White Paper

Northern Eurasia Future Initiative (NEFI):

Facing the Challenges and Pathways of Global Change in the 21st Century

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Northern Eurasia Future Initiative (NEFI): Facing the challenges and pathways of Global Change in the 21st century

1. Introduction

This white paper was conceived at the Workshop "*Ten years of Northern Eurasia Earth Science Partnership Initiative (NEESPI): Synthesis and Future Plans"* hosted by Charles University in Prague, Czech Republic (April 9-12, 2015). This event was attended by more than 70 participants from Japan, China, Russia, Ukraine, Kyrgyzstan, Kazakhstan, the European Union, and the United States. The Workshop included an overview, synthesis presentations, and scientific visions for NEESPI in its transition to the "Northern Eurasia Future Initiative, NEFI". The results of the Workshop were immediately delivered at a dedicated open public Splinter Meeting at the European Geophysical Union Assembly in Vienna Congress Center, Austria http://neespi.org/web-content/PragueWorkshopSynthesisBriefing.pdf (April 16th, 2015). The following are the major achievements of NEESPI and the consensus of the future NEFI vision to address the challenges and develop pathways to mitigate future changes in the region.

During the past 10 years, NEESPI has been quite successful at conducting, highlighting and advancing research in Northern Eurasia. Its Science Plan was prepared by an International Research Team of more than 100 geoscientists from 11 countries in 2004, peer reviewed and released at http://neespi.org/science/science.html. Its Executive Summary was prepared in English, Russian, and Chinese and later published in Groisman and Bartalev (2007). Over the years, NEESPI progress was reported in several programmatic papers (Groisman et al. 2009, 2014; Groisman and Soja 2009), and overview books (Gutman and Reissell, 2011; Groisman and Lyalko 2012; Groisman and Gutman 2013; Chen et al. 2013; Gutman and Radeloff 2016). The NEESPI implementation program has accommodated 272 projects focused on different environmental issues in Northern Eurasia. These projects were different in size and scope, funded by multiple national and international agencies, and have involved in different years a total of more than 750 scientists from 200 institutions representing 30 countries. More than 80 PhD students defended their theses while working within the NEESPI framework. Since 2006, 32 dedicated NEESPI Workshops and 23 NEESPI Open Science Sessions were convened at International Meetings. The NEESPI research domain is shown in Figure 1 and its duration was estimated to be 10-12 years starting from 2004.

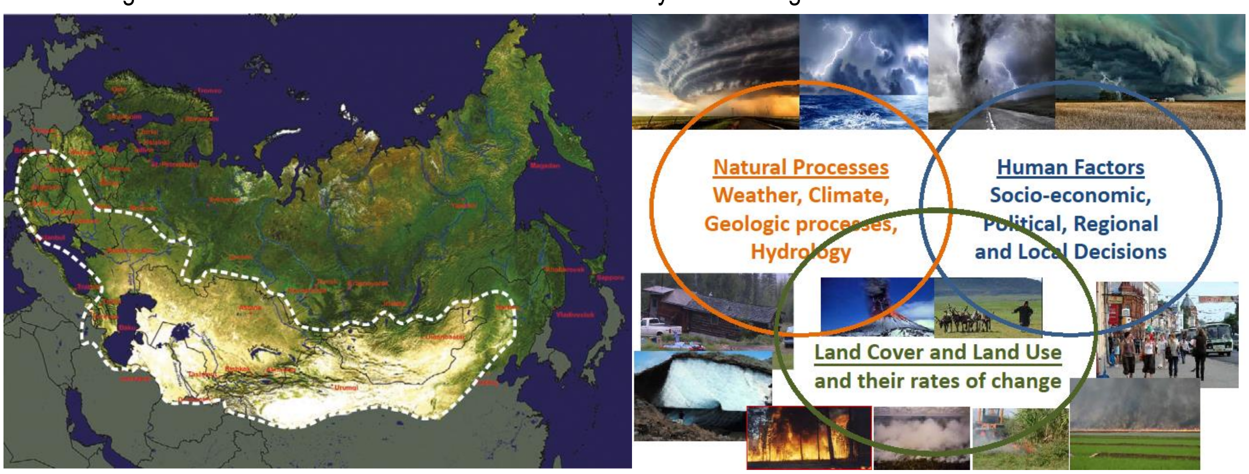

Figure 1. Left. The NEESPI study area is loosely defined as the region between 15°E in the west, the Pacific Coast in the east, 40°N in the south, and the Arctic Ocean coastal zone in the north. In this map green corresponds to vegetated lands. Light brown and yellow indicate sparse vegetation and arid areas, respectively. The Dry Latitudinal Belt of Northern Eurasia is sketched on the map by a dashed white line (Groisman et al. 2009). **Right**. Major natural and direct anthropogenic processes that affect Northern Eurasia.

More than 1500 peer-reviewed journal papers and 40 books have been published during this period. This created a new research realm because NEESPI scientists self-organized in a broad research network, accumulated the knowledge and developed new tools (observations, datasets, models, and collaborative networks) to deliver new results, and can now apply these results to directly support decision-making for various societal needs. Furthermore, during the same period, two important changes have occurred:

- The Global Earth System has significantly changed with the changes in Northern Eurasia being substantially larger than the global average. There are arguments that the rate of the global near-surface air temperature change has recently slowed (Figure 2; see, however, Karl et al. 2015 and Table 1). Subsequently, the NEFI endeavor is to analyze this *new state* with its unexpected novel features and distributions –from shifts of the seasonal cycle in various climatic characteristics to changes in intensity, frequency, and spatial and temporal distributions of extreme events. These changes have already occurred, but their impacts upon (and feedbacks to) inertial components of the Earth System are ongoing. These include atmospheric, biospheric, cryospheric, oceanic, and macro-socioeconomic processes. Socio-economic dynamics in the major nations of Northern Eurasia have dramatically changed, including their ability to withstand and adapt to the adverse manifestations of environmental change.

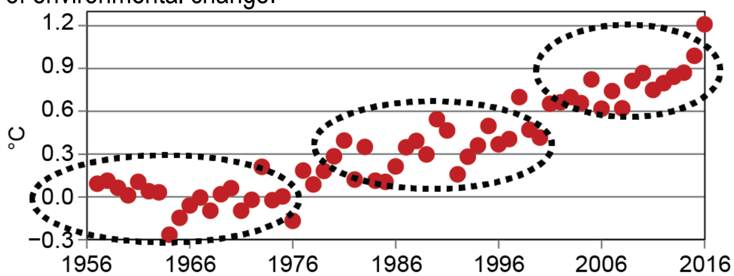

Figure 2. Global annual surface air temperature anomalies (°C) derived from the meteorological station data for the 1957-2014 period (Lugina et al. 2006, updated; value for 2015 is preliminary). The reference period used for calculations of anomalies is 1951-1975.

- An innovative trans-disciplinary objective has been proposed to the Earth Science communities worldwide. Instead of addressing questions, such as those that define the understanding and quantify the amount of change currently and by the end of the 21st century in the Earth System, our communities have begun to increasingly receive inquiries about what mitigation and/or adaptation strategies are possible for the upcoming decades. These questions were reformulated in the framework of the new International Council for Science Union research initiative *Future Earth* (http://www.icsu.org/future-earth/). *Future Earth* focuses on sustainable societal development under changing climatic and environmental conditions because societal decision-making impacts and feeds back on the environment. Meanwhile, the major anthropogenic causes of global change remain and both the Earth science community *and society,* in general, will need to be informed and prepared in order to assure a sustainable future.

Table 1. Linear trend estimates (1957 – 2014) of the global surface air temperature time series shown in Figure 2 as a function of the starting point of the trend estimate. This time series is based upon the land-based surface air temperature station data with a processing algorithm developed 25 years ago by Vinnikov et al. (1990). Linear trend estimates in °C per 10 years are provided with their standard deviations (±) and t-statistics, which characterize statistical significance of the absolute values of trend estimates. Significance remains high even with the short time series and drops down only when the length of the time series decreases to 7 years (i.e., five degrees of freedom).

Period	Trend °C/10yr	t-statistic		Period	Trend °C/10yr	t-statistics
1957-2014	0.17 ± 0.011	16.		1994-2014	0.23 ± 0.032	7.2
1965-2014	0.20 ± 0.011	19.		1998-2014	0.19 ± 0.045	4.3
1970-2014	0.20 ± 0.013	16.		2000-2014	0.21 ± 0.050	4.2
1975-2014	0.21 ± 0.016	14.		2002-2014	0.16 ± 0.053	3.0
1980-2014	0.20 ± 0.019	11.		2004-2014	0.18 ± 0.074	2.4
1985-2014	0.23 ± 0.022	10.		2006-2014	0.27 ± 0.087	3.1
1989-2014	0.23 ± 0.028	8.1		2008-2014	0.26 ± 0.138	1.9

In this vein, the major NEESPI Science questions have been reformulated for NEFI. The former overarching objective remains intact: **"How do Northern Eurasia's terrestrial ecosystem dynamics interact with and alter the biosphere, atmosphere, and hydrosphere of the Earth?"** However, this objective has been reformulated and expanded altering the academically curious **"how?"** into the practical **"what?"**: **What dynamic and interactive changes will affect societal well-being, activities, and health, and what might be the mitigation and adaptation strategies that could support sustainable development and decision-making activities?**

NEESPI researchers and all those who are interested in contributing to the regional research in Northern Eurasia can build upon past achievements by using the results of NEESPI scientific research, data, models, and knowledge to directly support decision-making activities that address societal needs. This will address the core motivation of NEFI which is to best use science to serve the decision-making process, the Earth System "health", and society. Over the last decade, there have already been climatic and environmental changes quantified, and these will require expeditious direct responses on behalf of human well-being and societal health toward sustainable future.

2. Three Unique Features of Northern Eurasia of Global Concern and Related Major Science Questions

To develop effective mitigation and adaptation strategies, future NEFI activities will need to consider three unique features of Northern Eurasia: 1) the sensitivity of land surface characteristics to global change that feedback to influence the global energy budget; 2) potential changes in the Dry Latitudinal Belt of Northern Eurasia that will have a large influence on the availability of water for food, energy, industry, and transportation; and 3) evolving social institutions and economies. Below, we look at these three features in more detail.

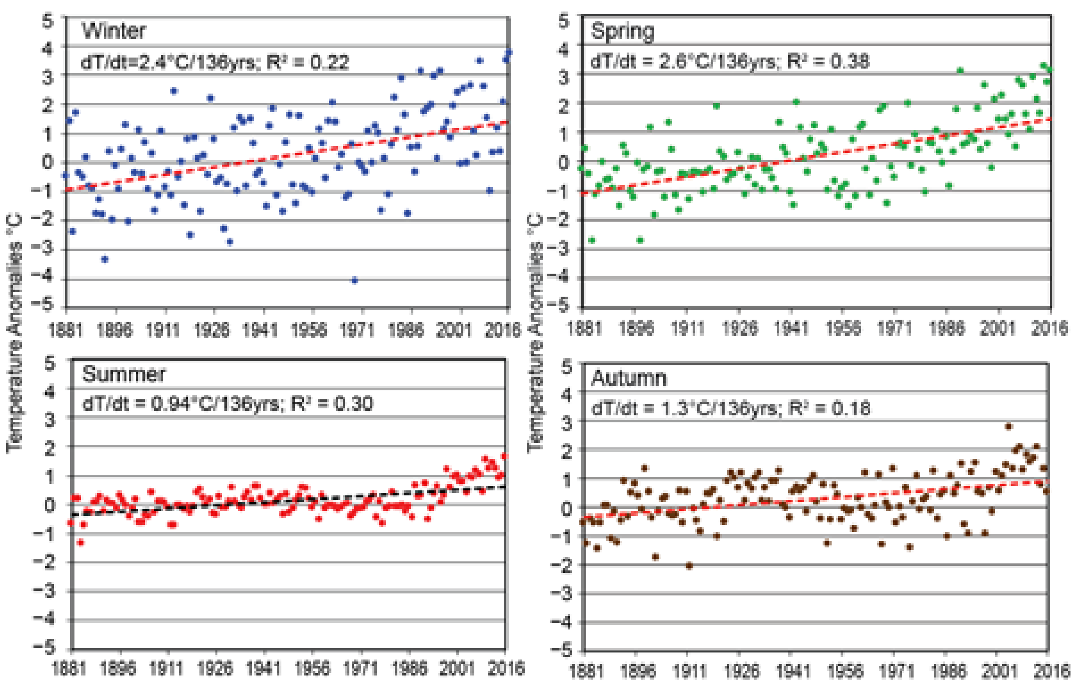

Figure 3. Seasonal temperature anomalies over Northern Eurasia (the NEESPI study domain) for the 1881-2014 period. The reference period used for calculations of anomalies is 1951-1975 (Archive of Lugina et al. 2006 updated). The annual anomaly for 2014 is +1.5°C. Linear trend estimates are shown for demonstration purposes only. Note the strong systematic increase in spring temperatures enhanced by positive snow cover feedback and the summer temperature increase. This phenomenon is important for extratropical biosphere and has manifested itself only in the past decades.

2.1. Sensitive land surface characteristics to global change

The Arctic, Arctic Ocean shelf, and the Boreal Zone of Eurasia are areas of substantial terrestrial carbon storage (e.g., wetlands, soil, boreal forest, terrestrial and sea shelf permafrost) and powerful carbon-cryosphere interactions and variability that:

a. intertwine with strong climatic (Figure 3) and environmental changes (Figure 4), and
b. can generate positive feedback to Earth System changes via both biogeochemical (changes in atmospheric composition and plant metabolism) and biogeophysical (surface albedo, fresh water budget, and thermohaline circulation of the World Ocean) impacts.

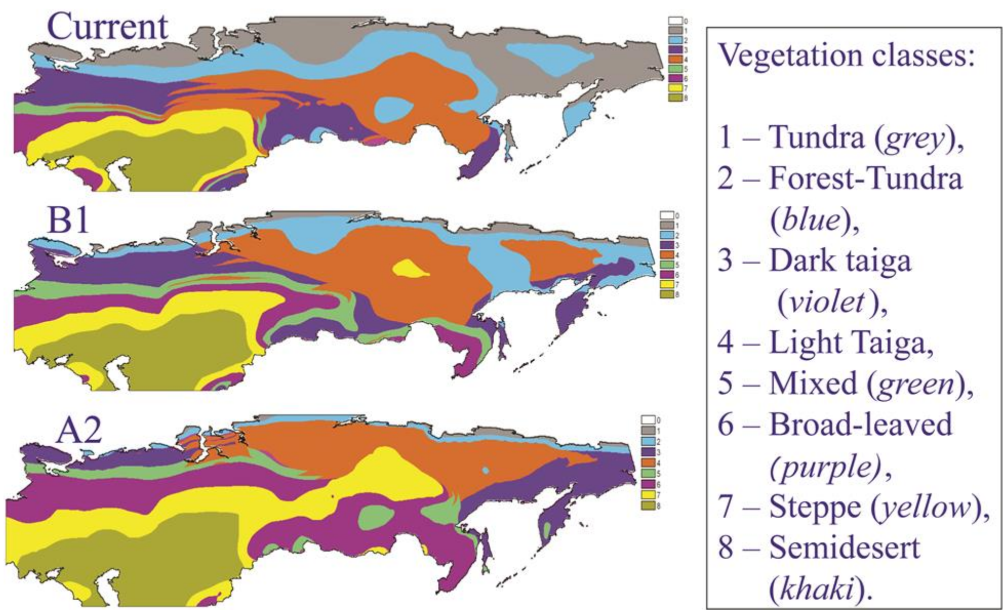

Figure 4. Vegetation distribution under present conditions and equilibrium vegetation distribution under future climate conditions (scenarios) over Northern Eurasia in current climate and by year 2090 calculated by the RuBCliM ecosystem model extended from the SibCliM ecosystem models (Tchebakova et al. 2009, 2010, 2016) using the ensemble of Canadian (CGCM3.1), UK (HadCM3) and French (IPCLCM4) GCM outputs for B1 and A2 scenarios, i.e., for corresponding greenhouse gases induced global warming to 2090 by 3 - 5°C and 6 - 8°C Tchebakova et al. 2016). Changes shown in this figure *question the wisdom of tentative partition of Northern Eurasia into 3 zones (Arctic, boreal and dry zones). These zones can be shifted => within the structure of the future NEFI studies, special attention should be paid to the boundary changes of these zones.*

The first Major Science Question is thus: "How can we quantify and project the ecosystems dynamics in Northern Eurasia that influence the global energy budget when these dynamics:

- ***are internally unstable (e.g., operate within narrow temperature ranges, John et al. 2013; Liu et al 2015, Shuman et al. 2015);***
- ***are interrelated with highly variable components of the cryosphere (seasonal snow cover) and/or are vitally controlled by components that have been systematically changing (e.g., glaciers and permafrost); and,***
- ***have a potential to impact the Global Earth system with unprecedented rates of change over few decades due to, for example, catastrophic forest fires (Conard et al. 2002; Goldammer 2013), dust storms (Goudie and Middleton 1992; Sokolik 2013), and controversial future methane release from frozen ground in high latitudinal land and shelf areas (Kirschke et al. 2013; Shakhova et al. 2013, 2015)?"***

2.2. Dry Latitudinal Belt of Northern Eurasia

The interior of the World's largest continent is mostly cut off from the water vapor transport from the tropics by mountain ridges and plateaus spread across the central regions of Asia, thereby creating the Dry Latitudinal Belt of Northern Eurasia (DLB; shown in Figure 1), the largest dry area in the extratropics. The DLB may expand northward (cf., Shuman et al. 2015; Figure 4) as it has done in past millennia (Chen et al. 2008, 2010; Kozharinov and Borisov 2013). Parts of the DLB are quite densely populated (e.g., Northern China, Central Asia) and have fertile land (e.g., black soils in Ukraine and European Russia both providing substantial grain export to the global market). However, the DLB has physical limitations: (a) it has very limited fresh water supply which is highly dependent upon irregular extra-tropical cyclones (mostly from the North Atlantic) and a shrinking regional cryosphere; (b) increases in evapotranspiration from increases in warm season temperatures and expansions of the growing season in DLB are generally not compensated by precipitation increase; and (c) changes in spatio-temporal shifts in precipitation pattern increase the probability of various unusual (extreme) events affecting the livelihoods of regional societies and their interactions with the global economy (e.g., Henebry et al. 2013; Chen et al. 2015a). This region is a source of dust storms that can adversely impact the environment, climate, and human well-being.

The second Major Science Question is thus: "What are the major drivers of the ongoing and future changes in the water cycles of Northern Eurasia and how will their changes affect regional ecosystems and societies, and feedback to the Earth system and global economy?"

2.3. Evolving social institutions and economies

Institutional changes in Northern Eurasia in the past decades have led to large changes in the socio-economic fabric of societies in the region, affecting land use and the natural environment, and resulting in emerging challenges, including:

- The transitions from command-driven to market-driven economies in the countries of Northern Eurasia, which have occurred at different rates and societal costs, and created unexpected economic and environmental opportunities and problems (Bergen et al. 2013). This is the case especially in the newly independent states of the former Soviet Union, Mongolia, Eastern Europe and also to some extent in China. Concomitant environmental changes and problems include massive agricultural land abandonment (Alcantara et al. 2013, Griffiths et al. 2013; Wright et al. 2012), inefficient and illegal forest logging (Kuemmerle et al. 2009; Knorn et al. 2012), degradation of cultivated lands (cf., Ioffe et al. 2012; Chen et al. 2015a,b), and spread of human-induced fires (Soja et al. 2007). As a result, many of these outcomes became important concerns with policy implications at the national and intergovernmental levels.
- The countries of Northern Eurasia with 'transitional' economies are playing an increasingly important role in the World Economic system. However, they are now facing an imperative challenge to find their places in highly competitive economic conditions under additional stresses of climatic, environmental, and internal societal changes. For countries with resource-rich lands and low populations, their development is expected to be dependent on natural resources ranging from forests and forestry to oil/gas to agriculture and hydropower (Bergen et al. 2013). Other countries (e.g., Asian countries such as China and Japan) with very large populations and strained resources may be strong consumers of natural resources from elsewhere in Northern Eurasia.

The third Major Science Question is thus: "How can the sustainable development of societies of Northern Eurasia be secured in the near future by overcoming the 'transitional' nature of their economics, environmental and climatic change challenges, and by untying restrictive institutional legacies?"

Considering the triad "climate - environmental impacts – socio-economic impacts", NEESPI is currently sufficiently covering regional climate diagnostics and, to a somewhat lesser extent, diagnostics of environmental and ecosystem characteristics. However, the socio-economic impacts of variability and/or systematic changes in climate and environmental variables are still poorly covered. This makes it difficult to effectively plan future (and to accurately interpret already performed) model experiments. These model-based projections of climate and environmental changes still have to be attributed to and associated with the mid-term and long-term strategies for the development of different sectors of the economy, such as transport, fishery, development of the on-shore and off-shore structures, etc.

3. Major Research Foci: Why do they matter?

During the past 20 months, the direction of future research over Northern Eurasia have been discussed in light of the new information gained from past NEESPI activities and the unique features of Northern Eurasia of global concern. Nine major research foci have been identified for potential future NEFI work (listed in no specific order):

1. **Global change, particularly the warming of the Arctic;**
2. **Increasing frequency and intensity of extremes (e.g., intense rains, floods, droughts, wildfires) and changes in the spatial and temporal distributions of inclement weather conditions (e.g., heavy wet snowfalls, freezing rains, untimely thaws and peak streamflows);**
3. **Retreat of the cryosphere (snow cover, sea ice, glaciers, and permafrost);**
4. **Changes in the terrestrial water cycle (quantity and quality of water supply available for societal needs);**
5. **Changes in the biosphere (e.g., ecosystem shifts, changes in the carbon cycle, phenology, land-cover degradation and dust storms);**
6. **Pressures on agriculture and pastoral production (growing supply demand, changes in land use, water available for irrigation, and food-energy-water security);**
7. **Changes in infrastructure (roads, new routes, construction codes, air, water, and soil pollution, and strategic planning);**
8. **Societal actions to mitigate the negative consequences of the environmental change and to benefit from the positive consequences; and**
9. **Quantification of the role of Northern Eurasia in the global Earth and socioeconomic systems to advance research tools with an emphasis on observations and models.**

Socio-economic research challenges are the top priority for several of these foci.

These challenges have not been overlooked in the past but simply have not been addressed to satisfaction worldwide and the introduction of the Future Earth research objectives has been a reaction to this gap. Thus, there is an urgent need to incorporate socio-economic studies into NEESPI by aiming to link the achievements of climate and environmental analyses (both diagnostic and model-based) with the requirements for the regional infrastructure which can only be derived from the detailed treatment of socio-economic conditions. We are establishing this strategy as the foundation for the Northern Eurasia Future Initiative (NEFI) and are expecting that it will bridge climate and environmental studies with the economic consequences of the observed changes, providing the synergy between them and spurring the advances of physical sciences in quantifying observed and projected climate and environmental changes and the advances of the economic analyses and impacts. This new strategy will directly benefit many stakeholders and end-users. It will provide them with recommendations and assessments going far beyond those based exclusively on the analysis of climate and environmental variables. It will also provide them with a new suite of modeling tools and new data sets to enable much better and smarter decision making. Furthermore, this strategy will provide a strong feedback on further planning of climate and environmental studies, pointing to the parameters, phenomena and mechanisms which, so far, were not studied and quantified to a full extent. This will make it possible to revisit and comprehensively review the 10-yr NEESPI legacy in order to transform conventional climate and environmental metrics to those relevant for building more effective economic strategies and risk assessment.

Below, we examine and justify the issues related to these proposed major research foci in more detail and in the next Chapter propose an universal modeling approach that would allow addressing them to perfection (eventually).

3.1. Global Change and the Arctic.

Global changes are ongoing and until the causes of these changes are eliminated or mitigated, there are no expectations that they will slow down (IPCC 2014, Karl et al. 2015; see also Figure 2 and Table 1). Regionally, the temperature changes in Northern Eurasia have been among the largest (Figure 3). However, there are special reasons to list the changes in the Arctic among major concerns for future environmental well-being in the extratropics. This small sliver of the globe (the zone north of 60°N occupies only 7% of the Globe surface) plays an important role in global climate. Its changes in the past decade were unprecedented for the period of instrumental observations (Figure 5, left) and well above the 2°C warming threshold set by the recent United Nations Climate Change Conference (30 November to 12 December 2015, Paris, France).

There are two major consequences of Arctic warming: (a) changes in the Arctic sea ice and (b) changes in the meridional gradient of air temperature. The Arctic has become increasingly closely interlinked with the polar atmosphere with the ongoing retreat and thinning of the sea ice (Figure 5, bottom). The depletion of sea ice increases the heat and water vapor exchange with the atmosphere, especially in the cold season (i.e., from mid-September through early June), affecting weather, climate, and the water cycle across the extratropics and, possibly, over the entire hemisphere (cf., Drozdov 1966; Newson 1973; Groisman et al. 2003, 2013a; ACIA 2005, AMAP 2011; Bulygina et al. 2013). There are direct practical implications for transportation, regional infrastructure development and maintenance, and fisheries (AMAP 2011; Farré et al. 2014; Strategic Assessment of Development of the Arctic 2014; Streletskiy et al. 2015a).

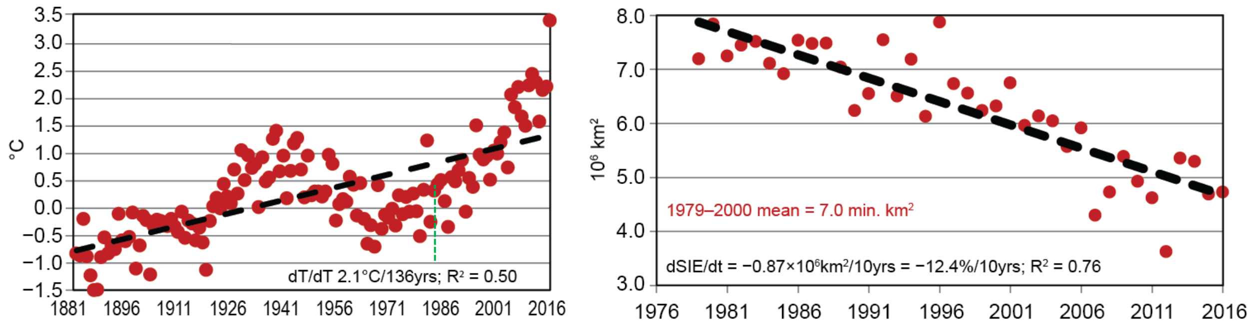

Figure 5. Left. Annual surface air temperature (°C) area-averaged over the 60°N - 90°N latitudinal zone (AMAP 2011, Ch. 1, updated; the first year of the second plot, 1975, is marked by green dotted line). **Right.** September Arctic sea ice extent, SIE, 10^6 km^2 (U.S. National Snow & Ice Data Center, Boulder, Colorado, USA web-site, http://nsidc.org/data).

The Arctic is closely interlinked with the North Atlantic Ocean and together they (a) control (drive), to a large extent, the World Ocean thermohaline circulation providing most of the cold water influx into the deep ocean and (b) define climate of the northern extratropics (especially the regions adjacent to the North Atlantic) due to intense meridional heat and mass exchange in the atmosphere and ocean in the Atlantic Sector of the Arctic and following its transport inside the continents. This exchange creates a strong deviation from the zonal temperature distribution (for example, compare the climate of Edinburgh, Scottland, UK with Churchill, Canada and Yakutsk, Russia). Both of these features of the Arctic are highly volatile. Relatively small deviations of the oceanic salinity and sea ice distribution in the northernmost Atlantic may affect the deep water formation process with adverse global consequences (cf., LeGrande et al. 2006). The ongoing decrease of the meridional temperature gradient in the cold season (Groisman and Soja 2009) may weaken westerlies, causing cold winter outbreaks in the interior of the continent, larger meandering of the cyclone trajectories over the extratropics (cf., Francis and Vavrus 2012), and increasing probability of blocking events (Lupo et al. 1997; Mokhov et al. 2013a, Schubert et al. 2014) that can devastate regional agriculture through the combination of harsh winters and summer heatwaves (Wright et al. 2014).

Future studies within this focus area should be concentrated on (a) enhanced monitoring of changes in the Arctic, and (b) integrated assessments, including Earth System Model (ESM) simulations, of the hemispheric consequences in the energy and water cycles, cryosphere, land cover, economy, and human well-being that are associated with changes in the Arctic.

3.2. Frequency and intensity of extremes

In the past decades, changes in the frequency and intensity of various extreme weather events have been documented in all areas of Northern Eurasia. These events include an increase in intense rainfall and prolonged no-rain periods (summarized in Groisman et al. 2013b; Figure 6; see also Zhai et al. 2014), extraordinary temperature anomalies accompanied by droughts in summer (cf., Barriopedro et al. 2011; Lei 2011; Lupo et al. 2012; Bastos et al. 2014; Horion et al. 2016) and cold outbreaks and/or thaws in winter (ACIA 2005), an increase in the frequency of extensive and intense wildfires (Conard et al. 2002; Soja et al. 2007; Kukavskaya et al. 2013b; Shvidenko and Schepaschenko 2013) and intense dust storms (Xi and Sokolik 2015). Official Russian statistics on “dangerous meteorological phenomena (DMP), which provided significant damage to national economy and vital activity of population" reports seven years of the last decade (2006-2015) as the years with the largest numbers of DMP (from 385 to 467). The impacts of these events often extend far beyond Northern Eurasia sending aftershocks into global markets and raising concerns about global food security (Loboda et al. 2016).

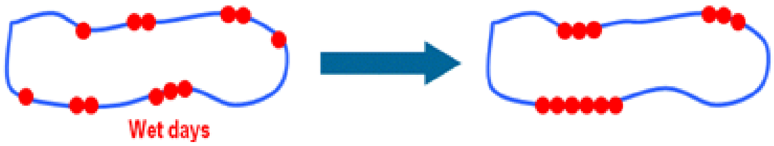

Figure 6. A string of beads with a fixed number of beads illustrates how we can encounter in the same region increases in prolonged Wet Day and Dry Day Periods even with unchanged precipitation totals. The arrow shows a major tendency in the past decades across most of the northern extratropical land areas including Northern Eurasia.

The changes in the spatial and temporal distribution of inclement weather conditions (e.g., heavy wet snowfalls, freezing rains, untimely thaws and peak streamflow) that, while not being extremes *per se*, substantially affect societal well-being and health (e.g., freezing events, Bulygina et al. 2015; Groisman et al. 2016) or indirectly impact the regional water budget (e.g., winter thaws and early snowmelt and the following water deficit for the growing season, Bulygina et al. 2009, 2011; Groisman and Soja 2009). Societal consequences of changes in the frequency and intensity of these extreme events has become an urgent task to address for the entire Earth Science research community. In this regard, it is not enough to report and/or to project changes in characteristics of these events but to help develop of a suite of strategies for resilient responses to new climate conditions that are forthcoming and/or have a higher probability than was previously expected.

Extreme events that affect the biosphere (i.e., disturbances) and their temporal and spatial changes represent a special focus for NEFI studies because they directly affect human well-being. Regardless of whether the disturbance is natural (e.g., fire, outbreaks of insects) or anthropogenic (e.g., logging, agriculture or urban transition of land), the altered landscape interacts with biospheric processes and the climate to maintain ecosystem functioning, diversity and services.

Climate specifics of recent decades accelerate regimes of natural disturbances (Figure 7). For example, the average extent of burnt area during the last 15 years over Russia is estimated from 10-13 x10^6 ha year^{-1} with the post-fire forest mortality rate of 1.76 Mha year^{-1} during the past decade (cf., Krylov et al. 2014; Bartalev et al. 2015). A typical feature of the current fire regime is increasing frequency and severity of mega-fires. These fires may cause the irreversible transformation of the forest environment for the period which exceeds the life cycle of major forest-forming species (Sukhinin 2010, Shvidenko et al. 2011). Mega-fires of the last decade have led up to a twofold increase in the share of crown and peat fires and may last for a long time during the entire warm season. Post-fire dieback in the area of mega-fires as a rule exceeds 50%. A substantial part of post-fire areas may become unsuitable for forest growth for hundreds of years; for instance, such areas in the Russian Far East are estimated to cover tens of million hectares (Shvidenko et al. 2013). Furthermore, the increasing aridity of the climate provokes outbreaks of harmful insects which could envelope large areas (e.g. the outbreak of Siberian silk worm enveloped an area of about 10 x10^6 ha in 2010). Human- and climate-induced change in disturbance regimes is currently acting in-concert to force ecosystems to move more quickly towards a new equilibrium with the climate (Soja et al. 2007).

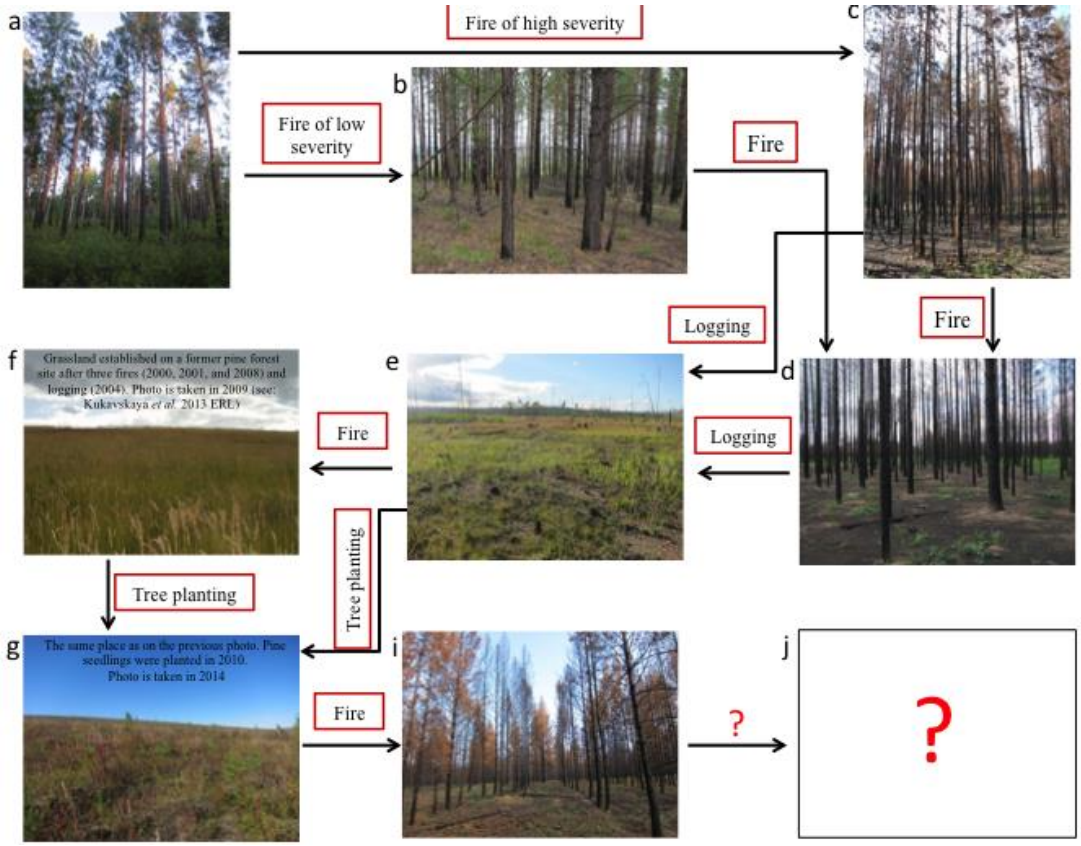

Figure 7. Typical fire-induced forest transformations in the light-coniferous forests of southern Siberia: (a) unburned forest; (b) forest burned by low-severity fire with the majority of trees survived; (c) forest burned by high-severity fire with the majority of trees died; (d) forest repeatedly burned with almost all organic layer consumed; (e) logging after tree mortality; (f) proliferation of tall grasses on the open site repeatedly burned and logged; (g) plantation of the Scots pine on the site repeatedly disturbed with no regeneration; (i) burned plantation; (j) the "question" marks mean that the future of the forests in the region would greatly depend on the actions people undertake (Archive of Kukavskaya et al. 2013a, 2015).

Wildfires in boreal regions play a double-facet role. In remote unmanaged forests fire is a natural regulator needed for maintaining ecosystem functioning, productivity and health. In the south, fire provides the most dangerous threat to forest ecosystems. Even though wildfire is largely an integral natural process that interacts with weather and climate to maintain existent landscape–scale ecosystems, human- and climate-induced change is altering fire regimes and the dependent mosaic pattern of ecosystems. This is significant because the boreal forests hold the largest reservoir of terrestrial carbon (Pan et al. 2011, Gauthier et al. 2015), making their impacts on global carbon cycle particularly significant. Two-thirds of the boreal forests are located in Russia constituting about 20% of the world's forest. During the extreme fire seasons, fires adversely affect human health and serve as an interface between the biosphere, atmosphere and climate systems by affecting carbon balances, hydrologic regimes, modifying patterns of clouds and precipitation, permafrost structure, and radiative forcing by changing surface and planetary albedo, both directly (i.e. vegetation change due to younger and more reflective species; black carbon deposition on snow/ice) and indirectly (i.e. precipitation change due to changes in cloud condensation nuclei).

Under the control of weather and climate, fire is an important driving force of ecosystem change (van der Werf et al. 2010; Giglio et al. 2013); however, climate (temperature and precipitation) holds the ultimate key to altering boreal ecosystems (Shuman and Shugart 2009). Under current climate change scenarios, it is predicted that boreal fire frequency and area burned are expected to increase by 25-50% (cf., Flannigan et al., 2000, 2013). Other predictions report even much larger numbers to 300 - 400% (Shvidenko and Schepaschenko 2013, Abbot et al. 2016). The length of the growing and fire seasons are predicted to increase by up to 50 days (mean estimates are around 30 days), and fire weather severity is predicted to increase by 50%. Climate model sensitivity experiments (cf., Ward et al. 2012) show that the net radiative forcing of the climate system due to fires in the year 2000 has been negative -0.55 Wm^{-2} and is expected to become even more negative (-0.85 Wm^{-2}) by 2100.

Severe fire events are increasingly becoming the new normal across Russia. In the past 15 years, extreme fires have been reported across nearly all large geographic regions, including very remote zones (e.g. Yakutia in 2002) and densely populated regions (European Russia in 2010). Fire weather (temperature, precipitation, relative humidity and wind speed) in recent decades (2003-2012) is much more dangerous than in an earlier decade (1984-1993). In 2008, emissions from early season extreme agricultural/clearing fires in Kazakhstan, Transbaikalie and Amur Oblast' were observed in the Arctic, where this early season deposition would result in more rapid snow and ice melting further altering albedo impacts of the ice sheet (Warneke et al. 2009). In 2010, the Moscow region experienced record drought and the hottest summer in Russian recorded history (42°C), which resulted in extreme fires that burned in previously drained peatlands. This lethal combination of natural and human forcings resulted in monetary losses of 3.6×10^9 $US (by other estimates up to 10×10^9 $US) and the deaths of 56,000 people (excess mortality rate). Furthermore, Flannigan et al. (2013) predicted that for Northern Eurasia cumulative fire severity would increase by three times and fire season length could increase by 20 days by 2091.

There is already evidence of climate-induced forest changes in some parts of Northern Eurasia (Soja *et al.* 2007; Groisman and Gutman 2013; Shvidenko and Schepaschenko 2013) with southern regions being particularly vulnerable to climate change and fires (Malevsky-Malevich et al. 2008). Repeated fires resulted in substantial decreases in fuel loads and led to soil erosion, overheating, absence of nearby seed sources, proliferation of tall grasses, and, as a result, lack of natural postfire regeneration of forests and their conversion to steppe vegetation (Kukavskaya et al. 2015). There is an urgent need for planning adaptive forestry and fire management activities designed specifically for the regions that take into account trends in conditions and local features of the area (climatic, forest-vegetation, social, technical, and economic).

Using remotely sensed data, we can monitor the rate of disturbance change, however assessing fire severity and depth of burn requires boots and eyes on the ground. The relationships that link fire weather to fire characteristics such as severity, depth-of-burn, type (crown, surface), and the dependent availability of fuels, which is ecosystem dependent, is largely unquantified. These data and information govern the amount of emissions and the injection height of smoke, which directly influences transport and feedbacks to air quality and climate. Improvements in understanding these physical interconnected processes are required to better characterize fire in integrated models.

Future studies within this focus should be concentrated on (a) risk assessments based upon the projections of changes in the probabilities of each type of extreme event and disturbance over Northern Eurasia; (b) development of new protection strategies against wildfires and hydrological extremes; and (c) transition to adaptive forest and agricultural land management within the paradigm of sustainable management of regional ecosystems on a landscape-ecosystem basis.

3.3. Retreat of the cryosphere

In the last 30-40 years, observations indicate a warming of permafrost in many northern regions with a resulting degradation of ice-rich and carbon-rich permafrost. Increases of permafrost temperatures observed in Northern Eurasia, Canada, and Alaska have resulted in the thawing of permafrost in natural, undisturbed conditions in areas close to the southern boundary of the permafrost zone (Romanovsky et al. 2010a). Most of the permafrost observatories in Northern Eurasia show its substantial warming since the 1980s. The magnitude of warming has varied with location, but was typically from 0.5 to 3°C. The close proximity of the exceptionally ice-rich soil horizons to the ground surface, which is typical for the arctic tundra biome, makes tundra surfaces extremely sensitive to the natural and human-made changes that resulted in the development of processes such as thermokarst, thermal erosion, and retrogressive thaw slumps that strongly affect the stability of ecosystems and infrastructure. A main aim of the future NEFI efforts related to cryosphere is to evaluate the vulnerability of permafrost under climate warming across the permafrost regions of the northern and high-elevation Eurasia with respect to ecosystems stability, infrastructure, and socioeconomic impact. A second aim is to estimate the volume of newly thawed soils, which could be potential source or sink of additional amount of carbon in the Earth System.

The cryosphere retreat has a continent-wide spatial scale with temporal scales that vary from the millennia to century for glaciers and permafrost to seasonal for snow cover extent (Shahgedanova et al. 2010, 2012, 2014; ; Aizen et al. 2007; Bulygina et al. 2011; Gutman and Reissell, 2011; Sorg et al. 2012; Chen et al. 2013; Groisman and Gutman, 2013; Nosenko et al. 2013; Khromova et al. 2014; Blunden and Arndt 2015; Farinotti et al. 2015; Syromyatina et al. 2014, 2015; Fausto et al. 2016). This retreat affects:

- the continental energy balance changes due to surface albedo decrease, increasing heat flux into the upper surface layers, earlier spring onsets and longer growing seasons;
- depletion of the continental water storage accumulated during the past millennia in ground ice with the subsequent desiccation of lands that rely upon water supply from glacial melt and permafrost thaw; and
- large-scale biosphere changes (cf., Figure 4) that are especially prominent in the regions where cryosphere was intrinsically linked with the survival/dominance of major species within biomes (e.g., larch forest over the permafrost areas in northern Asia).

The Global Terrestrial Observing System (GTOS) has identified permafrost as one of the key indicators of climate change (WMO, 1997) and initiated permafrost monitoring through the Global Terrestrial Network for Permafrost (GTN-P). The GTN-P was established in 1999 to provide long-term field observations of the active layer and permafrost thermal state, http://www.gtnp.org). Permafrost measurements are particularly important for determining the long-term terrestrial response to surface climate change. Permafrost monitoring for climate change includes measurements of temperature profiles in perennially frozen ground and of the thickness and temperature of the overlying active layer (seasonally thawing and freezing soil). For these purposes, a sufficient number of permafrost sites are required to monitor variations in active layer conditions and ground temperatures near the surface and in deep boreholes in major permafrost regions of the world. For the further development of the GTN-P, it is recommended to continue expanding the Northern Eurasian permafrost network, to equip existing boreholes with modern sensors and loggers, and to establish new sites (without borehole drilling) for monitoring the near-surface ground temperature regime at different altitudes and landscapes. A database should be developed and continually improved by combining the collection and analysis of long-term instrumental observational data with data on the spatial distribution of permafrost, ground ice, and glaciation.

During the NEESPI studies of the past decade, the cryosphere retreat and its major manifestations were documented (Figure 8) and it was shown that this process plays a critical role in environmental changes over Northern Eurasia.

Future studies within this focus should be concentrated on further analyses of the consequences of this retreat for the environmental stability and social well-being across Northern Eurasia, particularly in highland areas.

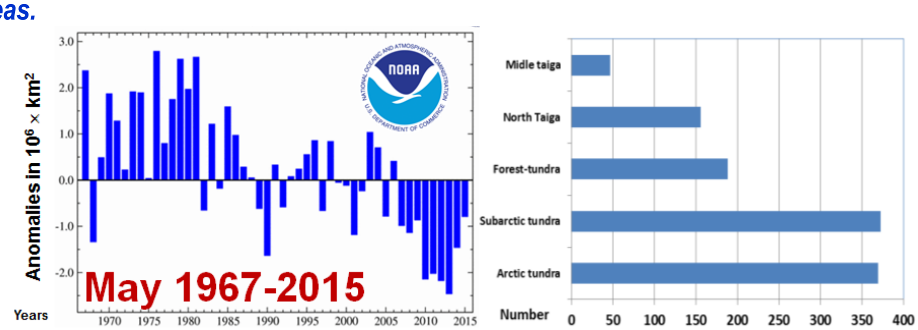

Figure 8. Manifestations of the cryosphere retreat: **(left)** Spring snow cover extent anomalies over Eurasia; **(center)** Number of newly emerging thermokarst lakes in West Siberia during the 1973-2013 period (Polishchuk et al. 2015); **(right)** Altai Mountains on the boundary of Russia, China, and Mongolia; Kozlov glacier change from 1906 to 2013 (Syromyatina et al. 2015).

3.4. Changes in the terrestrial water cycle

Mountains cut off Northern Eurasia from the major sources of water supply in the tropics. Even in the regions of “sufficient” moisture, this sufficiency is secured not by an abundance of water, but rather by suppressed evapotranspiration during the lengthy cold season, soil insulation from the atmosphere by seasonal snow cover, and by external water supply from the cryosphere storage. The rest of the water is provided through unstable atmospheric circulation (e.g., cyclones). Changes caused by global warming decrease and/or redistribute water supply from the cryosphere, increase the vegetation period, and affect the water vapor transport from the oceans into the continent interiors where both absolute changes and variation in the water vapor transport matter. Both natural ecosystems and human activities rely upon the stability of the water supply. Looming changes include: (a) depletion of relatively stable water sources (cryosphere; cf., Khromova et al. 2014), (b) an already unstable water source (atmospheric circulation) becoming even more variable (cf., Schubert et al. 2014), and (c) a longer and warmer period for vegetation growth ("greening") increasing the biospheric water demand (cf., Park et al. 2016). Given these, it becomes clear that changes in the terrestrial water cycle across Northern Eurasia can adversely affect the well-being of local societies as well as the world economy.

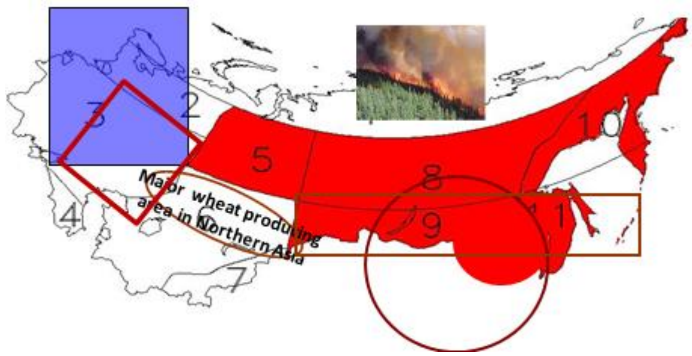

Figure 9. Changes in the surface water cycle over Northern Eurasia that have been statistically significant in the 20th century; areas with more humid conditions (**blue**), with more dry conditions (**red**), with more agricultural droughts (**circled**), and with more prolonged dry episodes (**rectangles**) (Groisman et al. 2009, updated).

There is ample evidence of changes in the terrestrial water cycle across Northern Eurasia (cf., AMAP 2011; IPCC 2014; Figure 9), including reduced snow cover (Brown and Robinson 2011), intensifying spring melt (Bulygina et al. 2011), increasing river flow (Shiklomanov and Lammers 2009, 2013; Georgiadi et al. 2011, 2014a,b; Holmes et al. 2015), disappearance of lakes (Smith et al. 2005; Shiklomanov et al. 2013) lengthened ice free period in lakes and rivers (Shiklomanov and Lammers 2014), degradation of permafrost (Streletskiy et al. 2015a), and melting of glaciers (Velicogna and Wahr 2013; Duethmann et al. 2015) among the others.

River flow is an integrated dynamic characteristic connecting numerous environmental processes and their changes aggregated over large areas. River runoff plays a significant role in the fresh-water budget of the Arctic Ocean and water supply especially during low flow seasons (fall-winter). Ocean salinity and sea ice formation are critically affected by river input (Rawlins et al. 2009). Changes in the fresh water flux to the Arctic Ocean can exert significant control over global ocean circulation by affecting the North Atlantic deep water formation with irreversible consequences for Northern Hemisphere climate (Peterson et al. 2002; Rahmstorf 2002; Fichot et al. 2013). Eurasia contributes 74% of the total terrestrial runoff to the Arctic Ocean and the total annual discharge of six large Eurasian rivers increased from 1936 to 2010 by approximately 210 km^3—more than the annual discharge of the Yukon River (Shiklomanov and Lammers 2011), with 2007 having the new historical maximum (Figure 10; Shiklomanov and Lammers 2009; Holmes et al. 2015).

The Northern Eurasian freshwater cycle has been an important focus of ongoing research, and a great deal of work has been carried out to understand the increases in the river discharge to the Arctic Ocean and to identify whether or not the regional hydrological system is accelerating (e.g., Smith et al. 2007; White et al. 2007; Rawlins et al. 2010; Holmes et al. 2013). Although a variety of theories have been put forward, the physical mechanisms driving the observed runoff changes are not yet fully understood. Comprehensive analyses of water balance components (Rawlins et al. 2005, 2010; Serreze et al. 2006; Shiklomanov et al. 2007), human impacts (McClelland et al. 2004; Yang et al. 2004; Adam et al. 2007; Shiklomanov and Lammers 2009), and hydrological modeling experiments (Bowling and Lettenmaier 2010, Troy et al, 2012) have not revealed a clear cause of the observed increase in river discharge. Precipitation in the Eurasian pan-Arctic, which is the most important water balance component for the runoff generation, does not show a significant change to support the observed increasing trend in river flow (Adam and Lettenmaier 2008).

In contrast, the increase in air temperature across the pan-Arctic has been widely and consistently documented (Overland et al. 2014) and it is expected to continue with the higher rates in the future (IPCC 2014). The air temperature rise leads to significant changes in the regional cryosphere including less frozen soil in the winter season, deeper annual thaw propagation in the permafrost zone (deeper active layer) and melting of glaciers. Several local or regional studies have shown the important influence of changes in different cryospheric components including the permafrost thaw (Davydov et al. 2008; Woo 2012; Streletsky et al. 2015), glacier melt (Bennett et al. 2015), frozen ground (Markov 1994, 2003), and river ice on river runoff generation (Gurevich 2009; Shiklomanov and Lammers 2014). But it is not clear from these studies how these locally observed changes will interact among each other and with spatially varying precipitation changes to affect the river flow over the entire region. There is also considerable uncertainty about how these local changes will scale up to regional and continental scale impacts.

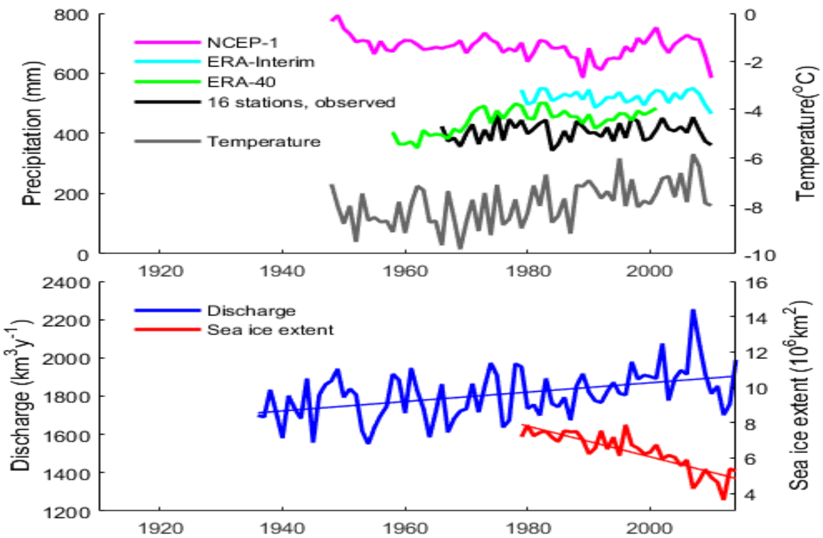

Figure 10. Top panel: Annual precipitation and surface air temperature in Siberia (east of the Ural Mountains, excluding Chukotka) from stations and reanalysis fields. Lower panel: Total annual river discharge to the Arctic Ocean from the six largest rivers in the Eurasian Arctic for the observational period 1936-2014 (Holmes et al. 2015) and annual minimum sea ice extent for 1979-2014.

Terrestrial evaporation and transpiration (evapotranspiration) are the most difficult to project components of the hydrological cycle in Northern Eurasia with few direct observations (see, however, Speranskaya 2011, 2016). Near-surface air temperatures are increasing, and one can expect that the evaporation from wet land surfaces should increase but the near-surface wind speeds have been decreasing in the past several decades (Bulygina et al. 2013) and this may reduce the air-surface water vapor exchange. Furthermore, most of Northern Eurasian land surfaces are not "wet" and a temperature increase does not automatically induce an increase in evaporation, opposite processes may prevail due to evaporation suppression by dry upper soil layer (Golubev et al. 2001). Finally, future ecosystem shifts can dramatically change the vegetation composition (cf., Figure 4) and the transpiration rate of the new communities can induce further nontrivial changes to the regional water cycle. All of the processes above suggest that changes in this component of the hydrological cycle are not trivial and should be assessed within new models that properly account for the interactions among atmosphere, soil, and biosphere. Large-scale geochemical and geophysical runoff changes (biological and inorganic matter transports) also should be accounted for.

Accelerated climate-induced changes in the physical environment significantly impact various human activities and raise the level of concern. Hydrological aspects are particularly relevant because changes in the water level, streamflow, snow, ice, and frozen ground have pronounced effects on local and regional economies and the well-being of the Northern Eurasian residents. In particular, there may be immediate implications for water supply, irrigation, energy production, navigation, land and water transport, and structural engineering. Intensification of the hydrological regime in Northern Eurasia is producing more and more freshwater input to the Arctic Ocean. Such changes in river flux, along with thawing of sea ice, and increasing precipitation over the ocean may exert a significant control over the North Atlantic meridional overturning (thermohaline) circulation with potentially dramatic consequences for climate of the entire Northern Hemisphere. Accordingly, to project possible extreme events and better adapt to ongoing and upcoming environmental changes we should expand our knowledge to better understand these hydrological processes.

The long-term (few decades and more) variability of annual and seasonal runoff of the largest rivers of East-European Great Plain (Volga, Don, Dnieper) and Siberia (Ob', Yenisey, Lena) are one of the main features for their interannual changes (Georgiadi et al. 2014b; Georgiadi and Kashutina 2016). This long-term variability (phases) is interlaced with corresponding air temperature and intensity of zonal air and water vapor transfer changes. The phases' duration can be several decades (up to 90 years for winter and summer-autumn season runoff) and are characterized by significant runoff differences, especially for the Eastern European Rivers. Anthropogenic factors have significantly changed the characteristics of this variability, especially the winter runoff, and transformed their amplitude for "conditionally natural" runoff.

Future studies within this focus should be concentrated on (a) the thorough quantification of ongoing and projected changes in the terrestrial water cycle over Northern Eurasia for the coming decades; (b) understanding and quantification of causes and drivers of these changes through extended monitoring and improved representation of physical processes at different scales in hydrological models; (c) analysis and projection of possible consequences of the changes in the regional water cycle for human societies and infrastructure; and (d) the preemptive development of mitigation measures (infrastructure investments, new technologies in water management and agriculture practices) based upon newly conducted risk assessments related to the plausible future regional water cycle states.

3.5. Changes in the biosphere

In the long term, terrestrial ecosystems establish a dynamic balance with the states of climate, water resources, the lithosphere, and cryosphere. When these four driving forces are changing, the biosphere also begins to change, but it has its own resilience (stability). Numerous negative feedbacks support ecosystem functioning in less than optimal conditions and/or actively resist changes in the near-surface climate to preserve the once-achieved equilibrium, e.g., by the regulation of transpiration, access to otherwise unavailable water resources (e.g., oases), etc. Ongoing climate change already impacts the ecosystems of Northern Eurasia. These impacts are manifold and relate to diverse features of ecosystems state and behavior like health, productivity, resilience, change of natural disturbance regimes, major biogeochemical cycles, among many other (Figure 11).

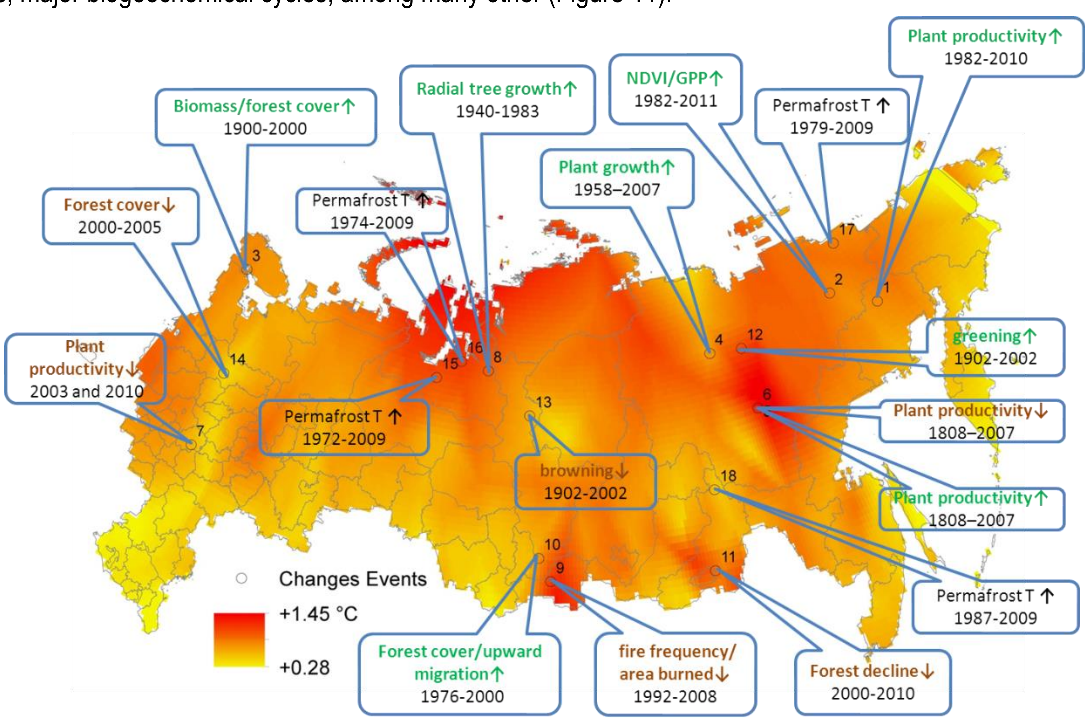

Figure 11. Synthesis of observed climate change impacts on Russian forests. The green (brown) text indicates positive (negative) impacts on vegetation while black text indicates the trend of changes (Schaphoff et al. 2015).

The most visible impacts have been observed in forests as these tree species have a long life span. While productivity of forests at the continental level is increasing during the last decades at a rate of 0.2-0.3% per year due to increasing temperature and lengthening of the growth period, there are large territories with decreasing productivity (Schaphoff et al. 2015) and enhanced mortality of trees mirroring the general picture for the entire boreal belt (Allen et al. 2010). The forests over large territories in different regions of Northern Eurasia are exposed to substantial dryness, particularly those which are dominated by dark coniferous tree species (Shvidenko et al. 2013) as a result of growing water stress and impacts of forest pests and pathogens. Increasing climate aridity has caused the morphological structure of forests to change (Lapenis et al. 2005). High variability of climate and an increase in the frequency and severity of long dry and hot periods (heat waves) impact forest health and the productivity of ecosystems in a clearly negative way (Bastos et al. 2014, Gauthier et al. 2015). Impacts of seasonal weather on net primary production and soil heterotrophic respiration is ecosystem/ soil type and bioclimatic zone specific (Shvidenko and Schepaschenko 2014; Mukhortova et al. 2015).

Influences of climate changes on vegetation are primarily manifested in the alteration of the basic biogeochemical functions of ecosystems and, first of all, the exchange rates of water vapor and carbon dioxide between plant ecosystems and the atmosphere. When ecosystems respond to transformations in ambient temperature and moisture conditions, the response can be both direct and rapid. For example, an increased frequency and duration of droughts result in a transformation of the functional role of wetlands to be a source rather than a sink of CO_2 for the atmosphere.

The global growth of CO_2 in the atmosphere is compensated to a large extent by terrestrial biosphere sequestering 2 to 4 gigatons of carbon every year as known globally from atmospheric composition measurements (Le Quere et al. 2015). The sink, which amounts to less than 4% of global net primary production, is disproportionally allocated to high and mid latitudes of the Northern hemisphere, and largerly to North Eurasia by atmospheric inverse models (Dolman et al. 2012), including those that use atmospheric observations over Siberia (Stephens et al. 2007; Maksyutov et al. 2003; Saeki et al. 2013). Terrestrial biosphere models and long term atmospheric observations (Graven et al. 2013) reveal an increase of biospheric CO_2 seasonal exchange driven by rising temperatures and atmospheric CO_2 concentrations. Maintaining the amount of the carbon sink in Northern Eurasia into the 21st century requires about the same measures as what is needed for sustaining forestry - fire protection and efficient forest management (Shvidenko et al. 2013). In spite of the high level of natural and human-induced disturbances, ecosystems of Northern Eurasia serve as a net sink of carbon of 500-600 Tg C yr^{-1} (Dolman et al. 2012) with about 90% of the sink occurring in forests. However, large areas of disturbed forests, basically on permafrost, have become a carbon source. The process of switching from a carbon sink to a source is driven by the complicated interplay of many natural and anthropogenic drivers (Figure 12).

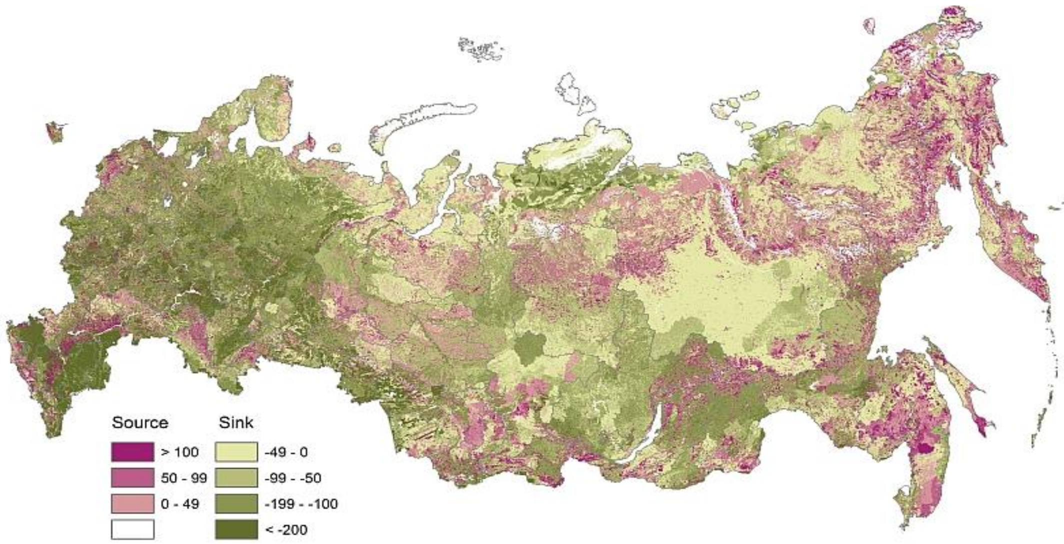

Figure 12. Full carbon account of Russian terrestrial ecosystems (average for 2007-2009). Units of sinks and sources are g C m^{-2} yr^{-1} (Shvidenko and Schepaschenko 2014).

Current models report diverse predictions based on the acceleration of the above processes by future climate change. A particular risk is expected for ecosystems on permafrost. However, many important features of ecosystems at high latitudes are not adequately incorporated in these models. For the permafrost-region in Russia, current estimates indicate that the end-of-the-century release of organic carbon from the Arctic rivers and collapsing coastlines can increase by 75% and the carbon loss via burning may increase fourth-fold. The expected changes of ecosystems in permafrost regions assume forest decline over large territories due to changing hydrological regime and increasing water stress. Still, it is not clear whether northern forest ecosystem would reach a tipping point, but this is very likely under regional warming above 7^{o}C (Gauthier et al. 2015, Schaphoff et al. 2015). Uncertainty of such prediction is high. However, it is very likely that the permafrost region will become a carbon source to the atmosphere by the end of this century, regardless of the warming scenario; although purposeful forest management could substantially slow down this process (Abbot et al. 2016).

Ecosystems in Northern Eurasia are subjected to the direct impact of human activities over the entire continent. In the northern part, this is mostly oil/ gas exploration and extraction, mining, and infrastructure development on permafrost; timber harvesting in the forest zone; and agricultural and pastoral activities in the forest-steppe and steppe zones. The ecological and environmental unfriendly industrial development leads to physical destruction of landscapes, changes of the hydrological regime, and widespread contamination of ai, soil and water.

Logging is an important disturbance factor in many forest areas of Northern Eurasia (Achard et al. 2006, Gauthier et al. 2015). Although the harvest volume in Russia is presently lower than during Soviet times, logging activity has remained high (180-200 x10^6 m^3 commercial wood annually during 2010-2012). Logged sites are usually highly susceptible to fire due to a combination of high fuel loads in leftover debries and accessibility for human-caused ignition (Loboda and Csiszar 2007). These sites typically experience higher severity fires than unlogged forests and, thereafter, fires can spread to the adjacent areas (Ivanov et al. 2011; Kukavskaya et al. 2013a). In the dry lands, clearcut logging accelerates converting from forest or forest-steppe to steppe vegetation. Illegal logging activities that are particularly intensive in boundary regions of North-West of Russia, Siberia and the Russian Far East since the 1990's result in an increase in fire hazard and higher carbon emissions. Throughout the Taiga zone, timber harvesting (Bergen et al. 2008) and human-exacerbated forest fires (Kasischke et al. 1999) are major contributors to change in the biosphere of Northern Eurasia. Forest harvest in Russia as a whole, and in particular in Siberia and the Russian Far East (RFE) has changed over the past fifty years. In terms of harvest rate, high rates characterized the late Soviet era (up to 350×10^6 m^3). After the dissolution of the former Soviet Union, these rates uniformly dropped to less than to 100×10^6 m^3 and only recently have they somewhat increased again (Bergen et al. 2008). The geography of forest harvest has also changed. The early Soviet era saw an emphasis on harvest from Western Russia. Since the 1980s, the greater development of forestry in Siberia and RFE was documented. The latter was spurred by declining western reserves, incentives to establish industry in the eastern reaches of Russia, and agreements with Japan for forestry infrastructure in Siberia/RFE. Most recently, trade has been enormously influenced by increasing demand from China (Figure 13), with the greatest impact on the health and intactness of Siberian forests.

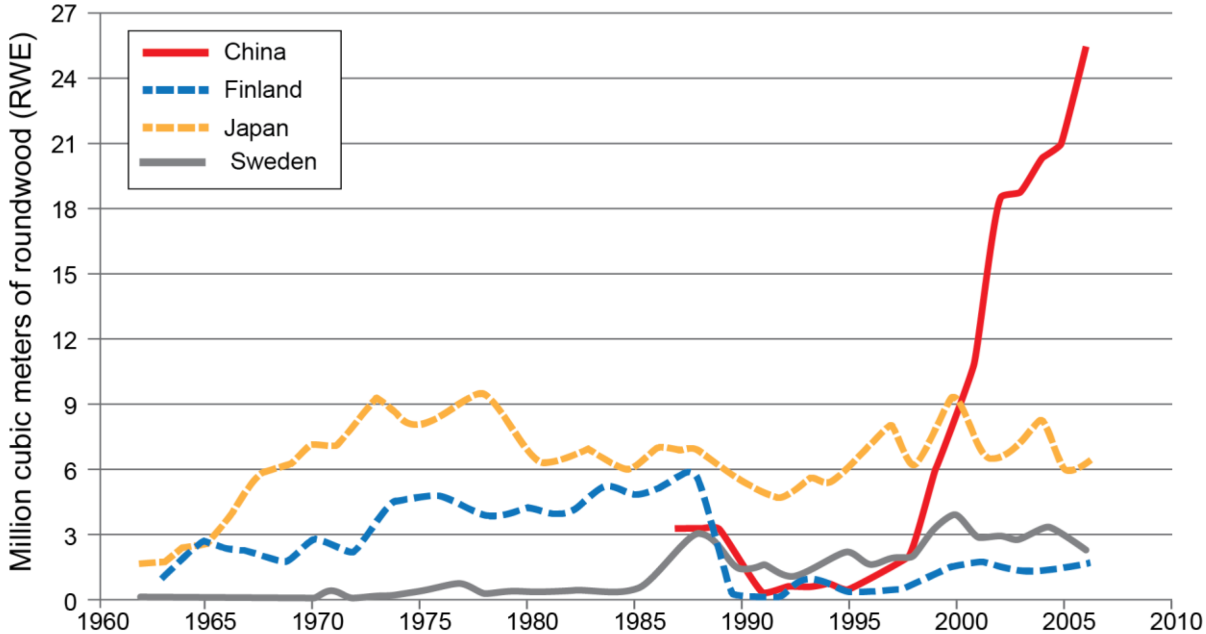

Figure 13. Major export markets for Russian forest products 1960—2009 (archive of Newell and Simeone 2014).

Predictions of the future distribution and state of ecosystems in high latitudes are not consistent (Gustafson et al. 2011a,b; Tchebakova and Parfenova 2012). Study results from the region suggest that modest climate change (with global warming up to 2˚C) are tolerable to maintain current forest structure and biomass, but above this level any sustainability of forest and forest landscapes cannot be provided (Gauthier at al. 2015; Schaphoff et al. 2015). Some models predict substantial shifts of vegetation to the north, and forest steppe and steppe are predicted to be dominant across large southern territories of the forest zone (Schaphoff et al. 2006, Tchebakova and Parfenova 2012). The changes in climatic conditions during the last several decades occurred very rapidly. The response of vegetation cover to changes of climatic variables is usually characterized by significant delay. However, past and current dispersal rates (Udra 1988) are about 10-fold slower than the rate of the predicted climate change. A similar conclusion was reached based on comparison of palynological data and radio-carbon dating in Western Europe (Huntley and Birks 1983) and in the European part of Russia (Velichko 2002; Velichko et al. 2004). It has been shown that under warming during the first half of the Holocene, the expansion rate of the majority of tree species was 200 - 300 m per year and only for pioneer species (birch and aspen) did the rate reach 500 - 1000 m per year. Similar estimates of the expansion rate of the boreal and temperate tree species in the early Holocene (from 100 to 1000 m per year) have been obtained from palynological data (Higgins and Richardson 1999; Tinner and Lotter 2001; Higgins and Harte 2006).

The results of paleoclimatic and paleogeographical reconstructions of the past epochs can be useful (as analogies) for prediction of the possible changes of the vegetation cover due to the projected change of climate conditions in the 21st century. Furthermore, numerous refugia (areas with species that are different from the surrounding dominant ecosystems/populations) provide clues to the boundaries of the past ecosystems and also show the level of their resilience to a changing environment. Many global and regional paleoclimatic reconstructions have been compiled for various warming and cooling periods of the Late Pleistocene and Holocene (Velichko 2002). According to available paleogeographical data, the thermal maximum of the Holocene (about 6-5.5 ka BP) could be considered as an analogue of the climatic conditions for the middle of the 21st century and the optimum of the last Interglacial (Mikulino-Eemian-Sangamon, Stage 5e of the deep-sea oxygen curve, about 125 ka BP) period could be considered as a paleoanalogue for the end of the 21st century (Velichko et al. 2004). Still it is not clear how much dispersal rates may accelerate under climate change, but it is very likely that the southern parts of the forest zone will be under very high risks, and the potential loss or decline of southern taiga forests will not be compensated by increasing forest area beyond the current northern tree line.

Future studies within this focus should be concentrated on

- ***Development of an integrated observing system on environment, land, landscapes and ecosystems, capable for early recognition of changes in terrestrial biota;***
- ***Development of new classes of ecosystem process-based models on the structure, growth, productivity and resilience of vegetation (particularly forests) under global change at different scales and complexities as part of both integrated observing systems and the scientific background for sustainable ecosystem management;***
- ***Development of integrated modelling clusters that would include ecological, social and economic components as inputs to Earth system models that incorporates external forcing, internal Earth System feedbacks, and scenarios of human activities within and beyond Northern Eurasia;***
- ***Development of strategies, technical programs and policy recommendations for sustainable ecosystem management, including adaptation to, and mitigation of, expected climate change.***

3.6. Pressure on agriculture and pastoral production

3.6.1. Land abandonment.

During the past quarter-century, land abandonment is associated with fundamental institutional changes regarding agricultural production and land use across temperate Europe and Asia, caused by the breakup of the Soviet Union in 1991 (Lerman et al. 2004). The loss of guaranteed markets and subsidized production during the Soviet time, particularly in the livestock sector, caused an unprecedented decline in fodder crops production, plummeting livestock numbers (Schierhorn et al. 2013), a decline in grain yields (Trueblood and Arnade 2001) and widespread agricultural land abandonment (Alcantara et al. 2013; Griffiths et al. 2013; Lieskovský et al. 2015). Approximately, 59 Mha of sown areas became abandoned from 1991 to 2000 across the post-Soviet countries with a large portion (33 Mha) in Russia (Figure14). Abandonment rates varied across the countries and were mediated by national and regional settings regarding support of agriculture (Prishchepov et al. 2012) or access to new markets (de Beurs and Ioffe 2014). For instance, one of the lowest rates of abandonment was observed where land reforms were successfully completed in a short period (Poland) or were absent (Belarus). Strong regional differences were also observed within countries. For example, one study (Ioffe et al. 2012) looked at the contrasting situation of Kostroma, an oblast in the north of European Russia and Samara, an oblast in southern European Russia. In the northern oblast, agriculture is now limited and in retreat beyond relatively small scale operations in suburbia, while in Samara agricultural activity now appears to be sustainable, albeit on a somewhat less extensive spatial scale than in the past. In southern Russia where the physical attributes, location, and human capital are best positioned to support agricultural activity (e.g., in The Stravropol' Krai), growth trajectories for agriculture in Russia are currently found. We see evolving specialization of former socialized farms in response to market conditions (in Stavropol' involving the shrinkage of animal husbandry and the release of surplus labor); increased levels of absentee (corporate) ownership of farmland in the more favorable locations; decoupling of the economic fate of large farms (success) from local municipal budgets (deficiency); and the expansion of non-Russian ethnic communities in the countryside (Ioffe et al. 2014).

Dynamics of cultural landscapes in Europe are also characterized by two opposite processes – intensification and extensification (Fjellstad et Dramstad 1999, Bičík et al. 2015). Intensification occurs when cropping intensity or livestock stocking increases on some land and may also be accompanied by abandonment of other, more marginal cropland, pastures, or rangeland. In contrast, extensification occurs when more cropland or pastures are needed so that additional natural lands are converted to agriculture. Land abandonment in Central and Eastern Europe since the 1950´s has resulted from a complex multi-dimensional process with environmental, ecological, economic and social consequences (Kuemmerle et al. 2008, Keenleyside and Tucker 2010). Detailed information about abandoned lands is missing in European national land resource statistics. Multidisciplinary research using Earth Observation platforms, botanical, landscape ecological, and socio-economic assessments should result in new methodologies for identification and classification of abandoned lands linking botanical characterization and satellite-based Land Cover/Land Use (LC/LU) classifications. An extensive Earth Observation dataset comprising both current and historical imagery in selected areas within Eastern and Central Europe creates an empirical base for defining a new LC/LU class and its subclasses related to abandoned lands in the future. Driving forces (physical, social, economic) of land abandonment and their contribution to typology of abandoned lands should be evaluated simultaneously.

After 2000, a partial recultivation of abandoned lands has been observed which is primarily driven by adjustment of agricultural policies and growing prices for agricultural commodities (de Beurs and Ioffe 2014; Estel et al. 2015; Meyfroidt et al. 2016; Smaliychuk et al. 2016). Yet, recultivation rates were leveled off by ongoing agricultural land abandonment; abandonment reached 60 Mha by 2010 (Figure 14). In the temperate zone abandoned fields are often slowly, but steadily encroached by shrubs and forests. By 2010, approximately 5 Mha of new forests were observed on formerly agricultural fields in Eastern Europe cultivated during the Soviet time (Potapov et al. 2015). Abandonment and natural reforestation of agricultural collectives was also observed in 2000 and was ascertained to have started much before the dissolution of the former Soviet Union in case study sites of the more marginal cropped lands in Siberia (Bergen et al. 2008). From 2000 to 2010, grain yields have increased (Trueblood and Arnade 2001; Liefert et al. 2010); however, the application of fertilizers is still far below the Soviet rates, particularly in Russia and Ukraine.

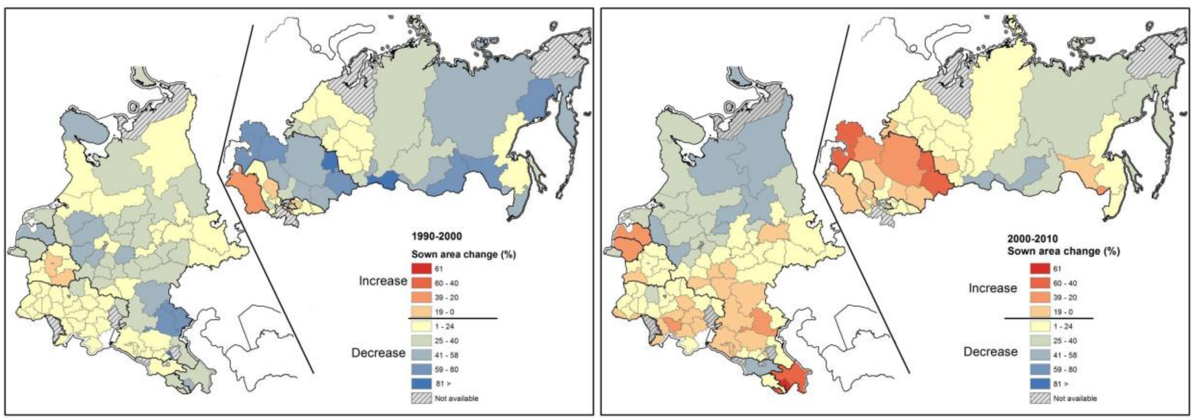

Figure 14. Changes in sown areas across the former Soviet Union (left) from 1990 to 2000 and (right) from 2000 to 2010; areas of abandoned sown areas from 1990 to 2010 are: 40 Mha in Russia; 5.4 Mha in Ukraine; and 13 Mha in Kazakhstan (Prof. Alexander Prishchepov, University of Copengagen, Denmark, Personal communication).

Overall, the abandoned agricultural fields in Eastern Europe and Russia represent a great amenity in terms of the increase of forest cover, becoming a major terrestrial carbon sink for the world during the late 20th and early 21st centuries (Schierhorn et al. 2013; Kurganova et al. 2014, 2015) and provides options for future cropland expansion and biofuel production. However, the future of some abandoned lands is uncertain, due to the fluctuation of prices for agricultural commodities, growing interest in biofuel production and development of national food security programs by the successors of the former Soviet Union. In some post-Soviet countries (e.g., Ukraine), land reforms are not yet completed to this date (2016), which limit recultivations of abandoned lands. Adverse demographic conditions in Eastern Europe with the exodus of rural population (Nikodemus et al. 2005; Prishchepov et al. 2013) and hollowing of the rural areas in China (Liu et al. 2010) may trigger additional land abandonment. The increase of weather extremes represents a real threat for future agricultural production in Northern Eurasia due to limited institutional and economic ability to adapt to changing weather patterns. This may limit the possibility to close existing yield gaps (Dronin and Kirilenko 2010; Lioubimtseva and Henebry 2012; Schierhorn et al. 2014a; Horion et al. 2016). Last but not least, the observed increases in cropping intensity (de Beurs and Ioffe 2014) without adequate application of fertilizers may reduce soil fertility and lead to stagnation of yields. In sum, the region represents a great potential to boost agricultural production (Schierhorn et al. 2014b), but also provide other ecosystem services on abandoned lands. However, climate change and socio-economic and political development may substantially limit such opportunities (Meyfroidt et al. 2016).

3.6.2. Dryland belt of North Eurasia (DLB).

Over the past three decades, the DLB has gone through several major changes that drive regional agricultural and pastoral land changes. First, the regional population has increased at a moderate rate similar to the global population trend but some areas, especially around urban agglomerations in the Asian part of the DLB have increased at a much more rapid rate, resulting in a greater differential pressure on agricultural and pastoral lands (Qi et al. 2012a, b; Kraemer et al. 2015). Second, there was an institutional shift, primarily in the Central Asia region, where the former Soviet Union coordinated resources uses (e.g., food and water), but the newly independent states have disparate natural resource endowments. To balance food security with commodities for export, these new nations have shifted agricultural priorities that has changed regional water demands and subsequently resulted in agricultural abandonment in some places and intensification in others. Both processes (abandonment and intensification) strongly impact the regional carbon budget shifting the C stocks in soils and vegetation. For instance, the total extra C sink in abandoned croplands in Kazakhstan (12.9 Mha) over 1991-2010 is estimated to be nearly 31±2 Mt C yr^{-1}, which could compensate annually for about 49% of the current fossil fuel emissions in this country (Kurganova et al. 2015). Third, most countries within the DLB implemented various reform policies to promote economic growth while improving quality of life. The new governance and policies increased GDPs, but at the same time resulted in shifting food demands, moving towards more processed, high protein animal products, which drive an increase in grasslands-based livestock production.

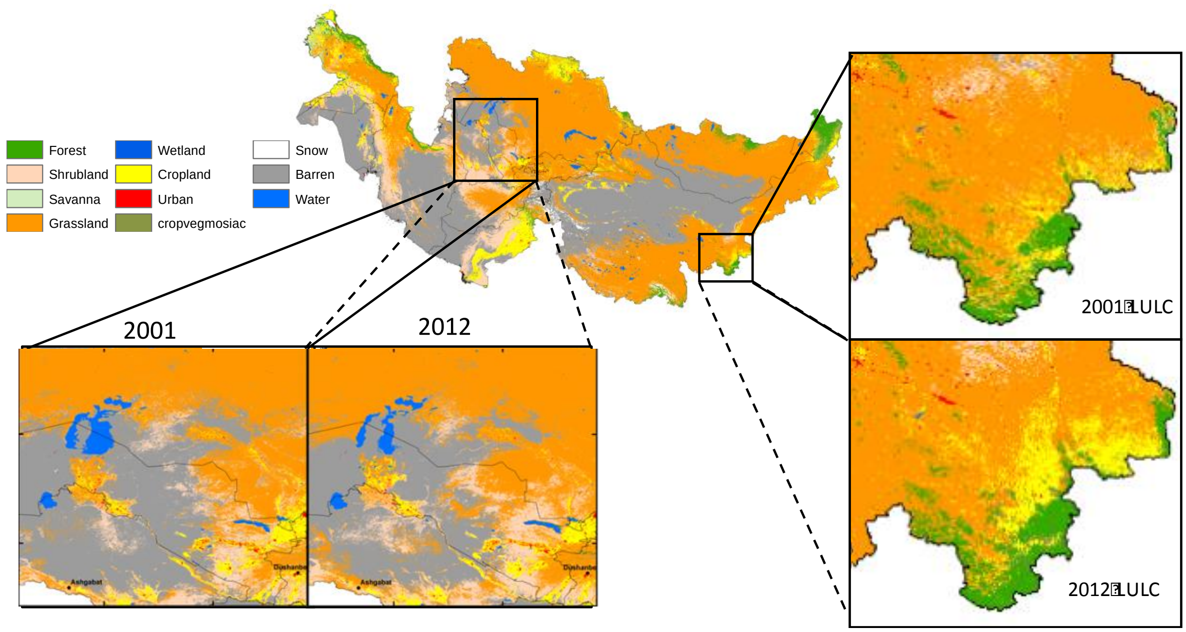

Figure 15. Land use and land cover change in the Asian dryland belt from 2001 to 2012 (Qi et al. 2012a,b, 2016).

A large-scale land-use change analysis of the DLB with MODIS data suggests spatial heterogeneity in land-use change with cropland abandonment (zoomed in details on the left) in the western part and expansion in the east (zoomed in details on the right) driven primarily by shifts in governance and economic development (Figure 15). Therefore, the region has seen an increase in the demand for food quantity and quality on one hand, and a decrease in food production on the other hand, resulting in unbalanced pressures on agricultural and pastoral lands.

Future studies within this focus should be concentrated on (a) assessing agricultural potentials under the multiple constraints of water availability, accessibility, and distribution, (b) balancing the local production and demand, given the shift in diet, to achieve a sustainable strategy to prevent overgrazing and C losses while ensuring sufficient food supplies, and (c) improving regional coordination for efficient resource utilization to account for differential natural resource endowments.

3.6.3. Cryosphere in montane areas of Central Asia.

The mountains and plateaus of Central Asia are a major regional source of fresh water for surface runoff, groundwater recharge, hydropower plants, community water supply, agriculture, urban industry, and wildlife habitat in all countries in the region (Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, Mongolia, Russia and China). Central Asia is included in water-stressed areas where projected climate change could further decrease stream flow and groundwater recharge (IPCC 2007). The ongoing climate warming has already affected the surface and ground ice

of these mountain ecosystems (Jin et al. 2000, 2007; Marchenko et al. 2007; Wu et al. 2013). During the past few decades, most glaciers in Central Asia have substantially thinned and retreated (Sorg et al. 2012; Farinotti et al. 2015; Pieczonca and Bolch 2015). Projections point to a substantial decline in water resources provided by the mountain cryosphere in the near future, but the decline in a particular catchment depends upon the nature of the catchment. Yet, these projections rarely consider mountain permafrost, which may substantially buffer the loss of glacial mass. Permafrost and associated periglacial landforms can store large quantities of fresh water in the form of ice (30-70% by volume, Bolch and Marchenko 2009, e.g., Figure 16).
It is anticipated that under the current climate warming trend in the mountainous DLB, the recession of glaciers in Central Asia will accelerate, leading to a runoff increase in the dry season on a short time scales (from 10 to 50 years). However, on longer time-scales (> 50 years), the crucial dry season glacier runoff will be substantially reduced, as glaciers will lose most or all their ice storage. In the same period, the melt of ground ice (initially trapped and accumulated in the permafrost) could become an increasingly important source of freshwater in the region.

Figure 16. The ice-saturated landforms (rock glacier) in northern Tien Shan, Kazakhstan (left) and ice exposure at the frontal part of a rock glacier (right).

Food security in Central Asia critically depends on the water availability from the mountains, especially given the drying, browning, and brightening trends that characterize the region during the past 15 years (de Beurs et al. 2015). Some parts of High Asia have already experienced water scarcity, imposing a major threat to food production. Some countries started taking practical measures by constructing reservoirs in order to ensure their economic development. These actions would have short-term benefits, but long-term adaptation and mitigation strategies are needed to develop estimates of contemporary and future water resources that will originate from the high mountain cryosphere at the regional scale. These estimates will be used for socio-economic vulnerability assessments of the benefits of local communities whose livelihood depend on the quantity and seasonality of water discharges from the Central Asian mountains with respect to regional and national priorities. This specific objective will require blending geosciences and social sciences to evaluate the role of high-elevation ice storage in permafrost and glaciers for levels of vulnerability and the resilience of mountain ecosystems and the people who live there and downstream.

Future studies within this focus should address the following science and societal questions:

- ***What is the impact of climate change in Northern Eurasia on permafrost dynamics in the mountainous environment in Central Asia (permafrost and ground ice, glacier ice, snow cover) and how does the cryosphere change impact river runoff patterns and downstream freshwater availability?***
- ***What is the volume of subsurface ice that could be a potential source of freshwater and what is the amount of melt water that ice-rich permafrost could contribute to total river runoff in connection with recent climate change across the High Asia?***
- ***What are the feedback mechanisms among glaciers, hydrology, snow cover and ice-rich permafrost in montane areas and how can we detect, quantify, and model these interactions?***

The most important science question for this region is:

- ***How do changes of the mountain cryosphere-controlled regional water resources affect the livelihood and prosperity of local communities in densely populated downstream regions?***

3.7. Changes in infrastructure

3.7.1. High latitudes of Eurasia.

Recent decades show marked social, economic, and institutional change across the circumpolar North. However, socioeconomic changes attributable to drastic political and economic transformations have been most pronounced in the Arctic regions of Northern Eurasia (e.g., Stammler 2005; Forbes et al. 2009; Kumpula et al. 2011; Pelyasov 2011; Hitztaler and Bergen 2013; Andrew 2014). Here, several socioeconomic processes, likely to affect other Arctic regions in the near future, have being functioning as major anthropogenic drivers of environmental change since the 1960s, including migration, urbanization, and industrialization (e.g., Heleniak 2010, 2014). Ongoing and projected climate-induced changes in natural systems will impact the human environment with direct, immediate implications for land use, the economy, subsistence, and social life. Although some climatic changes can be economically beneficial (e.g., decrease in climate severity and associated heating costs, longer navigation season), other changes negatively impact the natural environment, traditional and nontraditional sectors of the economy, and socioeconomic regional conditions. Moreover, the climatic-induced changes in natural environments exert additional pressure on marginal environments of Eurasian Arctic, already stressed by human activities (e.g., Fondahl 1996; Crate 2006; Forbes et al. 2009). For example, infrastructure development and climate change are interacting in complex ways to alter permafrost over large areas of the Eurasian Arctic (Shur and Goering 2009). Communities, urban environments, and industrial infrastructure built on ice-rich soils can be catastrophically affected by thawing permafrost (Streletkiy et al. 2012; Shiklomanov and Streletskiy 2013; Shiklomanov et al. 2016). At the same time, permafrost thawing caused by both climate and infrastructure affects natural landscapes and ecosystems (Raynolds et al. 2014; Khrustalev and Davidova 2007; Khrustalev et al. 2011). Permafrost thawing and its associated impacts on natural and built environments have been identified as priority issues for all regions of the Arctic (Walker and Pierce, 2015). This problem is the most pronounced for the Arctic regions of Northern Eurasia due to unprecedented levels of urban and industrial development.

Complex interactions among a rapidly changing climate and continuously evolving social, economic, and political systems in Northern Eurasia require an integrative approach for studying cumulative effects of infrastructure and climate change on high-latitude social-economic and natural systems. The research should be focused on assessing vulnerability of communities, industries, and ecosystems and aimed at developing adaptation and mitigation strategies and plans for sustainable development of the Arctic infrastructure. Studies of complex interactions among multiple climate- and human-induced drivers of environmental change and their socioeconomic implications conducted in/for the high latitudes of Eurasia, the most complex and dynamic Northern regions, can serve as a basis for developing effective climate mitigation policies and adaptation measures for entire circumpolar north.

Future studies within this focus should be concentrated on: a) Integrative analysis of the cumulative effects of northern infrastructure in the context of both social and natural systems and the implications of climate and socio-economic changes on ecosystem services, residents, and industry; b) Research aimed at developing new construction norms and adequate, economically-viable adaptation and mitigation strategies for northern communities and areas of intensive industrial development in the Eurasian Arctic.

3.7.2. The Taiga and Far East zones.

In the realm of population, infrastructure and forest resource trends, the taiga – especially in the eastern Siberian part, and the Russian Far East (RFE) – has seen particularly dramatic pendulum-like shifts between the late Soviet, early post-Soviet, and the present eras. This time span has also been punctuated by multiple severe fire years and the growing implications of climate change.

Due to State incentives which encouraged its citizens to populate and develop the eastern reaches of the Soviet Union, Siberia's population expanded by 9 million people (23.5 to 32.5 million) between the years 1959 to 1989; similar trends occurred in the RFE. This led to a demographic phenomenon in these peripheral regions in which population growth was a product of migration instead of natural growth, setting the stage for a significant shift in population and resource use patterns in the post-Soviet era (Bergen et al. 2013). Subsequent population out-migration, which pervaded East Siberia and especially the northern RFE beginning in ~1990, has only recently been lessening (Figure 17).

In the forestry sector, during the final three decades of the Soviet era, high rates of timber production in Siberia helped meet a rising demand for forest products in western Russia and also Japan. During that time, official agreements with Japan included payment for the relocation of timber operations to eastern regions (Siberia and RFE). Despite a commitment of the Federal Forest Service to scientific forestry, the on-ground activities of forest harvesting proceeded on a scale often marked by enormous losses and inefficiencies (Shvidenko and Nilsson 1994). These losses occurred in part due to large distances that separated forest markets or industries (primarily western Russia), and the wood supply from each other. Immediately subsequent to political dissolution, in 1991 harvest volumes significantly declined such that by 1994 the total timber harvest was approximately 175 million cubic meters compared to 439 cubic meters in 1989 (Bergen et al. 2013). Net growth did not occur in the forest industry until 2009.

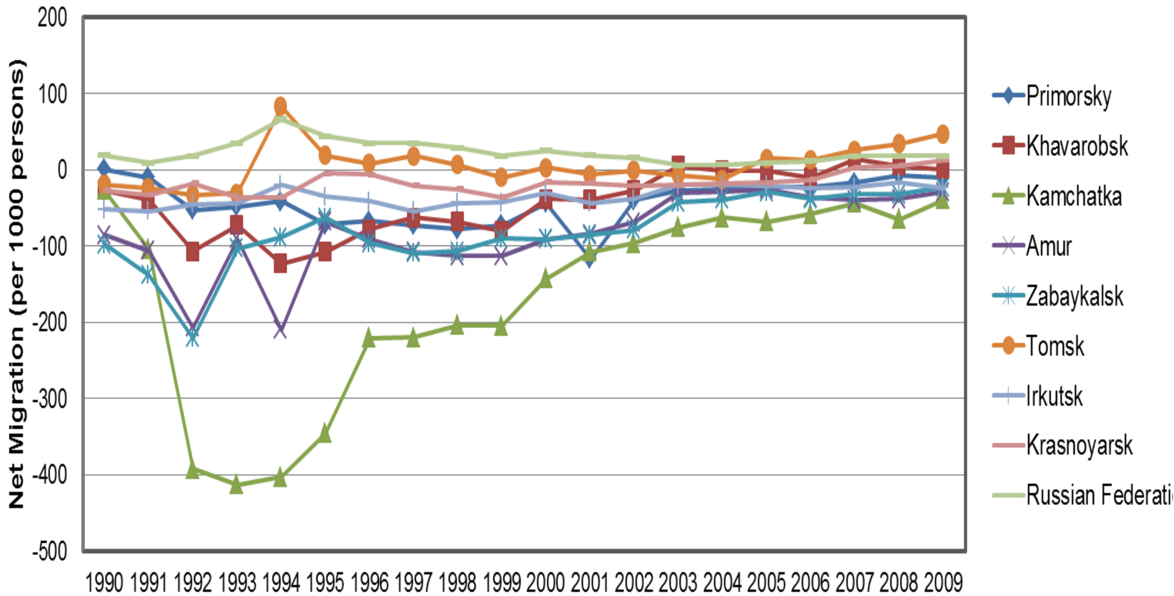

Figure 17. Net population migration 1990-2009 within the Russian Federation and in selected Siberian and Far Eastern provinces (Goskomstat Rossia).

As governance and institutions have regrouped after the early post-Soviet transition era, emerging developments in the forest and energy sectors have begun to come to the fore. The Taiga and Far East zones together comprise part of the world's largest forest, and mapping projects from remote sensing have shown that they contain some of the world's most intact remaining forests (Potapov et al. 2008). It is now recognized that the RFE in particular is home to unique ecosystems and biodiversity (Newell and Wilson 2004). However, forested Northern Eurasian regions of Siberia and the RFE lie adjacent to other Far East countries (China and other Asian nations) having some of the world's highest human population numbers, most far-reaching global-industrial and trade conglomerates, and depleted forest resources (Crowley 2005; Bergen et al. 2013). Thus, in Russia, the geographic location of forest exploitation is shifting to areas that can easily supply and transport logs to the growing Asian market (Newell and Simeone 2014). Although evidence of illegal logging operations surfaced in the early post-Soviet years, this phenomenon is now acknowledged to be significant and growing, despite difficulties in documenting and observing it directly through remote sensing. Several new Russian Forest Codes with their liberalization and decentralization aims have not been able to limit this activity.

It is of significant current economic importance that the Siberian and RFE regions are rich in oil, gas and mineral resources. Within Russia there is likely to be a shift in oil and gas extraction to East Siberia and the RFE as the historic large oil reserves of western Siberia are thought to be approximately 75% tapped (Dienes 2004). The ESPO (Eastern Siberia-Pacific Ocean) pipeline has recently been completed, as has a spur directly into northern China.

Furthermore, Russia sees its energy sector as a central pillar to its re-establishment as a global economic power (Dienes 2004; Hashim 2010) and it is likely that such extraction and associated infrastructure will increase.

Future studies within this region and focus should be concentrated on: a) integrated modeling of forest growth, fire, logging, infrastructure and other human land-use decisions, along with climate, providing the ability to build different combined scenarios based on proximate and underlying drivers; b) new remote sensing approaches – direct or indirect – for observing and monitoring illegal logging, and c) envisioned sustainable futures involving legitimate economic uses of forest and geologic resources which also preserve carbon sinks and biodiversity.

3.7.3. Temperate zone of East Europe.

After the collapse of the Soviet Union and subsequent cessation of the state subsidies for the cultivation of less productive agricultural, large areas of croplands were either abandoned (Alcantara et al. 2012, 2013; Prishchepov et al. 2012) or fallow periods increased (de Beurs and Ioffe 2014). Potapov et al. (2015) reported that 32% of total forest regrowth between 1985 and 2012 was due to afforestation of former agricultural lands. Afforestation of abandoned croplands is likely to have major impacts on carbon budget of the region (Kuemmerle et al. 2011b; Schierhorn et al. 2013). However, afforestation of abandoned croplands is currently not included in the official forestry reports (Potapov et al. 2012), and the legal status of these lands remains uncertain.

Widlfires are uncommon in Eastern Europe and European Russia (Krylov et al. 2014) but anthropogenic fires in agricultural areas, including croplands and pastures, is quite common (Soja et al., 2004; Dubinin et al., 2011), documented in governmental reports as early as the 1980s (Derevyagin, 1987). Romanenkov et al. (2014) noted that a peak of satellite fire detections occurred in cropland areas in Russia, Baltic countries, Belarus, Ukraine, and Kazakhstan directly after the snow melt in the spring (indicating field preparation) and after agricultural harvests in the fall. However, prescribed fire in forests, grasslands, or croplands is either illegal or not reported by national agencies in Lithuania, Belarus, and Russia (Narayan et al. 2007). Agricultural burning is a source of short-lived climate pollutants like black carbon (McCarty et al. 2012).

Climate-smart agricultural systems are resilient to climate change and offer carbon and GHG emissions mitigation potential without compromising on productivity, food security, and the livelihoods of those working in the agricultural sector. Iizumi and Ramankutty (2016) found that statistically significant increases in wheat yields in Ukraine were explained by improved agro-climatic conditions, i.e., warmer and longer growing seasons, and not management strategies. The temperate zone of East Europe will need to invest in climate-smart agriculture techniques to sustain and/or continue improved agricultural yields and livestock production given forecasted climate change.

Ecosystems in Central Europe have been long-term affected by climatic and anthropogenic pressures and amongst them air pollution has been recognized as a key threat for forest ecosystems since the second half of the 20th century. At the end of the 20th century, sulphur and nitrogen depositions in Europe connected with lignite combustion and high concentration of industry reached their highest levels. However, during the past 25 years, the deposition of S has decreased by >80% (Schöpp et al. 2003), with concurrent reductions in NH_3 and NO_x (Kopáček and Posh 2011). The decrease of SO_2 emissions in Czechia has been one of the most pronounced (Vestreng et al. 2007), and is believed to have profound consequences for ecosystem biogeochemistry (Oulehle et al. 2011). This reduction in pollution has to be continued and monitoring of its rates remains an important future task. For example, Norwegian Spruce is a tree species that is sensitive to air pollution. Thus, Norwegian spruce forests in the mountains of Central and Eastern Europe have been selected as exemplary study areas for regional studies of the interaction of climate and socio-economic drivers. One such area is Krusne Hory (Ore Mountains) in western Czechia. Here, several airborne hyperspectral datasets and long-term field observations have been used to monitor changes of Norwegian spruce forest physiological status (Campbell et al. 2004, Mišurec et al. 2016) in a link to soil conditions (Kopačková et al. 2014, 2015). In order to understand the forest response to air pollution, a network of 15 small forested watersheds (GEOMON) was established in 1994 in the Czechia. Since that time, it has provided element budgets that could serve as a testbed for exploration of element cycling on a watershed scale using modern remote and proximal sensing methods (Fottová 1995; Oulehle et al. 2008). The temperate zone of East Europe is a region with heavy anthropogenic impacts on ecosystem services. The monitoring of the ecosystems' status using novel tools and integrated approaches remains an important task, at least, for the next decade.

Future studies within this focus should be concentrated on: a) mapping the intensity of land use more frequently than on a decadal basis; b) in-depth research of the underlying and proximate land-use change drivers and how socio-ecological interactions cause land-cover change; c) regional quantification of the relationships between land-use change and biotic and abiotic processes such as greening/browning, hydrological changes, wildfires and anthropogenic fires, and vector borne diseases; d) assessment of trade-offs between land use and regional ecosystem services revealing optimal strategies for resource and climate-smart agriculture and land use, including shift in diets and agricultural management; and e) impact of wildfires and anthropogenic fires on carbon management, CO_2 emissions, and short-lived climate pollutants.

3.7.4. Central Asia, Mongolia and Northern China.

Along with drastic changes in economics, institution and governance, land use in Central Asia, Mongolia and China of the dryland Asia region includes the improvements of major infrastructures that have facilitated or resulted in the transition of these nations. An obvious one is the region-wide installation of mobile communication facilities that enabled information exchanges for effective and efficient communications. A second major infrastructure improvement is the development transportation networks including aviation, railways and highways across the region that enabled an efficient logistics management, efficient distribution of goods within countries as well as trade across countries.

Future studies within this focus should be concentrated on (a) how these infrastructure changes have facilitated regional food security from both production and consumption perspectives, (b) if and how these major infrastructure changes reduced or escalated socioeconomic disparity at different spatiotemporal scales within and across the states in the region, and (c) what is the infrastructures needed to enable rural communities to improve their well-being aand sustainable livelihoods.

3.8. Societal feedbacks in response to environmental changes

In the distant past, humans reacted to environmental changes passively – they migrated away from environments that became adverse or unsustainable for their well-being. Now, many societies are equipped with tools and resources to withstand the negative consequences of environment change, to some extent. Common approaches to addressing adverse environmental changes include irrigation, construction of dams and dikes, diversion of water streams, large-scale geo-engineering projects (e.g., reforestation), mandatory ecological standards to curb pollution, more effective agronomic practices and robust crops, new construction codes, and the application of ecological expertise to each new large development.

Planning in order to minimize the risks related to the increasing possibility of these changes is also now beginning to be practiced to reduce the adverse impact of disasters and increase resilience of the communities at risk. Implementation of these activities has associated costs and requires careful planning based upon numerical experiments with models that realistically describe processes of environmental changes in all their complexity and interactions. It should also consider the "black swan" nature and disruptive effects of environmental hazards given the uncertainty of the future environment state and the trend of increasing frequency of loss events and damage produced by disasters and creeping environmental crises both globally and regionally (Figure 18; Porfiriev 2001, 2016). The need for a suite of such models is more urgent when the risks of negative consequences of environmental change are higher (Porfiriev 2012, 2013, 2014).

Human activities have been the drivers of certain ongoing environmental changes. It is important to recognize the loop: societal feedbacks in response to these changes may facilitate the recurrence of disasters or cause a second cycle of inadvertent environmental change if the response misses the target or is ill-designed. For instance, reforestation may cause more intense rainfall, dykes may increase flood peaks; curbing industrial development may lessen human well-being and the overall societal resilience. This means that studies of the impact of environmental changes on societies and the development of adaptation and mitigation measures in response to their detrimental consequences should be accompanied by thorough assessments of the "end state" resulting from the environmental changes and the actual and projected societal response to these changes. This can be implemented only by mainstreaming all these kinds of impacts and feedbacks into comprehensive Earth System models (cf., Section 4 of this White Paper).

Future studies within this focus should be concentrated on development of models with direct and explicit social feedbacks.

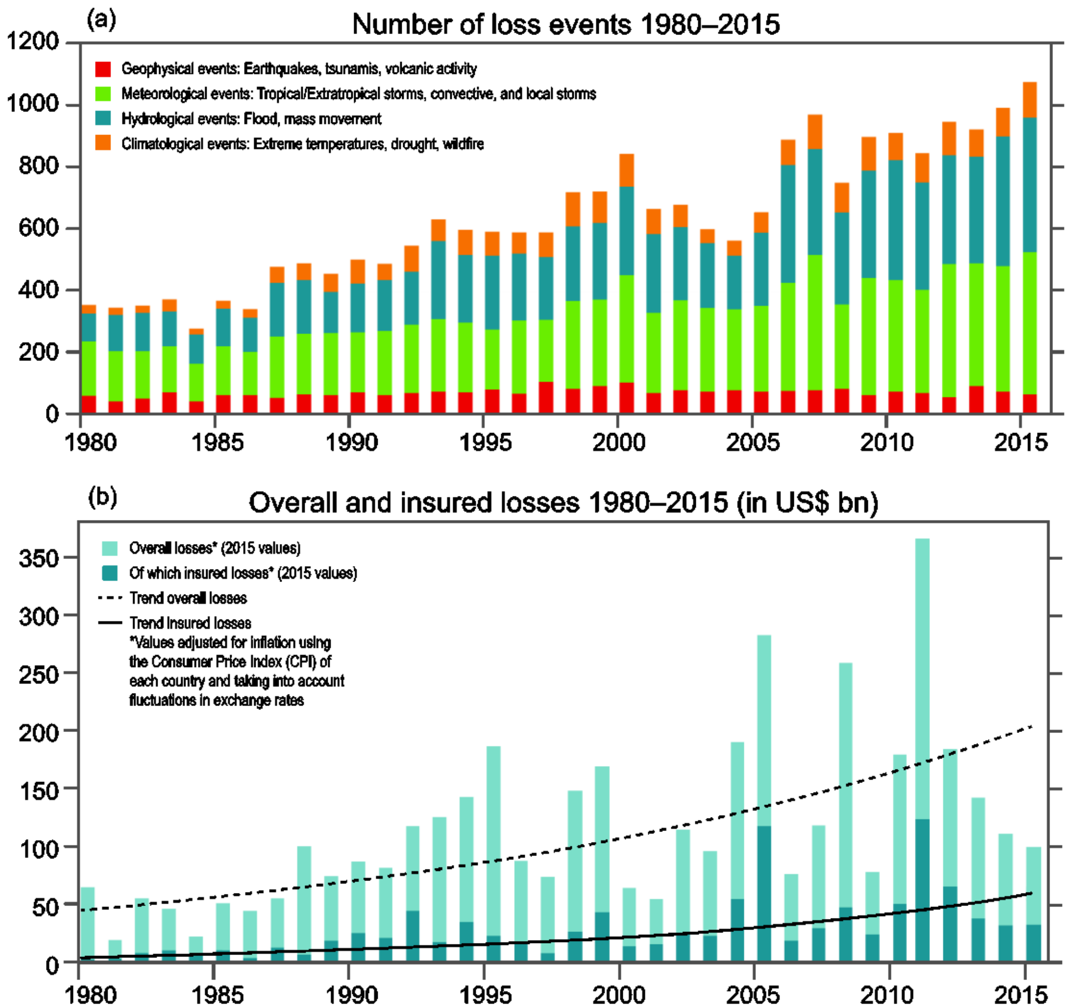

Figure 18. The frequency and damage of the major natural and environmental disasters across the globe. Source: Munich Re-insurance NatCatSERVICE (http://www.munichre.com/en/reinsurance/business/non-life/natcatservice/index.html).

3.9. Role of Northern Eurasia in the global Earth and socioeconomic systems

Being a substantial part of the land surface of the Earth (19%; and 60% of land surface north of 40°N) where climatic and environmental changes were among the largest in the past century and socioeconomic conditions were subjected to dramatic changes that included replacements, degradations, and resurrections, Northern Eurasia is a key part of the Global Earth and socioeconomic systems. In many aspects, changes here presage the rates of global change including global temperature rise (Figure 3); strength of the snow cover - temperature biogeophysical feedback; biogeochemical feedback due to depletion of the surface and upper soil layer carbon and frozen ice storages (Figure 8; Romanovsky et al. 2010a; Schepaschenko et al. 2013; Shakhova et al. 2015); atmospheric dust load from extensive DLB desert areas (Lioubimtseva and Henebry 2009, Sokolik 2013; Sokolik et al. 2013), atmospheric pollution from industrial development (Lu et al. 2010) and from boreal forest fires (Soja et al. 2007). Large areas of natural and anthropogenic land-cover changes are closely related to cryosphere and terrestrial hydrology changes (Tchebakova et al. 2009; Zhang et al. 2011, Mátyás and Sun, 2014; Figures 4 and 19) and human activity (Qi et al. 2012a, b; Chen et al. 2013, 2015a; Horion et al. 2016, Figures 13 and 14).

Future studies within this focus should be concentrated on exploitation of Earth System models (mentioned in the previous Focus and described in Section 4) under different environmental and socioeconomic change scenarios with tracking how changes within the Northern Eurasia domain affect, and are influenced by, changes beyond the Northern Eurasia domain (i.e., teleconnections).

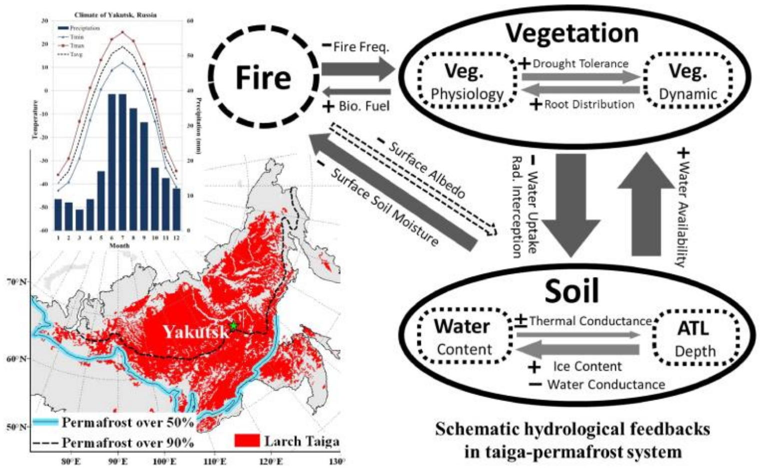

Figure 19. Schematic diagram of feedbacks of soil, vegetation and fire in the Siberian taiga-permafrost system (Zhang et al. 2011).

4. Global Change Modeling for Northern Eurasia

As shown in the previous Sections, Northern Eurasia consists of a variety of complex and dynamic ecosystems that have different time-varying responses to changes in climate and land, water and energy management associated with global change. In turn, these regional ecosystem responses may feedback to affect Earth system processes that will modify how global change evolves in the future and the ability of the Earth system to provide ecosystem services to humans including the provisioning of food, water, fiber, construction materials, and energy. Over the past few decades, a substantial effort has been put toward the development of a variety of models to organize and improve our knowledge of Earth system processes in Northern Eurasia including their interactions and their future responses to global change. In most of these modeling studies, however, global change has been imposed on Northern Eurasia and the regional responses to global change have not had any feedback effects on Earth system processes. More recently, Earth system models have been developed by coupling together models of different Earth system components (e.g., land, ocean, atmosphere) to examine the potential importance of feedbacks among these components on the evolution of global change and the responses of ecosystems, including those in Northern Eurasia, to that change. A parallel effort exists to represent how humans influence the Earth system through the emissions of greenhouse gases, aerosols and land, water and energy management. However, most modeling studies fail to account for how the changes in the Earth system impact these human decisions and their consequences for the environment. For example, future land management should respond to both changes in climate, atmospheric chemistry, and global demand for food, water, fiber, construction materials, and energy, with potential adjustments through global trade. Most recently, integrated assessment models have been developed by coupling Earth system models to economic models that allow economic decisions to respond to changing environmental conditions to support mitigation and adaptation efforts.

Because there is imperfect knowledge of regional and global Earth system processes, and economic behaviors, a variety of modeling approaches have been used to simulate these processes and behaviors using a large number of different assumptions. As a result, there is considerable uncertainty in the projections of global change effects on ecosystems in Northern Eurasia and the relative importance of this region on Earth system processes. Below, we first review a few important general modeling approaches that have been applied to study Earth system dynamics in Northern Eurasia to better understand this uncertainty (Section 4.1). Next, we review the various Earth system components that have been modeled in Northern Eurasia (Section 4.2) and then describe the potential benefits and limitations of Earth system models (Section 4.3) and integrated assessment models (Section 4.4) for improving our knowledge of the role of Northern Eurasia on Earth system dynamics. Finally, we discuss how modeling may help to gain insights about new issues emerging in the region as a result of global change and address questions of uncertainty in future projections (Section 4.5).

This work is still ongoing and the Section, while highlighting past achievements and progress will lay down the pathways toward a suite of Earth System models for Northern Eurasia. This suite and its applications should be the major output of NEFI. With these modeling resources, NEFI researchers can serve, interact, and provide guidance to decision makers in their joint goal to secure sustainable and prosperous development of the societies in Northern Eurasia and around the World.

4.1. What are models?

Two major classes of models can be identified: 1) *Empirical* models that are based solely on observed data without fully describing the system; and 2) *Process-based* models that focus on simulating detailed processes that explicitly describe the behavior of a system. Both types of models come with numerous advantages and limitations.

Empirical models can be expertly calibrated to reproduce past and current behavior of the system when sufficient observational datasets are available to derive robust statistical relationships. A major limitation of empirical models relates to their applicability to studies using out-of-sample conditions, when an extrapolation of their statistical relationships outside of the conditions used to calibrate the model is necessary. As a result, using empirical models for future climate change impact studies, when conditions are likely to diverge from the past, is problematic. Empirical models calibrated to specific regions or specific components of a system with unique properties are generally not extendable to other regions or components with different properties and are limited in their application to specific regions where abundant observations are available. For example, empirical models of crop yield (often referred to as econometric models) are crop-specific and have been extensively used in studies focusing on the United States (Lobell and Asner, 2003; Schlenker and Roberts, 2009; Sue Wing et al., 2015) but less so over Northern Eurasia. While empirical models may be very good for representing relationships in a system, these models do not explain why such relationships exist.

Unlike empirical models, process-based models aim to explicitly represent mechanisms and processes to control the behavior of a system, and the influence of external environmental factors. As a result, process-based models can better represent responses to evolving future conditions. They are also particularly well suited for uncertainty analysis when large simulation ensembles where parameters are systematically perturbed are used to better understand the response of a system to a particular change in input. With increasing computing powers, such experiments are becoming more widespread. In addition, processed-based models are often used to estimate the behavior of a system where observational datasets are scarce or non-existent, such as gap-filling or re-analysis datasets. However, because there is often a lack of consensus on the underlying theory to describe a specific process, process-based models can behave similarly under contemporary conditions but substantially diverge under future conditions.

Furthermore, process-based models can suffer from significant biases due to the large number of parameters used to represent complex interactions. 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. As a result, most models use a hybrid approach that combines both process-based and empirical methods. In addition, a comparison between empirical and process-based models could ensure that process-based models reproduce the relationship observed and. in turn, be used to test why these relationship exist.

Two approaches have been used to address the level of detail, both in terms of complexity and scale, in a model: 1) *Agent-based models* simulate individual agents of a system in order to assess the behavior of the system as a whole; and 2) *Systems models* focus on the interactions among the various components of a system, with a simplified representation of each component, often assumed to be homogeneous in scale and properties. Agent-based 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 most useful to study feedback processes. Most models fall in-between agent-based models and systems models, with a compromise made between the detailed representation of systems and their interactions. Simplifications are also made in models when moving to larger scales, mainly driven by computational demand and a lack of available data. 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. 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).

4.2. Past and ongoing modeling studies over Northern Eurasia

Many models have been developed and used to study various components of the Earth systems with a focus on Northern Eurasia. In particular, during the past decade, NEESPI scientists have developed various models (climatic, weather, hydrological, permafrost, biospheric, aerosol dynamics, water management, agrometeorological, demographic, risk management, etc.). Table 2 presents a non-exhaustive list of modeling studies focusing on specific aspects of the Earth system over Northern Eurasia. Because Northern Eurasia accounts for 60% of the land area north of 40ºN and includes roughly 70% of the Earth’s boreal forest and more than two-thirds of the Earth’s permafrost (Groisman et al., 2009), past and ongoing research on the effects of climate change on 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).

Table 2 Non-exhaustive list of modeling studies focusing on specific aspects of the Earth System in Northern Eurasia

Permafrost	Shkolnik et al. 2012b; Gao et al. 2013; Hayes et al. 2014
Wildfire	Balshi et al. 2007; Dubinin et al. 2011; Schulze et al. 2012; Tchebakova et al. 2012; Kantzas et al. 2013; Vasileva and Moiseenko 2013
Hydrological cycle	Oltchev et al. 2002a,b; Callaghan et al. 2011a; Gelfan 2011; Georgiadi et al. 2011, 2014a,b; Kuchment et al. 2011; Georgiadi and Kashutina 2012, 2016; Georgiadi and Milyukova 2012; Khon and Mokhov 2012; Klehmet et al. 2013; Liu et al. 2013, 2014, 2015; Motovilov and Gelfan 2013; Sokratov and Shmakin 2013
Energy balance	Oltchev et al. 2002a; Brovkin et al. 2006; Olchev et al. 2009a; Tchebakova et al. 2012; Gálos et al. 2013
Climate	Olchev et al. 2009b; Arzhanov et al. 2012a,b; Mokhov and Eliseev 2012; Salau et al. 2012; Zuev et al. 2012; Anisimov et al. 2013; Hallgren et al. 2013; Monier et al. 2013; Shkolnik and Efimov 2013; Shulgina et al. 2013; Volodin et al. 2013; Onuchin et al. 2014; Novenko and Olchev 2015; Lyalko et al. 2016
Weather (extremes)	Semenov, 2012; Shkolnik et al. 2012a; Rimkus et al. 2013
Terrestrial ecosystems characteristics	Shuman and Shugart 2012; Cresto-Aleina et al. 2013; Polishchuk and Polishchuk 2013; Shuman et al. 2013a,b; Ziółkowska et al. 2014
Agriculture (crop modeling)	Gelfan et al. 2012; Kattsov et al. 2012; Magliocca et al. 2013; Peng et al. 2013
Air quality (aerosols, ozone…)	Reilly et al. 2007; Darmenova et al. 2009; Baklanov et al. 2013; Siljamo et al. 2013; Sofiev et al. 2013
Sea ice	Mokhov et al. 2013
Carbon (in land and water)	Dargaville et al. 2002a; Lu et al. 2009; McGuire et al. 2010; Glagolev et al. 2011; Gustafson et al. 2011c; Hayes et al. 2011a,b, 2014; Kim et al. 2011; Koven et al. 2011; Dolman et al. 2012; Pokrovsky et al. 2012; Zhang et al. 2012; Bohn and Lettenmaier 2013; Bohn et al. 2013; Gao et al. 2013; John et al. 2013; Kicklighter et al. 2013, 2014; Olchev et al. 2013a,b; Zhu and Zhuang 2013; Zhu et al. 2013, 2014; Zhuang et al. 2013; Rossini et al. 2014; Rawlins et al. 2015

Vegetation shifts	Brovkin et al. 2006; Jiang et al. 2012, 2016; Tchebakova and Parfenova 2012; Parfenova et al. 2013; Kicklighter et al. 2014; Novenko et al. 2014; Shuman et al. 2014; Tchebakova et al. 2016)

Nonetheless, there are a few studies that try to integrate various aspects of the Earth system, in terms of scale (Gouttevin et al. 2012; Ermoliev et al 2014; Zhu et al. 2014), teleconnection or global feedbacks (Dargaville et al. 2002b; Macias-Fauria et al. 2012; Ermoliev et al 2014; Krichak et al. 2015) and processes (Euskirchen et al. 2006; Callaghan et al. 2011b; Sokolik et al. 2013; Parham et al. 2014). Many other studies focus on integrated systems where multiple disciplines overlap, such as modeling studies of water management (Shiklomanov et al. 2013) or land management (Gustafson et al. 2011a,b; Kuemmerle et al. 2011a,b, 2014; Lebed et al. 2012; Loboda et al. 2012; Robinson et al. 2013; Shuman et al. 2013a; Blyakharchuk et al. 2014). 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 (Darmenova et al. 2009); permafrost and terrestrial hydrology with water management (e.g., Zhang et al. 2011; Shiklomanov and Lammers 2013, 2014); 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 evaluate models based on experimental and observational datasets (e.g., Gouttevin et al. 2012; Anisimov et al. 2013; Zhu et al. 2014); and 2) prognostic modeling studies that focuses on the response of Earth system component to global change.

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); DOC export at the mouth of the river allows for the integration over 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 necessarily guarantee that the response to 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 http://www.wcrp-climate.org/wgcm/projects.shtml. 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.

Prognostic modeling studies focus on projections of climate change over the region (Arzhanov et al. 2012a,b; Shkolnik et al. 2012a; 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 (Kattsov et al. 2012) or forests (Tchebakova and Parfenova 2012; Olchev et al. 2013a). While highly focused modeling studies can greatly enhance our understanding of the response of a key mechanism, 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 pathways through which climate change can impact the emissions of greenhouse gases from the land system (Figure 20), including: 1) climate-induced vegetation migration; 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 pathway can enhance our understanding of the land biogeochemistry under future climate change, such as the work of Felzer et al (2005) who focus in 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 pathway in the overall system.

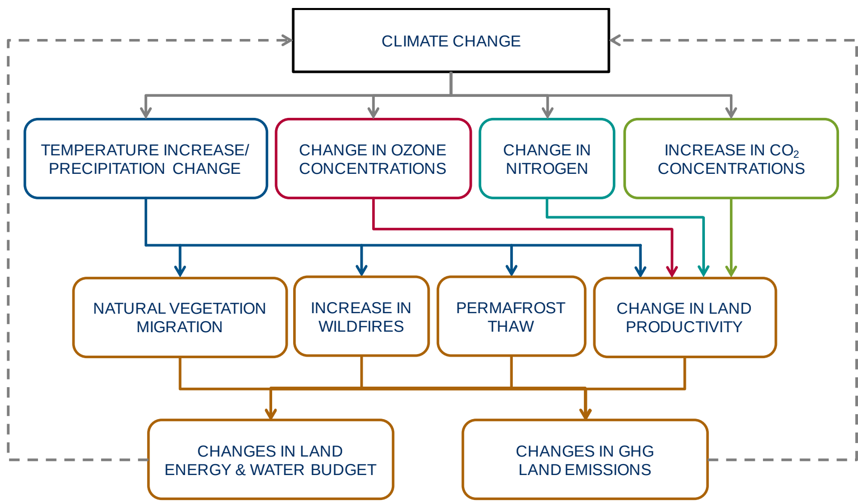

Figure 20. Schematics of a detailed, but non-exhaustive, accounting of climate change impacts on land biogeochemistry and biogeophysics. Dashed lines represent the potential feedback of terrestrial ecosystem responses to the climate system.

Furthermore, if interactions and feedbacks exist between the different pathways of climate change impacts, individual studies could be misleading. In addition, changes in land emissions of greenhouse gases 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. As a result, we argue that a greater understanding and comprehensive representation of feedbacks and interactions within the Earth system are required.

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. 2011). 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. The ensuing ensembles sample the model structural uncertainty that arise from differences in the parameterizations of climate processes, the climate system response and resolution. These multi-model climate ensembles based on coordinated scenarios have become the standard for the climate impacts research community. 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. Because climate change is prescribed, little attention is placed on potential feedbacks. For example, climate change can affect emissions of greenhouse gases (GHGs) from the land, through changes in land productivity, wildfires, and permafrost thaw. Because GHGs are usually well mixed in the atmosphere, this impact is largely global. In addition, climate change can induce plant migrations, which affect characteristics of the land surface, including albedo, roughness and hydrology, mainly at the local and regional scales. These global and regional feedbacks (Figure 20, dashed lines) can have major implications for the climate system, but they are not accounted for if climate change is prescribed. 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 are known as Earth system models.

4.3. Earth system models (ESMs)

The Earth system is a complex interaction among various physical, biological and chemical processes in different components that include, amongst others, the land, the atmosphere and the ocean. An exact definition of the Earth system is not formally agreed upon. Figure 21 shows various definitions of the Earth system commonly used. In this

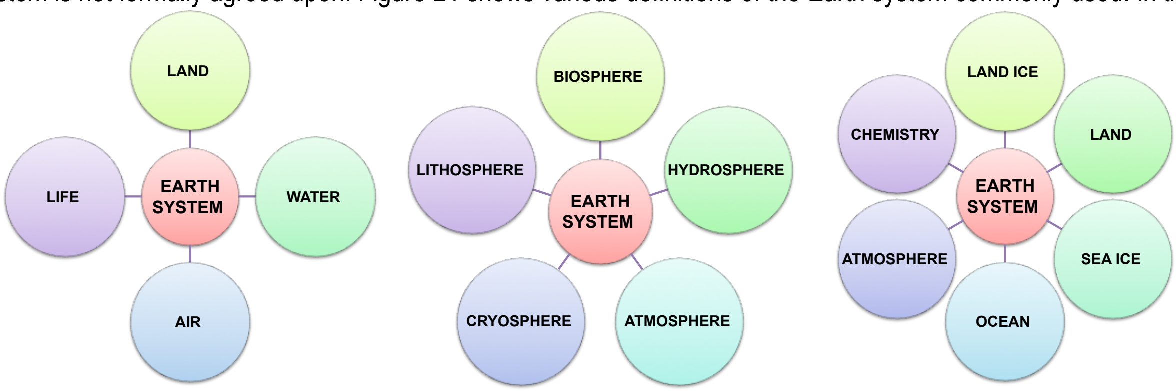

Figure 21. Schematics of three commonly used definitions of the Earth system.

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 provide 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. Because ESMs represent the entire Earth system, with the 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 cutting edge. While the development of Earth system models 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 both at the local and regional scale. 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. 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 and carbon cycle, is necessary to represent both feedback pathways.

4.4. Human-Earth coupled system

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, including water resources management, land-use change and land-use emissions (Melillo et al 2009), 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), and 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 through impacts on the cost of growing biomass and water availability. The influence of growing populations and climate change on land productivity will differ regionally, as well as opportunities to abate GHG emissions. International trade in food and energy commodities, however, can help smooth impacts across regions by exploiting the benefits of global change in some regions and reducing the costs of global change in other 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:

- The NEFI project needs to better identify the role of Northern Eurasia on the global system and put a greater focus on the global context.
- Many global studies of the Food-Energy-Water system lack a focus on specific regions other than the United States, Europe, China (i.e. Northern Eurasia). For this reason, tighter collaborations with these coordinated exercises could lead to major benefits for Northern Eurasia, with largely untapped potential.
- Some efforts to integrate the human system and the Earth system with a focus on Northern Eurasia exist and need continued efforts. For example, recently, a new coupled model, called WRF-Chem Dust, has been developed that enables an assessment of the impact of land use change on dust emissions (Xi and Sokolik, 2015). The model has been used to assess an anthropogenic fraction of emitted dust in Central Asia. The role of anthropogenic (i.e., caused by various human activities) dust has been further studied to assess its impacts on the environment, climate, and human well-being. The model is being used to establish the climatology of smoke emissions and assess smoke impacts on the environment and human health.

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, Rotmans et al. 1990; Alcamo et al. 1994; van Vuuren et al. 2006, 2007;MIT Integrated Global System Model or MIT-IGSM, Prinn et al 1999; Sokolov et al. 2005; Prinn 2013; MiniCAM, Wise et al. 2009; Model for Energy Supply Strategy Alternatives and their General Environmental Impact or MESSAGE, Riahi et al. 2007; Asia Integrated Model or AIM, Hijioka et al. 2008). 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, some 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. A schematic of the modeling framework used in Hallgren et al. (2013) is shown in Figure 22.

Reilly et al. (2012) use the same IAM to explore the role of land-use change on global mitigation strategies to stabilize global air temperatures to within 2°C of the preindustrial level and Kicklighter et al. (2014) further include climate-induced vegetation shifts and investigate their potential influence on future land use and associated land carbon fluxes in Northern Eurasia. These modeling efforts are highlighting the potential capability of IAMs to enhance our understanding of drivers of land-use change and the importance of land-use change for mitigation strategies. At the same time, they represent state-of-the-art IAM modeling and, unfortunately, do not represent the general state of land-use change modeling in current IAMs.

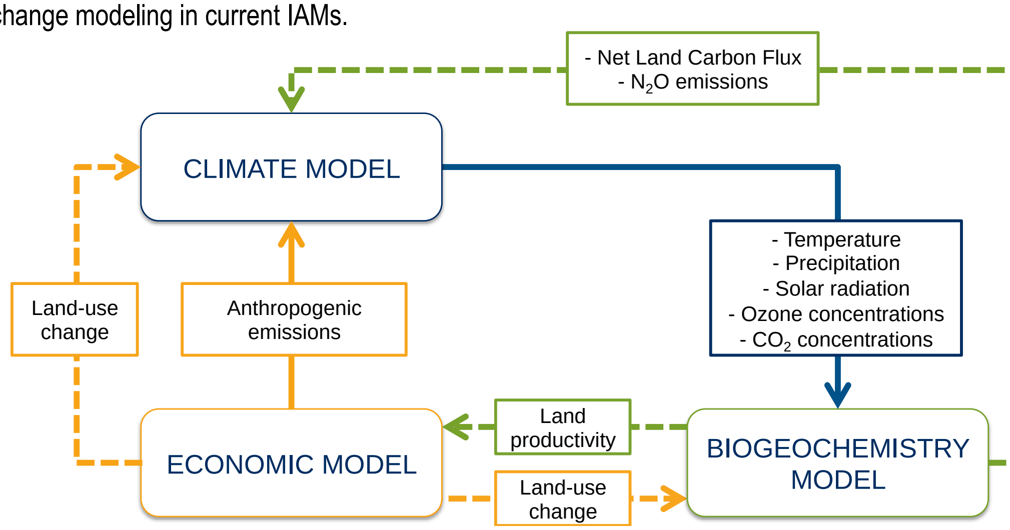

Figure 22. Schematic of modeling framework to investigate the biogeochemical and biogeophysical impacts of human-driven land-use change, similar to that used in Reilly et al. (2012) and Hallgren et al. (2013).

We strongly believe that the NEFI project could and should be taking advantage of IAM capabilities but putting a greater focus on Northern Eurasia.

4.5. Emerging issues

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 Food-Energy-Water (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 Food-Energy-Water system is often treated without considering its feedback on the economy, 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 through either biogeochemical and biogeophysical pathways. We argue that the complex interactions within the FEW system should be considered as 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, 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). Other issues that affect the FEW Nexus and that will be aggravated by climate change include the effect of land ownership and land use on food production, the consequences of more intense fertilizer and pesticide use for water quality and biodiversity, and the shifts in energy production technologies that may reduce GHG emissions but may produce other environmental effects. Governance issues must also be addressed because FEW Nexus thinking requires a collaborative and integrative approach to planning and to data collection and analysis. The implementation of the FEW Nexus at the basin and national scales has the potential to facilitate a more comprehensive and meaningful approach to Integrated Water Resources Management (IWRM) and to more integrated monitoring for the SDGs. NEFI will contribute to the activities of the Future Earth Knowledge Action Network (KAN) working on the Nexus. NEFI projects along with the survey studies of the UNECE are some of the few FEW studies being carried out in the geographical area.

We argue that 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. Such model development to enhance the integration of the FEW system within IAMs is underway but, since it has only been a recent focus, only little headway has been made.

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 demand for energy and population growth, 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), 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 23.

Social-Ecological Systems (SES) are used to spotlight that ecological and social systems are interdependent and constantly co-evolving in Northern Eurasia. SESs constitute complex, non-linear dynamic landscapes that are confined to specific areas, land use entities, and bound to political, institutional, and juridical constraints. They manifest themselves in their spatial differentiation at various scales and they are characterized by feedback loops across multiple interlinked scales. Such systems involve multiple ecological and social components whose non-linear behaviour is difficult to predict (Gunderson and Holling 2002). Regarding various key drivers such as climate change or societal change, SES are subject to far-reaching transformation processes that are far-ranging over Northern Eurasia particularly after the collapse of the former Sowiet Union. Taking into account that it is generally accepted today that human well-being and ecosystem integrity are fundamentally linked, these processes must be managed in a way that implies balancing economic capacity, environmental integrity, and resilience to future changes. Desired states of SES are those that are (a) able to deliver a broad flow of ecosystem servives in the long term, and (b) provide ecosystem services not only for an exclusive minority. This understanding connects the sustainability-related definition of resilience (Ott 2003) with the international debate on how to define and analyse planetary boundaries, and how to identify and govern a safe and just operating space for humanity (Rockström et al. 2009; Steffen et al. 2015). People in SES of Northern Eurasia differ in how they structure their thinking about environmental issues, how these cognitions are learned, and how this influences their behavior and future decisions. The simultaneous manipulation of several ecosystem services (ES) to a desired state is a challenging task. Simplified conceptual solutions are not auspicious, since the behaviour of people, legal constraints, and regional planning policies have to be integrated. It has been suggested that resilience-based (also called sustainable) ecosystem stewardship (Chapin III et al. 2009), also referred to as adaptive management of SES (Green and Garmestani 2012), constitutes an adequate conceptual framework to foster social-ecological sustainability. This concept embodies a fundamental shift in management based on assumptions of environmental steady-state conditions to one based on the assumption that the system itself is transforming. It emphasizes that SES should adapt to the interplay of gradual and rapid changes at various spatiotemporal scales, non-linear dynamics, thresholds, and uncertainty in order to sustain a broad flow of ES for human well-being within these. Key assumptions of resilience-based ecosystem stewardship are: (a) reducing vulnerability (reduce sensitivity and exposure to stresses), (b) enhancing adaptive capacity, (c) increasing resilience (foster a balance between stabilizing feedbacks and creative renewal; adapt governance to changing conditions), and (d) enhancing transformability (enhance capacity to learn from crisis, create and navigate thresholds for transformation, Chapin III et al. 2009). Resilience-based ecosystem stewardship for Northern Eurasia is thus a matter of time and scale. **Nevertheles, this stewardship must be a major overarching focus of NEFI.**

NEESPI postulates that no adequate and sufficiently integrated interdisciplinary methodological framework for resilience-based ecosystem development has yet been established in Northern Eurasia. 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, or the development new technologies), 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. 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.

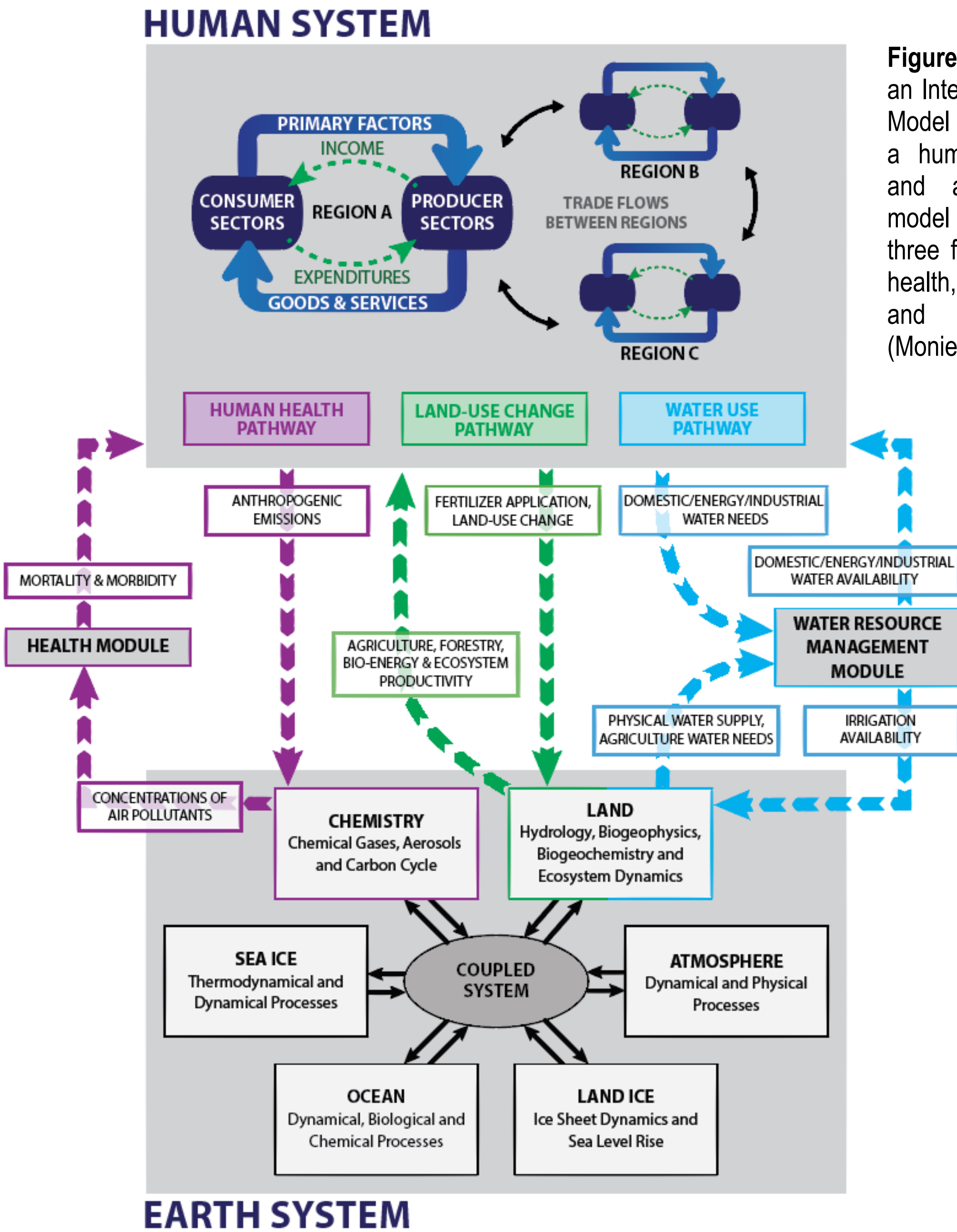

Figure 23. Schematic of an Integrated Assessment Model (IAM) that couples a human activity model and an Earth system model with a focus on three feedback pathways: health, land-use change, and water resources (Monier et al. 2017).

5. Final Words/Conclusions

When the embryonic NEESPI project began over a decade ago, a cynic or even a realist would have warned us that a program spanning Eurasia involving scientists from multiple disciplines based in a score of nations with complex and sometimes opposing diplomatic missions should have been a disaster. There were several significant factors which brightened and opposed such a dark forecast. Truly interdisciplinary interactions among engaged scientists who are tackling a shared problem is remarkable glue for holding research projects together. Creativity can prosper in “bottom-up” research programs. The role of Northern Eurasia as a recipient and generator of planetary climatic change is an important “big question” that captures the imagination of good scientists everywhere and transcends disciplines, cultures, languages and national politics. It is also a challenge whose unraveling requires teams working together openly in earnest and in good faith. The consequences of climatic change on this Northern Eurasian region and on our planetary home are simply too dire for pessimism. NEESPI was born from optimism and this optimism continues today.

NEESPI has great reason to be proud of its success. This document provides the reader with but a glimpse of what has been accomplished. However, it is not a time that the NEESPI participants should rest on their laurels. If, as Shakespeare noted in *The Tempest*, “What is past is prologue,” NEESPI has been an outstanding prologue to the present challenges. In particular, we must incorporate our knowledge of the consequences of human and social dimensions onto assessing the current and future changes in the NEESPI region. Across the region, the future strongly depends on these assessments to appreciate how we can ameliorate environmental change, how human populations will be affected by change, and how we bridge the considerable gaps in research procedures, capacity for prediction, and time- and space- scales that complicate the integration of human dynamics with environmental dynamics.

NEESPI has engaged these issues to a significant and increasing degree over its history (see Figures 22 and 23 and accompanying text). These developments parallel developments in the International Geosphere Biosphere Programme (IGBP) to better include human issues on the potentially transformative consequences of global climate change on human societies. The IGBP officially ended in December of 2015 after 30 years of success and many of its components transformed into the “Future Earth” Secretariat. Its mandate is promoting the former IGBP programs with an increased emphasis on interactions with stakeholders (Bondre et al. 2015). At the same time the International Council of Scientific Unions (ICSU), The United Nations Educational, Scientific and Cultural Organization (UNESCO) and The United Nations University (UNU) have joined to formulate a joint Programme on Ecosystem Change and Society (PECS). This program, the inheritor (heir?) of the Millennium Assessment, also emphasizes an increased role in incorporating humanity into our understanding of global change.

The NEESPI region has a central role to play in these significant international programs. It has undergone significant environmental changes, already having experienced a warming in the past few decades that already exceeds the 1.5ºC to 2.0ºC warming limits adopted in Paris. Many of the new international programs are emphasizing resilience and transformation of human/environmental systems in the face of environmental change. The NEESPI region presents a range of human/environment systems ranging from modern industrial societies to traditional indigenous cultures, all undergoing significant social change. Certainly the continuing transformation of the former USSR represents one of the largest and most profound social changes of recent decades. Through its new program "*Northern Eurasia Future Initiative*”, NEFI the work in the NEESPI region is moving to more effectively address shared goals with interdisciplinary programs at the global level. The research record that will help us launch NEFI is a logical consequence of the accomplishments of NEESPI. This situation and the need for progress is critical.

As Shakespeare wrote: *There is a tide in the affairs of men, which, taken at the flood, leads on to fortune; Omitted, all the voyage of their life is bound in shallows and in miseries. On such a full sea are we now afloat, and we must take the current when it serves, or lose our ventures*. W. Shakespeare (Julius Caesar Act 4, scene 3). Now is the time to press forward with this opportunity. The challenge is before us.

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