf. Ser.: Earth Environ. Sci.* **48** 012030
Olchev A, Novenko E, Desherevskaya O, Krasnorutskaya K and Kurbatova J 2009a Effects of climatic changes on carbon dioxide and water vapor fluxes in boreal forest ecosystems of European part of Russia *Environ. Res. Lett.* **4** 045007
Olchev A, Radler K, Sogachev A, Panferov O and Gravenhorst G 2009b Application of a three-dimensional model for assessing effects of small clear-cuttings on radiation and soil temperature *Ecol. Modell.* **220** 3046–56
Olchev A V, Deshcherevskaya O A, Kurbatova Yu A, Molchanov A G, Novenko E Yu, Pridacha V B and Sazonova T A 2013 CO_2 and H_2O exchange in the forest ecosystems of Southern Taiga under climate changes *Dokl. Biol. Sci.* **450** 173–6
Oltchev A, Cermak J, Nadezhdina N, Tatarinov F, Tishenko A, Ibrom A and Gravenhorst G 2002a Transpiration of a mixed forest stand: field measurements and simulation using SVAT models *J. Boreal. Environ. Res.* **7** 389–397
Oltchev A *et al* 2002b The response of the water fluxes of the boreal forest region at the Volga's source area to climatic and land-use changes *J. Phys. Chem. Earth* **27** 675–90
Onuchin A, Korets M, Shvidenko A, Burenina T and Musokhranova A 2014 Modeling air temperature changes in Northern Asia *Glob. Planet. Change* **122** 14–22
Osadchiev A 2015 A method for quantifying freshwater discharge rates from satellite observations and Lagrangian numerical modeling of river plumes *Environ. Res. Lett.* **10** 085009
Oulehle F, Cosby B J, Wright R F, Hruška J, Kopáček J, Krám P, Evans C D and Moldan F 2012 Modelling soil nitrogen: the MAGIC model with nitrogen retention linked to carbon turnover using decomposer dynamics *Environ. Pollut.* **165** 158–66
Pan Y *et al* 2011 A large and persistent carbon sink in the world's forests *Science* **333** 988–93
Park Y H and Sokolik I N 2016 Toward developing a climatology of fire emissions in Central Asia *Air, Soil Water Res.* **9** 87–96
Peng Y, Gitelson A A and Sakamoto T 2013 Remote estimation of gross primary productivity in crops using MODIS 250 m data *Remote Sens. Environ.* **128** 186–96
Pieczonka T and Bolch T 2015 Region-wide glacier mass budgets and area changes for the Central Tien Shan between ˜1975 and 1999 using Hexagon KH-9 imagery *Glob. Planet. Change* **128** 1–13
Prinn R, Heimbach P, Rigby M, Dutkiewicz S, Melillo J M, Reilly J M, Kicklighter D W and Waugh C 2011 A strategy for a global observing system for verification of national greenhouse gas emissions *MIT Joint Program on Science and Policy of Global Change* Report 200 92 pp (https://globalchange.mit.edu/sites/default/files/MITJPSPGC_Rpt200_0.pdf)
Rawlins M A *et al* 2010 Analysis of the Arctic system for freshwater cycle intensification: observations and expectations *J. Clim.* **23** 5715–37
Rawlins M A *et al* 2015 Assessment of model estimates of land-atmosphere CO_2 exchange across Northern Eurasia *Biogeosciences* **12** 4385–405

Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Cronin T, Sokolov A and Schlosser A 2012 Using land to mitigate climate change: hitting the target, recognizing the tradeoffs *Environ. Sci. Technol* **46** 5672–9

Reilly J *et al* 2013 Valuing climate impacts in integrated assessment models: the MIT IGSM *Clim. Change* **117** 561–73

Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N and Rafaj P 2011 RCP 8.5—A scenario of comparatively high greenhouse gas emissions *Clim. Change* **109** 33–57

Robinson D T, Sun S, Hutchins M, Riolo R L, Brown D G, Parker D C, Filatova T, Currie W S and Kiger S 2013 Effects of land markets and land management on ecosystem function: a framework for modelling exurban land change *Environ. Model. Softw.* **45** 129–40

Romanovsky V E, Sazonova T S, Balobaev V T, Shender N I and Sergueev D O 2007 Past and recent changes in air and permafrost temperatures in Eastern Siberia *Glob. Planet. Change* **56** 399–413

Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *Proc. Natl Acad. Sci. USA* **111** 3268–73

Rossini M *et al* 2014 Remote estimation of grassland gross primary production during extreme meteorological seasons *Int. J. Appl. Earth Obs. Geoinf.* **29** 1–10

Saari R K, Selin N E, Rausch S and Thompson T M 2014 A self-consistent method to assess air quality co-benefits from US climate policies *J. Air Waste Manage. Assoc.* **65** 74–89

Sabrekov A F, Runkle B R K, Glagolev M V, Kleptsova I E and Maksyutov S S 2014 Seasonal variability as a source of uncertainty in the West Siberian regional CH_4 flux upscaling *Environ. Res. Lett.* **9** 045008

Sabrekov A F, Glagolev M V, Alekseychik P K, Smolentsev B A, Terentieva I E, Krivenok L A and Maksyutov S S 2016 A process-based model of methane consumption by upland soils *Environ. Res. Lett.* **11** 075001

Saeki T *et al* 2013 Carbon flux estimation for Siberia by inverse modeling constrained by aircraft and tower CO_2 measurements *J. Geophys. Res.* **118** 1100–22

Schaphoff S, Reyer C P O, Schepaschenko D, Gerten D and Shvidenko A 2015 Tamm Review: Observed and projected climate change impacts on Russian forests and its carbon balance *Forest Ecol. Manage.* **361** 432–44

Schierhorn F, Müller D, Beringer T, Prishchepov A V, Kuemmerle T and Balmann A 2013 Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus *Glob. Biogeochem. Cycles* **27** 1175–85

Schierhorn F, Faramarzi M, Prishchepov A V, Koch F J and Müller D 2014a Quantifying yield gaps in wheat production in Russia *Environ. Res. Lett.* **9** 084017

Schierhorn F, Müller D, Prishchepov A V, Faramarzi M and Balmann A 2014b The potential of Russia to increase its wheat production through cropland expansion and intensification *Glob. Food Sec.* **3** 133–41

Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to US crop yields under climate change *Proc. Natl Acad. Sci. USA* **106** 15594–8

Schmitz C *et al* 2014 Land-use change trajectories up to 2050: insights from a global agro-economic model comparison *Agric. Econ.* **45** 69–84

Schubert S D, Wang H, Koster R D, Suarez M J and Groisman P Ya 2014 Northern Eurasian heat waves and droughts *J. Clim.* **27** 3169–207

Schulze E-D, Wirth C, Mollicone D, von Lupke N, Ziegler W, Achard F, Mund M, Prokushkin A and Scherbina S 2012 Factors promoting larch dominance in central Siberia: fire versus growth performance and implications for carbon dynamics at the boundary of evergreen and deciduous conifers *Biogeosciences* **9** 1405–21

Schuur E A G *et al* 2015 Climate change and the permafrost carbon feedback *Nature* **520** 171–9

Selin N E *et al* 2009 Global health and economic impacts of future ozone pollution *Environ. Res. Lett.* **4** 044014

Serreze M C, Barrett A P, Slater A G, Woodgate R A, Aagaard K, Lammers R B, Steele M, Moritz R, Meredith M and Lee C M 2006 The large-scale freshwater cycle of the Arctic *J. Geophys. Res.* **111** C11010

Shahgedanova M, Nosenko G, Khromova T and Muravyev A 2010 Glacier shrinkage and climatic change in the Russian Altai from the mid-20th century: an assessment using remote sensing and PRECIS regional climate model *J. Geophys. Res. Atmos.* **115** D16107

Shakhova N 2013 Ebullition and storm-induced methane release from the East Siberian Arctic Shelf *Nat. Geosci.* **7** 64–70

Shakhova N 2015 The east siberian Arctic shelf: towards further assessment of permafrost-related methane fluxes and role of sea ice *Phil. Trans. R. Soc.* A **373** 20140451

Shiklomanov A I and Lammers R B 2013 Changing discharge patterns of high-latitude rivers *Climate Vulnerability* ed R A Pielke (Oxford: Academic) pp 161–75 (https://doi.org/10.1016/B978-0-12-384703-4.00526-8)

Shiklomanov A I, Lammers R B, Lettenmaier D P, Polischuk Yu M, Savichev O G and Smith L G 2013 Hydrological changes: historical analysis, contemporary status, and future projections *Environmental Changes in Siberia: Regional Changes and their Global Consequences* ed P Groisman and G Gutman (Dordrecht: Springer) ch 4 pp 111–54 (https://doi.org/10.1007/978-94-007-4569-8_4)

Shiklomanov A, Prusevich A, Gordov E, Okladnikov I and Titov A 2016 Environmental science applications with Rapid Integrated Mapping and analysis System (RIMS) *IOP Conf. Ser.: Earth Environ. Sci* **48** 012034

Shiklomanov N I and Streletskiy D A 2013 Effect of climate change on Siberian infrastructure *Environmental Changes in Siberia: Regional Changes and Their Global Consequences* ed P Groisman and G Gutman (Springer) ch 5 pp 155–70 (https://doi.org/10.1007/978-94-007-4569-8_5)

Shiklomanov N I, Streletskiy D A, Swales T B and Kokorev V A 2017 Climate change and stability of urban infrastructure in Russian permafrost regions: prognostic assessment based on GCM climate projections *Geogr. Rev.* **107** 125–42

Shkolnik I M, Meleshko V P, Efimov S V and Stafeeva E N 2012 Changes in climate extremes over Siberia by the mid 21st century: ensemble projection using MGO RCM *Russ. Meteorol. Hydrol.* **37** 71–84

Shkolnik I M and Efimov S V 2013 Cyclonic activity in high latitudes as simulated by a regional atmospheric climate model: added value and uncertainties *Environ. Res. Lett.* **8** 045007

Shuman J K and Shugart H H 2009 Evaluating the sensitivity of Eurasian forest biomass to climate change using a dynamic vegetation model *Environ. Res. Lett.* **4** 045024

Shuman J K and Shugart H H 2012 Resilience and stability associated with the conversion of boreal forest *Remote Sensing of Biomass: Principles and Application* ed T E Fatoyinbo (Rijeka: InTech) ch 9 pp 195–216 (https://doi.org/10.5772/19515)

Shuman J K, Shugart H H and Krankina O N 2013a Assessment of carbon stores in tree biomass for two management scenarios in Russia *Environ. Res. Lett.* **8** 045019

Shuman J K, Shugart H H and Krankina O N 2013b Testing individual-based models of forest dynamics: issues and an example from the boreal forests of Russia *Ecol. Modell.* **293** 102–10

Shuman J K, Tchebakova N M, Parfenova E I, Soja A J, Shugart H H, Ershov D and Holcomb K 2015 Forest forecasting with vegetation models across Russia *Can. J. Forest Res.* **45** 175–84

Shvidenko A Z, Shchepashchenko D G, Vaganov E A, Sukhinin A I, Maksyutov S S, McCallum I and Lakyda I P 2011 Impact of wildfire in Russia between 1998–2010 on ecosystems and the global carbon budget *Dokl. Earth Sci.* **441** 1678–82

Siljamo P *et al* 2013 A numerical model of birch pollen emission and dispersion in the atmosphere. Model evaluation and sensitivity analysis *Int. J. Biometeorol.* **57** 125–36
Smaliychuk A, Müller D, Prishchepov A V, Levers C, Kruhlov I and Kuemmerle T 2016 Recultivation of abandoned agricultural lands Ukraine: patterns and drivers *Glob. Environ. Change* **38** 70–81
Sofiev M, Siljamo P, Ranta H, Linkosalo T, Jaeger S, Rasmussen A, Rantio-Lehtimaki A, Severova E and Kukkonen J 2013 A numerical model of birch pollen emission and dispersion in the atmosphere. Description of the emission module *Int. J. Biometeorol.* **57** 45–58
Soja A J, Cofer W R, Shugart H H, Sukhinin A I, Stackhouse P W Jr, McRae D J and Conard S G 2004 Estimating fire emissions and disparities in boreal Siberia (1998–2002) *J. Geophys. Res.* **109** D14S06
Soja A J, Tchebakova N M, French N H F, Flannigan M D, Shugart H H, Stocks N J, Sukhinin A I, Parfenova E I, Chapin III F S and Stackhouse P W Jr 2007 Climate-induced boreal forest change: predictions versus current observations *Glob. Planet. Change* **56** 274–96
Soja A J and Groisman P Ya 2012 Northern Eurasia earth science partnership initiative: evolution of scientific investigations to applicable science *Environ. Res. Lett.* **7** 045201
Sokolik I N *et al* 2013 Examining the linkages between land cover and land use, regional climate and dust in the drylands of East Asia *Dryland East Asia: Land Dynamics amid Social and Climate Change* ed J Chen *et al* (Berlin/ Boston, MA: Higher Education Press/Walter de Gruyter) pp 185–213 (https://doi.org/10.1515/9783110287912.183)
Sokolov A P 2005 MIT integrated global system model (IGSM) version 2: model description and baseline evaluation *MIT Joint Program on the Science and Policy of Global Change* Report 124 40 pp (https://globalchange.mit.edu/sites/default/files/MITJPSPGC_Rpt124.pdf)
Sokolov A P *et al* 2009 Probabilistic forecast for twenty-first-century climate based on uncertainties in emissions (without policy) and climate parameters *J. Clim.* **22** 5175–204
Sorg A *et al* 2012 Climate change impacts on glaciers and runoff in Tien Shan (Central Asia) *Nat. Clim. Change* **2** 725–31
Sperber K R, Annamalai H, Kang I S, Kitoh A, Moise A, Turner A, Wang B and Zhou T 2013 The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century *Clim. Dyn.* **41** 2711–44
Stephenson S R, Smith L C and Agnew J A 2011 Divergent long-term trajectories of human access to the Arctic *Nat. Clim. Change* **1** 156–60
Streletskiy D A, Shiklomanov N I and Nelson F E 2012 Permafrost, infrastructure and climate change: a GIS-based landscape approach to geotechnical modeling *Arct. Antarct. Alp Res.* **44** 368–80
Streletskiy D A, Tananaev N I, Opel T, Shiklomanov N I, Nyland K E, Streletskaya I D, Tokarev I and Shiklomanov A I 2015 Permafrost hydrology in changing climatic conditions: seasonal variability of stable isotope composition in rivers in discontinuous permafrost *Environ. Res. Lett.* **10** 095003
Stroeve J C, Kattsov V, Barrett A, Serreze M, Pavlova T, Holland M and Meier W N 2012 Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations *Geophys. Res. Lett.* **39** L16502
Sue Wing I, Monier E, Stern A and Mundra A 2015 US major crops' uncertain climate change risks and greenhouse gas mitigation benefits *Environ. Res. Lett.* **10** 115002
Tarr D, Rutherford T and Jensen J 2001 Social accounting matrices for the regions of Russia *World Bank Working paper* 4015 (http://go.worldbank.org/IDHFFMGYS0)
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc* **93** 485–98
Tchebakova N M and Parfenova E I 2012 The 21st century climate change effects on the forests and primary conifers in central Siberia *Bosque* **33** 253–9
Tchebakova N M, Parfenova E and Soja A J 2009 The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate *Environ. Res. Lett.* **4** 045013
Tchebakova N M, Rehfeldt G E and Parfenova E I 2010 From vegetation zones to climatypes: Effects of climate warming on Siberian ecosystems *Permafrost Ecosystems: Siberian Larch Forests* ed A Osawa *et al* (Ecological Studies vol 209)(Dordrecht: Springer) ch 22 pp 427–46 (https://doi.org/10.1007/978-1-4020-9693-8_22)
Tchebakova N M, Parfenova E I, Lysanova G I and Soja A J 2011 Agroclimatic potential across central Siberia in an altered twenty-first century *Environ. Res. Lett.* **6** 045207
Tchebakova N M, Parfenova E, Soja A and Blyakharchuk T A 2012 Predicted and observed climate-induced fire in the Altai-Sayan Mts, Central Asia, during the Holocene *Modelling Fire Behaviour and Risk* ed D Spano *et al* (Muros: Nuova Stampacolor) pp 78–84 (http://doc.utwente.nl/93370/1/evaluating%20fire%20risk.pdf)
Tchebakova N M, Parfenova E I and Soja A J 2016a Significant Siberian vegetation change is inevitably brought on by the changing climate *Novel Methods for Monitoring and Managing Land and Water Resources in Siberia* ed L Mueller, A K Sheudshen and F Eulenstein (Cham: Springer International) ch 10 pp 269–85 (https://doi.org/10.1007/978-3-319-24409-9_10)
Tchebakova N M, Parfenova E I, Korets M A and Conard S G 2016b Potential change in forest types and stand heights in central Siberia in a warming climate *Environ. Res. Lett.* **11** 035016
Thompson T M, Rausch S, Saari R K and Selin N E 2014 A systems approach to evaluating the air quality co-benefits of US carbon policies *Nat. Clim. Change* **4** 917–23
Thomson A M *et al* 2011 RCP4.5: a pathway for stabilization of radiative forcing by 2100 *Clim. Change* **109** 77–94
Thurner M *et al* 2014 Carbon stock and density of northern boreal and temperate forests *Glob. Ecol. Biogeogr.* **23** 297–310
Titov A, Gordov E, Okladnikov I and Shulgina T 2009 Web-system for processing and visualization of meteorological data for Siberian environment research *Int. J. Digital Earth.* **2** 105–19
Todd-Brown K E, Randerson J T, Post W M, Hoffman F M, Tarnocai C, Schuur E A and Allison S D 2013 Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations *Biogeosciences* **10** 1717–36
Troy T J, Sheffield J and Wood E F 2012 The role of winter precipitation and temperature on northern Eurasian streamflow trends *J. Geophys. Res. Atmos.* **117** D05131
Valin H *et al* 2014 The future of food demand: understanding differences in global economic models *Agric. Econ.* **45** 51–67
van Vuuren D P *et al* 2011a The representative concentration pathways: an overview *Clim. Change* **109** 5–31
van Vuuren D P *et al* 2011b RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C *Clim. Change* **109** 95–116
Vasileva A and Moiseenko K 2013 Methane emissions from 2000 to 2011 wildfires in Northeast Eurasia estimated with MODIS burned area data *Atoms. Environ.* **71** 115–21
Velichko A A, Borisova O K, Zelikson E M and Morozova T D 2004 Changes in vegetation and soils of the East European Plain to be expected in the 21st century due to anthropogenic changes in climate *Geogr. Pol.* **77** 37–45
Volodin E M 2013 The mechanism of multidecadal variability in the Arctic and North Atlantic in climate model INMCM4 *Environ. Res. Lett.* **8** 035038
Volodin E M, Diansky N A and Gusev A V 2013 Simulation and prediction of climate changes in the 19th to 21st centuries with the Institute of Numerical Mathematics, Russian Academy of Sciences, model of the Earth's climate system *Izv. Atmos. Ocean. Phys.* **49** 347–66
von Lampe M *et al* 2014 Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison *Agric. Econ.* **45** 3–20
Webster M *et al* 2012 Analysis of climate policy targets under uncertainty *Clim. Change* **112** 569–83

West J J, Szopa S and Hauglustaine D A 2007 Human mortality effects of future concentrations of tropospheric ozone *C. R. Geosci.* **339** 775–83

Weyant J *et al* 1996 Integrated assessment of climate change: an overview and comparison of approaches and results *Climate Change 1995: Economic and Social Dimensions of Climate Change: Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change* ed J P Bruce, H Lee and E F Haites (Cambridge: Cambridge University Press) pp 371–96

Xi X and Sokolik I N 2015 Seasonal dynamics of threshold friction velocity and dust emission in Central Asia *J. Geophys. Res. Atmos.* **120** 1536–64

Xi X and Sokolik I N 2016 Dust interannual variability and trend in Central Asia from 2000 to 2014 and their climatic linkages *J. Geophys. Res. Atmos.* **120** 12175–97

Xu L, Pyles R D, Paw U K T, Chen S H and Monier E 2014 Coupling the high-complexity land surface model ACASA to the mesoscale model WRF *Geosci. Model Dev.* **7** 2917–32

Yue C, Ciais P, Zhu D, Wang T, Peng S S and Piao S L 2016 How have past fire disturbances contributed to the current carbon balance of boreal ecosystems *Biogeosciences* **13** 675–90

Zhang N, Yasunari T and Ohta T 2011 Dynamics of the larch taiga–permafrost coupled system in Siberia under climate change *Environ. Res. Lett.* **6** 024003

Zhang X, Ermolieva T, Balkovic J, Mosnier A, Kraxner F and Liu J 2015 Recursive cross-entropy downscaling model for spatially explicit future land uses: a case study of the Heihe River Basin *Phys. Chem. Earth* **89** 56–64

Zhang Y, Sachs T, Li C and Boike J 2012 Upscaling methane fluxes from closed chambers to eddy covariance based on a permafrost biogeochemistry integrated model *Glob. Change Biol.* **18** 1428–40

Zhu Q and Zhuang Q 2013 Modeling the effects of organic nitrogen uptake by plants on the carbon cycling of boreal ecosystems *Biogeosciences* **10** 7943–55

Zhu X, Zhuang Q, Gao X, Sokolov A and Schlosser C A 2013 Pan-Arctic land-atmospheric fluxes of methane and carbon dioxide in response to climate change over the 21st century *Environ. Res. Lett.* **8** 045003

Zhu X, Zhuang Q, Lu X and Song L 2014 Spatial scale-dependent land-atmospheric methane exchanges in the northern high latitudes from 1993 to 2004 *Biogeosciences* **11** 1693–704

Zhuang Q, Chen M, Xu K, Tang J, Saikawa E, Lu Y, Melillo J M, Prinn R G and McGuire A D 2013 Response of global soil consumption of atmospheric methane to changes in atmospheric climate and nitrogen deposition *Glob. Biogeochem. Cycles* **27** 650–63

Ziółkowska E, Ostopowicz K, Radeloff V C and Kuemmerle T 2014 Effects of different matrix representations and connectivity measures on habitat network assessments *Landscape Ecol.* **29** 1551–70

Zuev V V, Semenov V A, Shelekhova E A, Gulev S K and Koltermann P 2012 Evaluation of the impact of oceanic heat transport in the North Atlantic and Barents Sea on the Northern Hemispheric climate *Dokl. Earth Sci.* **445** 1006–10