Report 311
May 2017

A Review of and Perspectives on Global Change Modeling for Northern Eurasia

Erwan Monier, David Kicklighter, Andrei Sokolov, Qianlai Zhuang, Irina Sokolik, Richard Lawford, Martin Kappas, Sergey Paltsev and Pavel Groisman

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To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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GLOBAL CHANGE

MAY 2017

A Review of and Perspectives on Global Change Modeling for Northern Eurasia

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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. Major modeling efforts have shown that environmental and socioeconomic impacts in Northern Eurasia can have major implications for the biodiversity, ecosystems services, environmental sustainability, and 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.

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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; 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), snow characteristics and icing conditions (Bulygina *et al.*, 2011, 2015), permafrost thaw (Romanovsky *et al.*, 2007), forest fires (Groisman *et al.*, 2007) as well as extensive land-use change and water management projects (Groisman *et al.*, 2009). These past and ongoing environmental and socioeconomic impacts can have major implications for the 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 15ºE in the west to the Pacific coast in the east and from 40ºN 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 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, developing and applying models or modeling framework 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 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

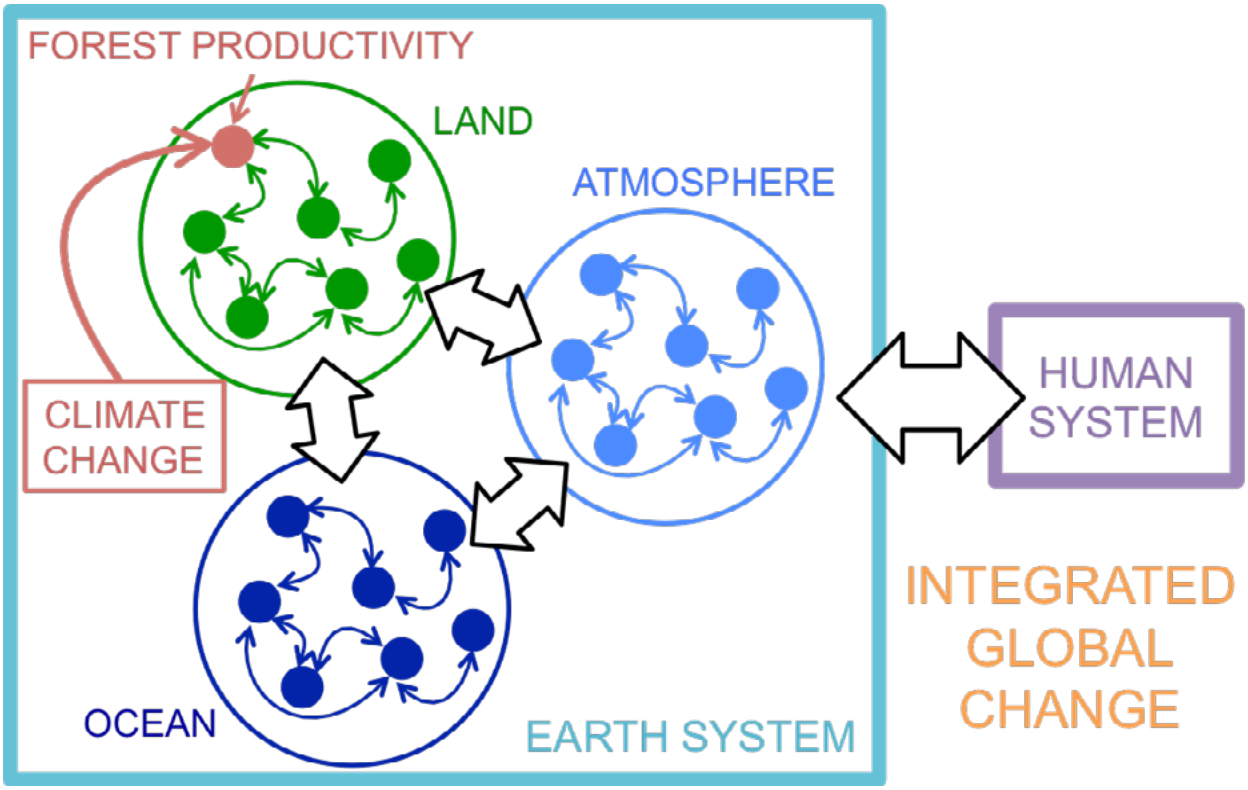

Figure 1. Schematic showing an example of a current study that focuses on the climate impacts on a single component of the Earth system, here imposing climate change on forest productivity (shown in red), compared to an example of a framework that links the Earth system (cyan), including the land (green), 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).

framework (see **Figure 1**). However, issues still exist, consequently NEESPI researchers need to develop a new paradigm of integrated global 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 and 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 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

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.

Category	Studies
Agriculture *(crop modeling, economics)*	Dronin & Kirilenko (2010); Gelfan *et al.* (2012); Iizumi & Ramankutty (2016); Kattsov *et al.* (2012); Magliocca *et al.* (2013); Peng *et al.* (2013); Schierhorn *et al.* (2014a,b); 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 & Sokolik (2015, 2016)
Carbon *(in land and water)*	Bohn *et al.* (2013, 2015); Cresto-Aleina *et al.* (2015); Dargaville *et al.* (2002a,b); Dass *et al.* (2016); Dolman *et al.* (2012); Gao *et al.* (2013); Glagolev *et al.* (2011); Gustafson *et al.* (2011); Hayes *et al.* (2011a,b, 2014); John *et al.* (2013); Kicklighter *et al.* (2013, 2014); Kim *et al.* (2011); Koven *et al.* (2011); Lu *et al.* (2009); Kuemmerle *et al.* (2011b); 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 & Shugart (2009); Shuman *et al.* (2013a); Yue *et al.* (2016); Zhang *et al.* (2012); Zhu *et al.* (2013, 2014); Zhu & Zhuang (2013); Zhuang *et al.* (2013)
Climate	Anisimov *et al.* (2013); Arzhanov *et al.* (2012a,b); Lyalko *et al.* (2016); Miao *et al.* (2014); Monier *et al.* (2013); Onuchin *et al.* (2014); Shahgedanova *et al.* (2010); Shkolnik & Efimov (2013); Volodin 2013; Volodin *et al.* (2013); Zuev *et al.* (2012)
Cryosphere *(snow, glaciers, sea ice…)*	Callaghan *et al.* (2011a,b); Farinotti *et al.* (2015); Hagg *et al.* (2006); Klehmet *et al.* (2013); Loranty *et al.* (2014); Pieczonka & 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 & Lettenmaier (2010); Cresto-Aleina *et al.* (2015); Gelfan 2011; Georgiadi *et al.* (2010, 2014); Hagg *et al.* (2008); Karthe *et al.* (2015); Khon & Mokhov (2012); Klehmet *et al.* (2013); Kuchment *et al.* (2011); Liu *et al.* (2013, 2014) (2015); McClelland *et al.* (2004); Motovilov & Gelfan (2013); Novenko & Olchev (2015); Olchev *et al.* (2009a, 2013); Oltchev *et al.* (2002a,b); Osadchiev 2015; Rawlins *et al.* (2010); Serreze *et al.* (2006); Shiklomanov *et al.* (2013); Shiklomanov & Lammers (2013); Sorg *et al.* (2012); Streletskiy *et al.* (2015); Troy *et al.* (2012); Zhang *et al.* (2011)
Land-use change	Griffiths *et al.* (2013); Gustafson *et al.* (2011); Hayes *et al.* (2011a); Hitztaler & 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.* (2014b); Smaliychuk *et al.* (2016); Zhang *et al.* (2015)
Infrastructure	Shiklomanov & Streletskiy (2013); Shiklomanov *et al.* (2017); Stephenson *et al.* (2011); Streletskiy *et al.* (2012)
Nitrogen	Kopáček *et al.* (2012); Kopáček & Posch (2011); Oulehle *et al.* (2012); Zhu & Zhuang (2013); Zhuang *et al.* (2013)
Permafrost	Euskirchen *et al.* (2006); Gao *et al.* (2013); Gouttevin *et al.* (2012); Hayes *et al.* (2014); MacDougall & Knutti (2016); Marchenko *et al.* (2007); Shakhova *et al.* (2013, 2015); Streletskiy *et al.* (2013, 2015); Zhang *et al.* (2011)
Terrestrial ecosystems characteristics	Cresto-Aleina *et al.* (2013); Kopačková *et al.* (2013, 2015); Lapenis *et al.* (2005); Lebed *et al.* (2012); Li *et al.* (2016); Shuman *et al.* (2013b); Shuman & 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,b); Tchebakova & Parfenova (2012, 2013); Velichko *et al.* (2004)
Weather *(i.e. extreme events)*	Barriopedro *et al.* (2011); Meredith *et al.* (2015); Semenov 2012; Shkolnik *et al.* (2012); Schubert *et al.* (2014)
Wildfire	Balshi *et al.* (2007); Dubinin *et al.* (2011); Gustafson *et al.* (2011); Kantzas *et al.* (2013); Loboda & Csiszar (2007); Malevsky-Malevich *et al.* (2008); Narayan *et al.* (2007); Park & Sokolik (2016); Schulze *et al.* (2012); Soja *et al.* (2004); Tchebakova *et al.* (2012); Vasileva & Moiseenko (2013)
Zoology	Kuemmerle *et al.* (2011a, 2014); Ziółkowska *et al.* (2014)

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 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). 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 representing interactions and feedbacks between 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).

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

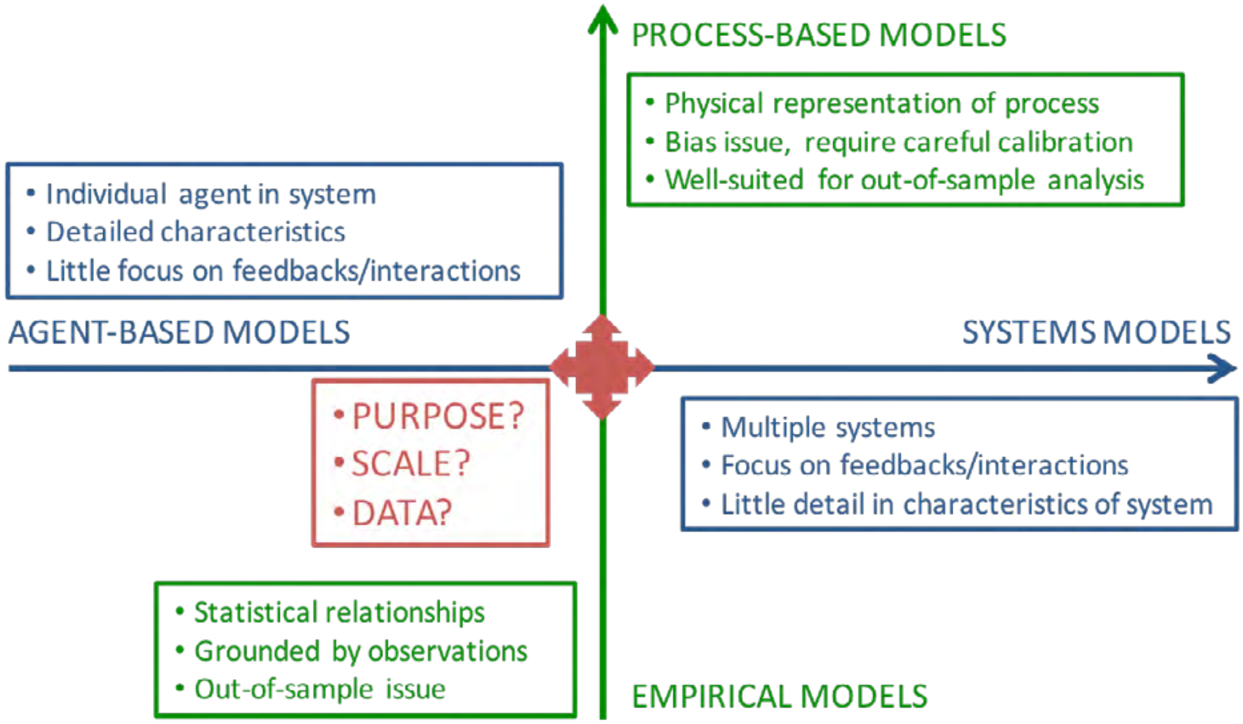

Figure 2. Schematic summarizing the strength and limitations of models based on the class of model (empirical models to process-based models) and modeling approaches (from agent-based models to systems models). The choice of model characteristics generally depends on the purpose, scale and data availability.

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 *et al.*, 2013). Many 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, 2007; 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; Xin and Sokolik, 2015a, b, c; 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, b); and biospheric and climate information (Tchebakova *et al.*, 2009, 2016; Shuman *et al.*, 2015).

These modeling studies generally fall into two categories: 1) diagnostic modeling studies that assess the present relationships between 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 component 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 fluxes, eddy-covariance is used for local high temporal resolution (Liu *et al.*, 2014, 2015); dissolved organic carbon (DOC) export at the mouth of the 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 (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.[1] Most MIPs usually include models that are structurally similar and that 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 between 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, b; 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

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[1] A list of MIPs can be found at http://www.wcrp-climate.org/wgcm/projects.shtml.

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 (Kattsov *et al.*, 2012) 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 between 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 internation-

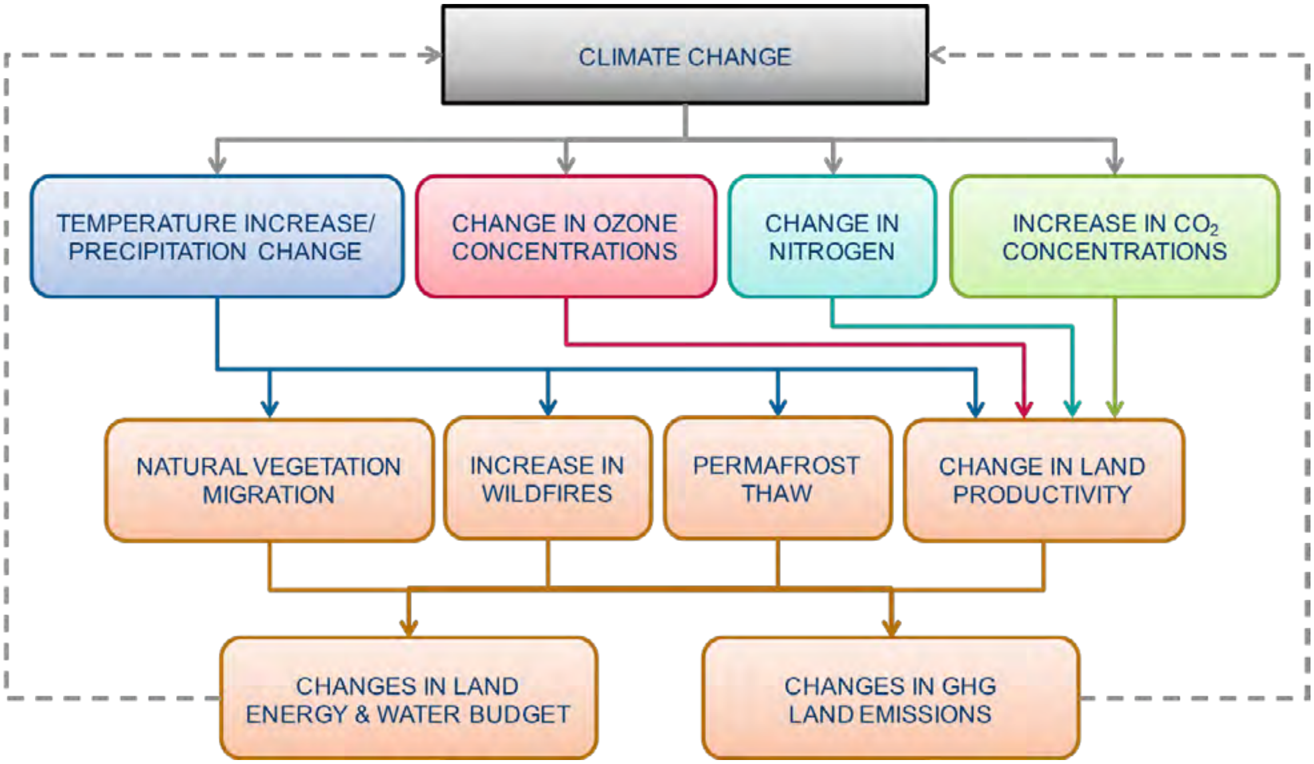

Figure 3. Schematic of a detailed, but non-exhaustive, accounting of climate change impacts on land biogeochemistry and biogeophysics. Dashed lines represent the potential feedback of terrestrial ecosystem responses to the climate system.

al 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 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 Modeling for Northern Eurasia

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 and since they simulate the global Earth system, they are not the preferred modeling framework for targeted studies focusing on specific regions like Northern Eurasia. In addition, since they 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).

3.2 Integrated Assessment Models

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". Indeed, 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 2015 United Nations Climate Change Conference (COP21) 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), 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 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.

In light of the need for a global perspective when investigating the impact of global change on Northern Eurasia, and the push toward a more integrated modeling framework between the human system and the Earth system, we make the following notes:

- Many global studies of the Food-Energy-Water (FEW) system lack a focus on specific regions other than the United States, Europe, China. Given the importance of the FEW for the region and the need for a focus, tighter collaborations with these coordinated exercises could lead to major benefits for Northern Eurasia.
- Some efforts to integrate the human system and the Earth system with a focus on Northern Eurasia exist and need to be continued and expanded upon. For example, recently, a new coupled model, called WRF-Chem-DusMo (dust module), has been developed to explore the linkage between dust, climate and land-use change dynamics in Central Asia (Xi and Sokolik, 2015, 2016).
- Future research projects need to better identify the role of Northern Eurasia in the global system and put a greater focus on the global context.

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 2xCO_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; 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 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). At the same time, 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 these 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.

4. Emerging Issues in the Coupled Human-Earth System

At the frontier of integrated assessment modeling, a large number of issues have emerged with the ongoing development of coupled human-earth system models. The FEW system is a good example of the need for new modeling frameworks and methodologies to better understand the complex connections between the human system and the Earth system. The impact of climate on the FEW system is often treated without considering its feedback on the economy, traditional social roles of agriculture, GHG emissions and the climate system. Well-recognized studies that integrate components of the FEW system in the context of the human-Earth coupled system generally do not consider climate change impacts on all three components of the FEW system and their interactions, for example not accounting for water availability for irrigation (Nelson *et al.*, 2014a, b; Schmitz *et al.*, 2014; Valin *et al.*, 2014; von Lampe *et al.*, 2014). Even the comprehensive work by Elliott *et al.* (2014) does not account for the land-use change feedback on the climate system

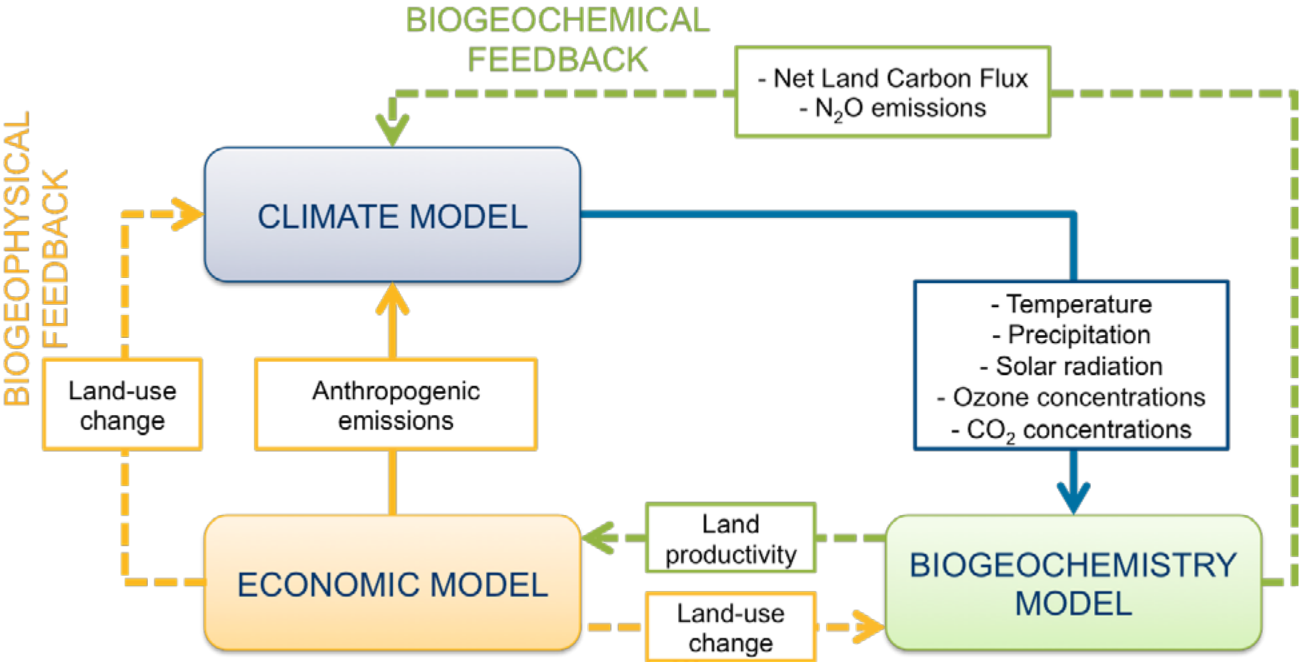

Figure 4. Schematic of modeling framework to investigate the biogeochemical and biogeophysical impacts of human-driven land-use change, similar to that used in Reilly *et al.* (2012) and Hallgren *et al.* (2013).

through either biogeochemical and biogeophysical pathways. The complex interactions within the FEW system should be considered along with the large forces of global change. Moreover, the sustainability of the FEW should be accounted for in future land-use change projections, as should the fate of the global economy and climate system. This is also true when constructing climate mitigation strategies such as soil carbon sequestration, since they can be detrimental to FEW-system outcomes if they do not explicitly consider sustainability across multiple dimensions (e.g., Hejazi *et al.*, 2015 for water stress in the U.S).

Major innovations at the nexus of the FEW system are needed, with more integrated modeling frameworks that consider the many interactions between the human and Earth systems. Reilly *et al.* (2013) provide a strategy for investigating the impacts of climate change on Earth's physical, biological and human resources and links to their socio-economic consequences. The model development to enhance 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 regional characteristics that are unique in each region (Lawford *et al.*, 2013) including the NEESPI region. The 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.

A similar assessment can be made of many other issues. New pathways for drivers of land-use change could be explored, with a particular focus on Northern Eurasia, as new models become more detailed. As the Arctic sea ice extent shrinks, Arctic trade routes will remain open for longer periods of time, and new routes will likely open. This could lead to major changes in energy exploration and for the ability of the timber industry 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). 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. Climate change, and especially changes in extreme events such as droughts and heat waves, is expected to increase the frequency and severity of wildfires. Emissions of particulate matter from the fires can have significant influence on the local and regional air quality and major implications for human exposure and health impacts. Quantifying the future economic impact of future air pollution, especially taking into account these complex pathways, can prove key to accurately inform policy responses. Similarly, the air quality co-benefits of climate policies have received a great deal of attention in countries like the United States (Thompson *et al.*, 2014, Garcia-Menendez *et al.*, 2015), but little work has focused on 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, health, land-use change, and water resources, 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, 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.

The International Geosphere Biosphere Programme (IGBP) officially ended in December 2015 after 30 years of

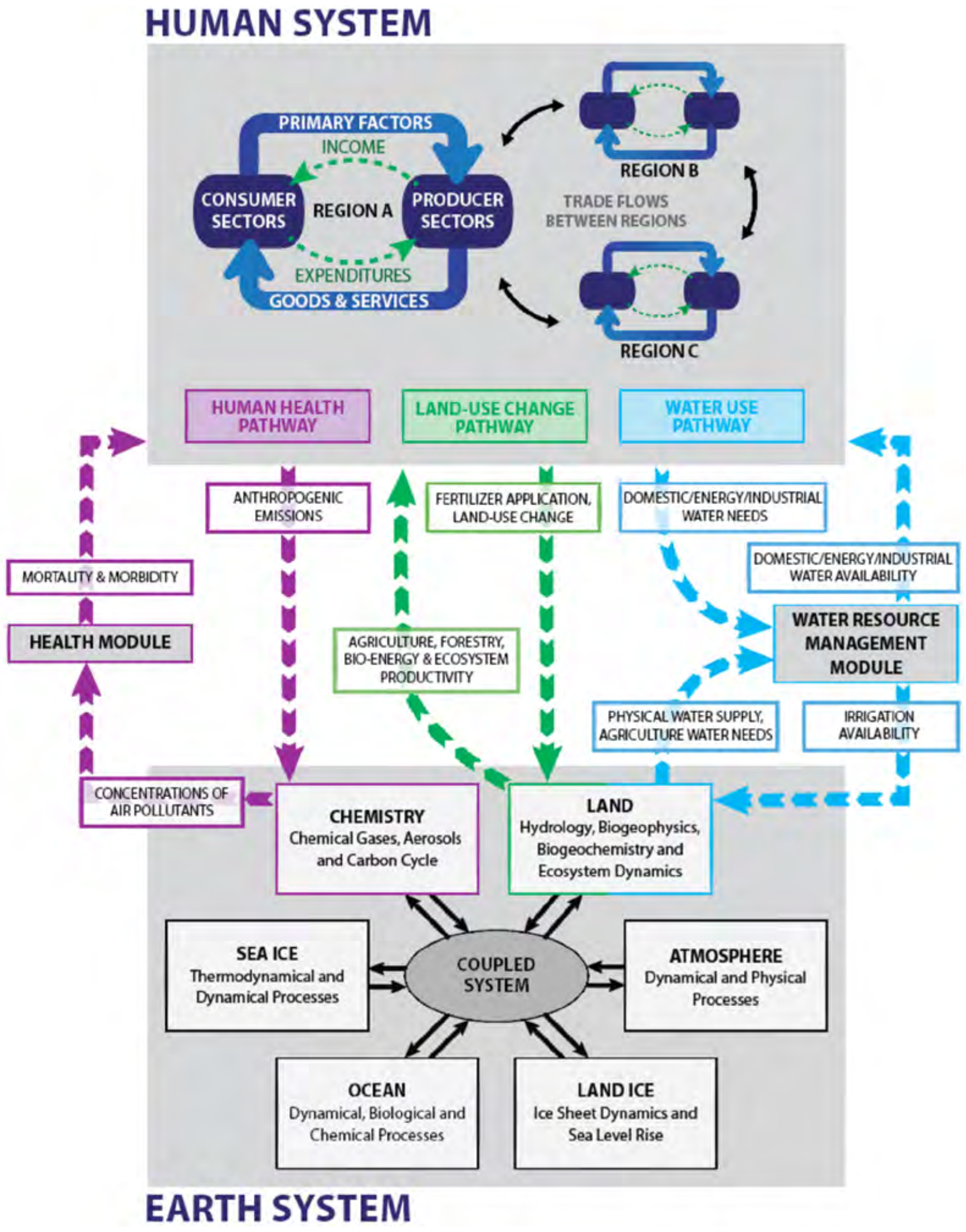

Figure 5. Schematic of an Integrated Assessment Model (IAM) that couples a human activity model and an Earth system model with a focus on three feedback pathways: health, land-use change, and water resources.

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 the multiple ways in which 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. The research limit that will help us launch 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 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 sponsor (for the complete list see http://globalchange.mit.edu/sponsors).

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