# *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

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**Abstract**

During the past several decades, the Earth system has changed significantly, especially across Northern Eurasia. Changes in the socio-economic conditions of the larger countries in the region have also resulted in a variety of regional environmental changes that can have global consequences. The Northern Eurasia Future Initiative (NEFI) has been designed as an essential continuation of the Northern Eurasia Earth Science Partnership Initiative (NEESPI), which was launched in 2004. NEESPI sought to elucidate all aspects of ongoing environmental change, to inform societies and, thus, to better prepare societies for future developments. A key principle of NEFI is that these developments must now be secured through science-based strategies co-designed with regional decision makers to lead their societies to prosperity in the face of environmental and institutional challenges. NEESPI scientific research, data, and models have created a solid knowledge base to support the NEFI program. This paper presents the NEFI research vision consensus based on that knowledge. It provides the reader with samples of recent accomplishments in regional studies and formulates new NEFI science questions. To address these questions, nine research foci are identified and their selections are briefly justified. These foci include: warming of the Arctic; changing frequency, pattern, and intensity of extreme and inclement environmental conditions; retreat of the cryosphere; changes in terrestrial water cycles; changes in the biosphere; pressures on land-use; changes in infrastructure; societal actions in response to environmental change; and quantification of Northern Eurasia's role in the global Earth system. Powerful feedbacks between the Earth and human systems in Northern Eurasia (e.g., mega-fires, droughts, depletion of the cryosphere essential for water supply, retreat of sea ice) result from past and current human activities (e.g., large scale water withdrawals, land use and governance change) and potentially restrict or provide new opportunities for future human activities. Therefore, we propose that Integrated Assessment Models are needed as the final

stage of global change assessment. The overarching goal of this NEFI modeling effort will enable evaluation of economic decisions in response to changing environmental conditions and justification of mitigation and adaptation efforts.

**Keywords**

Environmental Changes, Northern Eurasia, Ecosystems dynamics, Terrestrial water cycle, Cryosphere retreat, Extreme and inclement environmental conditions, Sustainable development, Land-cover and land-use change, Integrated assessment models for decision-makers

# Introduction

Northern Eurasia Future Initiative (NEFI) 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). That 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 NEFI. These results (http://neespi.org/web-content/PragueWorkshopSynthesisBriefing.pdf) were delivered at a dedicated open public Splinter Meeting at the European Geophysical Union Assembly in Vienna, Austria (April 16th, 2015). On May 20, 2016, a NEFI White Paper was released for public consideration on the NEESPI web site and four months later, after accounting for numerous comments and recommendations, it was finalized and posted at http://nefi-neespi.org/. The current paper presents the consensus of the future NEFI vision to address the challenges facing the region, and to develop pathways to mitigate future problematic changes.

During the past 12 years, NEESPI has been quite successful at conducting and advancing research within its large geographical domain of Northern Eurasia (Figure 1; Groisman and Bartalev 2007). The NEFI research domain is the same. The NEESPI program accommodated 172 projects focused on different environmental issues in Northern Eurasia. More than 1500 peer-reviewed journal papers and 40 books were published during the past decade (http://nefi-neespi.org/science/publications.html; Groisman et al. 2009, 2014; Groisman and Soja 2009). Several overview books further synthesized findings (Gutman and Reissell, 2011; Groisman and Lyalko 2012; Groisman and Gutman 2013; Chen et al. 2013; Gutman and Radeloff 2016). While the initial duration of the NEESPI research program was estimated to be 10–12 years, its momentum has exceeded original expectations. In addition to accumulating knowledge and publishing scientific journal papers and books, NEESPI scientists developed new observations, datasets, data networks, tools and models. As a result, a new research realm emerged for studies in Northern Eurasia, and we are now poised to apply these results to directly support decision-making for various coupled environmental-societal needs.

**Figure 1**.

The past accomplishments are not the only driver for the proposed NEFI initiative. Just as, or perhaps even more importantly, NEFI will address two significant and intertwined changes that have emerged. These are: 1) continued and exacerbated change in the global Earth and climate system, and 2) societal change and stress with a heightened need for mitigation and adaptation approaches. With respect to the first, the global Earth system has significantly changed, with the changes in Northern Eurasia being substantially larger than the global average (cf., Figures 2 and 3). Subsequently, one NEFI endeavor is to analyze this *new state* with its unexpected novel features and distributions. These novel characteristics include shifts of the seasonal cycle for various climatic functions to changes in intensity, frequency, and spatial patterns and temporal trends of extreme events. These changes have already occurred, but their impacts on (and feedbacks to) atmospheric, biospheric, cryospheric, hydrologic, oceanic, and macro-socioeconomic processes are ongoing.

**Figure 2.**

**Figure 3.**

The second significant change that NEFI will need to address concerns the socio-economic dynamics in the major nations of Northern Eurasia. These dynamics have also dramatically changed, including the ability of societies to withstand and adapt to the adverse manifestations of the above-described environmental changes. Fundamental to addressing this is the sound scientific understanding and quantification of the amount of Earth system change that societies are currently experiencing and may experience by the end of the 21st century. However, in addition to understanding the scientific basis, communities (and even nations) have increasingly begun to inquire about what mitigation and/or adaptation strategies are possible for the upcoming decades. These types of questions need to be addressed differently, because societal decision-making impacts the environment, which feeds back to influence future societal decision-making. The major anthropogenic causes of global change remain ongoing. Thus, the Earth science community and society in general will need to be informed and prepared to assure a sustainable future.

The results of scientific research, data, and models accumulated during the past decade will allow us to build upon this knowledge to directly support decision-making activities that address societal needs in Northern Eurasia. During the last decade, substantial climatic and environmental changes have already been quantified. While natural processes (except the high amplitude of their variations) are mainly the same as in other parts of the World, human factors and changes in land cover and land use in the NEFI domain during the past decades were dramatic and unique. Changes in the socio-economics of major nations in the region have ultimately transformed human-environment interactions. This in turn has transformed regional land cover and water resources towards conditions that endanger or even overcome the resilience of natural ecosystems (e.g., disappearing lakes and runoff diversions, deforestation, degradation and abandonment of agriculture fields and pasture; air, soil, and water pollution). These and projected changes will require expeditious direct responses on behalf of human well-being and societal health in order to move toward a sustainable future.

Therefore, the core motivation of NEFI is to best use science to serve the decision-making process to maintain Earth system health and to sustain society. In the next two sections, we:

- Formulate three major science questions of global concern associated with unique features of Northern Eurasia,
- Formulate the major research foci for the next decade that, as the NEFI Science Plan authors believe, are of crucial importance to be addressed expediently, and
- Examine and justify the issues related to these research foci in more detail.

An approach to regional studies in Northern Eurasia based on integrated assessment modeling is described and justified in the last section of the paper. Because this paper is an overview of a large amount of relevant findings from the past decade, we also provide a comprehensive list of references to those works.

# REVIEW

## Three unique features of Northern Eurasia of global concern and their 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 Land Belt of Northern Eurasia (DLB) 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 features in more detail and suggest that three major science questions emerge from this examination.

### Sensitivity of land surface characteristics to global change

The Arctic, Arctic Ocean shelf, and the Boreal Zone of Eurasia are areas of substantial terrestrial carbon storage in wetlands, soil, boreal forest, terrestrial and sea shelf permafrost. From these emerge powerful carbon-cryosphere interactions and variability that intertwine with strong climatic and environmental changes (Figure 4). These interactions also can generate positive feedback to Earth system changes via both biogeochemical (atmospheric composition, water quality, plant and microbial metabolism) and biogeophysical impacts (surface albedo, fresh water budget, and thermohaline circulation of the World Ocean). These intertwined linkages and feedbacks may increase the rate of global (or near-global) change and/or increase uncertainties about that change. In turn, this places the wellbeing of societies at risk if planned mitigation and adaptation measures are not implemented in a sound and timely fashion.

**Figure 4.**

Thus, in future studies within Northern Eurasia, special attention should be paid to the changes on the volatile boundaries of the Arctic, boreal, and dry zones. The highly variable components of the cryosphere (seasonal snow cover) which are vitally controlled by components that have been systematically changing (e.g., glaciers and permafrost) should be recognized. The rates of change due to 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; Zhu et al. 2013; Ruppel and Kessler 2017) must be accounted for or ameliorated.

*Based on the above, the first Major Science Question is: "How can we quantify and project ecosystem dynamics in Northern Eurasia that influence the global energy budget when these dynamics are internally unstable (e.g., operate within narrow temperature* *ranges), are interrelated and have the potential to impact the global Earth system with unprecedented rates of change?"*

**Water availability and the dry land belt of Northern Eurasia**

The interior of the Earth's largest continent is mostly cut off from water vapor transport from the tropics by mountain ridges and plateaus spread across the central regions of Asia, thus creating the Dry Land Belt of Northern Eurasia (DLB; Figure 1). The DLB is the largest dry area in the extratropics and may be expanding northward (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. For example, the Pannonian Lowland and the black soils in Ukraine and European Russia provide substantial grain export to the global market.

However, the DLB has strong physical limitations in the production of crops. It has a very limited fresh water supply, which is highly dependent upon irregular extra-tropical cyclones (mostly from the North Atlantic) and a shrinking regional cryosphere. Increases in evapotranspiration arising from increases in warm season temperatures and expansions of the growing season in the DLB are generally not compensated by precipitation increase. Further, changes in the spatio-temporal shifts in precipitation pattern increase the probability of various unusual or 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 (Darmenova et al. 2009).

*Arising from these considerations, the second Major Science Question is: "What are the major drivers of the ongoing and future changes in the water cycles within the regions of*

*Northern Eurasia with insufficient water resources (i.e., DLB and its vicinity)?"* In addressing this question, future studies should examine how changes in the water cycle will affect regional ecosystems and societies, and how these changes will feedback to the Earth system and the global economy.

**Evolving social institutions and economies**

Institutional changes in Northern Eurasia that have taken place over the past few decades have led to large changes in the socio-economic fabric of the societies in the region, affecting land use and the natural environment (cf., Lerman et al. 2004). One overarching challenge has been the transition from command-driven to "transitional" and more market-driven economics in the countries of Northern Eurasia. This phenomenon has occurred at different rates, with differing levels of success, and often with societal costs. This has created unexpected economic and environmental problems but also opportunities (Bergen et al. 2013; Gutman and Radeloff 2016). Environmental changes and their related 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; Newell and Simeone 2014), degradation of cultivated and pasture lands (Ioffe et al. 2012; Chen et al. 2015a, 2015b), growing water deficits and drought (especially in the DLB and new independent states), and the spread of human-induced fires (Soja et al. 2007; McCarty et al. 2017). Many of these outcomes have become important concerns with policy implications at the national and intergovernmental levels. Opportunities emerge mostly with advances of warmer climate conditions northward (agriculture benefits at high latitudes, better transportation conditions in the Arctic Seas; Tchebakova et al. 2011). Other opportunities are institutional, such as cooperation between nations and non-profit organizations in attempting to implement forestry certification.

Furthermore, the countries of Northern Eurasia with these “transitional” economies are playing an increasingly important role in the world economic system. Thus, they face further challenges in highly competitive economic conditions under the additional stresses of climatic, environmental, and internal societal change. For countries and/or regions with resource-rich lands and low population (e.g., Russia, Kazakhstan, Mongolia, and Turkmenistan), their development continues to depend on natural resources inclusive especially of timber, oil/gas, mining, fisheries, agriculture and hydropower (Bergen et al. 2013). Other countries (e.g., China and Japan) with very large populations and strained or limited resources (such as available domestic timber in China or Japan) may be strong consumers of natural resources from elsewhere in Northern Eurasia (Newell and Simeone 2014).

Considering the triad "climate – environmental – socio-economic impacts", past NEESPI investigations sufficiently embraced 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 defined. This makes it difficult to effectively plan for the future or to accurately interpret prospective actions based on existing 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 including agriculture and grazing, forestry, fisheries, mining, energy, and on-shore and off-shore infrastructure development. This will be an important NEFI endeavor.

*The third Major Science Question is: “How can the sustainable development of societies of Northern Eurasia be secured in the near future (the next few decades)?* In addressing this question, future studies should examine how societies can overcome the "transitional" nature of their economic, environmental and climatic change challenges, and resolve counterproductive institutional legacies.

## Major research foci: Why do they matter?

During the preparation and review of the NEFI Science Plan, the directions of future research over Northern Eurasia have been analyzed in light of the new information gained from past NEESPI activities, the apparent need to advance further in these directions addressing the latest dynamics of environmental and socio-economic changes, and the unique features of Northern Eurasia that are of global concern. Nine major research foci have been identified as NEFI priorities (listed in no specific order):

1. Influence of global change, with a focus on warming in 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 streamflow);
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 and demand, changes in land use, water available for irrigation, and food-energy-water security);
7. Changes in infrastructure (roads, new routes, construction codes, pipelines, risks with permafrost thawing, air, water, and soil pollution);

8. Societal adaptations and actions to mitigate the negative consequences of environmental changes and 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 have not been addressed satisfactorily in the NEESPI domain, nor indeed globally. The introduction of the Future Earth research objectives is a response to this gap (http://www.futureearth.org/). There is an urgent need to incorporate socio-economic studies into regional programs by linking the findings of diagnostic and model-based climate and environmental analyses with the requirements for the regional infrastructure, which arise from the detailed treatment of socio-economic conditions.

We are establishing this strategy as the foundation for the Northern Eurasia Future Initiative (NEFI) and expect that it will bridge climate and environmental studies with the economic consequences of the observed changes. This will spur advances in physical sciences to better quantify observed and projected climate and environmental changes and improve economic analyses of 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, have not been studied and quantified to a full extent. This will make it possible to revisit and comprehensively review the 12-year NEESPI legacy in order to transform conventional climate and environmental metrics to those relevant for building more effective economic strategies and risk assessments.

Below, we examine and justify the issues related to the above nine major research foci in more detail, and in the final section propose an integrated assessment modeling approach that would allow NEFI to eventually address them as best as current technology and knowledge will support.

**Research focus 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 (Intergovernmental Panel on Climate Change (IPCC) 2014; Barros et al. 2014; Karl et al. 2015; see also Figure 2). Regionally, the temperature changes in Northern Eurasia have been amongst the largest (Blunden and Arndt 2015, 2016). Additionally, 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 the global climate. Its air temperature changes during 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 (November 30–December 12, 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, right; Renner et al. 2014). The depletion of sea ice increases the heat and water vapor exchange with the atmosphere, especially during 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 (Drozdov 1966; Newson 1973; Groisman et al. 2003, 2013a; Arctic Climate Impact Assessment 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.**

The Arctic is closely interlinked with the North Atlantic Ocean. Together they control the World Ocean thermohaline circulation, which provide most of the cold water influx into the deep ocean. They define the climate of the northern extratropics (especially the regions adjacent to the North Atlantic) due to intense meridional heat and mass exchange of the atmosphere with the ocean in the Atlantic Sector of the Arctic and the subsequent transport of air masses inside the continents. This exchange is modulated by variations of the Arctic Oscillation, a large scale mode of climate variability, also referred to as the Northern Hemisphere annular mode (Thompson and Wallace 1998). All together, they create strong deviations from the zonal temperature distribution (for example, compare the climate of Edinburgh, Scotland, UK with Churchill, Canada and Yakutsk, Russia) and 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 for oceanic circulation (Gulfstream) and climate of the extratropics (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 (Francis and Vavrus 2012), and increasing probability of blocking events (Lupo et al. 1997; Semenov 2012; 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).

**Research focus 2: frequency and intensity of extremes**

There is already evidence of climate-induced change across Northern Eurasia during the past few decades (Soja et al. 2007; Groisman and Gutman 2013; Rimkus et al. 2013; Shvidenko and Schepaschenko 2013; Valendik et al. 2014) with southern regions being particularly vulnerable to climate change and fires (Malevsky-Malevich et al. 2008). First, there has been an increase in rainfall intensity and prolonged no-rain periods (summarized in Groisman et al. 2013b; see also Zhai et al. 2004 and Chen and Zhai 2014), which at times may occur in the same region. Second, an increase in extraordinary temperature anomalies has been accompanied by summer droughts (Barriopedro et al. 2011; Lei 2011; Lupo et al. 2012; Bastos et al. 2014; Horion et al. 2016). Third, cold outbreaks and/or thaws have increased during winter (Arctic Climate Impact Assessment 2005; Groisman et al. 2016). Fourth, an increase in the frequency of large and severe wildfires has occurred (Conard et al. 2002; Soja et al. 2007; Kukavskaya et al. 2013b; Shvidenko and Schepaschenko 2013). Finally, intense dust storms have occurred (Xi and Sokolik 2015a). Official Russian statistics on “dangerous meteorological phenomena” (DMP), which are events that caused significant damage to the national economy and vital activities of the population, report that seven years of the last decade (2006–2015) had 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).

There are also changes in the spatial and temporal distribution of inclement weather conditions (e.g., heavy wet snowfalls, freezing rains, rain on snow, 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., the influence of winter thaws and/or early snowmelt on the water deficit of the following growing season, Bulygina et al. 2009, 2011; Groisman and Soja 2009). Societal consequences of changes in the frequency and intensity of these extreme and inclement events have become an urgent task to address for the entire Earth Science research community (Forbes et al. 2016). In this regard, it is not enough to report and/or to project changes in characteristics of these events but also to develop a suite of strategies for resilient responses to new climate conditions that are forthcoming and/or have an increased higher probability than was previously expected.

Extreme events that affect the biosphere and their temporal and spatial changes represent a special focus for NEFI studies. Wildland fire is the dominant disturbance agent in the boreal forests, which are in turn the largest global reservoir of terrestrial carbon (Pan et al. 2011; Parham et al. 2014; Gauthier et al. 2015). While fire plays a critical role in maintaining the overall forest well-being through regulating ecosystem functioning, productivity, and health, extreme fire events and changing fire regimes intensify the impacts of climate change and variability on ecosystem states and deliver a suite of powerful feedbacks to the climate system. These events heighten the interactions among the biosphere, atmosphere, and climate systems by affecting carbon balances, hydrologic regimes, permafrost structure, modifying patterns of clouds and precipitation, and radiative forcing by changing surface and planetary albedo (Rogers et al. 2015). Wildfires, in general and particularly during extreme events, also have a direct adverse impact on human health, pose a considerable threat to life and property, and impose a substantial economic burden.

A typical feature of the current fire regime is increasing frequency and severity of mega-fires, defined as fires that involve high suppression costs, property losses, natural resource damages, and loss of life (Williams 2013). These fires may cause the irreversible transformation of the forest environment for a period that exceeds the life cycle of major forest-forming species (Sukhinin 2010; Shvidenko et al. 2011; Figure 6). Mega-fires of the last decade have led up to a twofold increase in the share of crown and peat fires. 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 (RFE) are estimated to cover tens of million hectares (Shvidenko et al. 2013). The increasing aridity of the climate provokes outbreaks of harmful insects that could envelope large areas, for example, the outbreak of Siberian silk moth (*Dendrolimus superans sibiricus*) which enveloped an area of about 10 x$10^6$ 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 (van den Werf et al. 2010; Soja et al. 2007).

**Figure 6.**

Severe fires, driven by anomalous weather conditions, are increasingly becoming the new norm 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 Figure 6, at the stages from b to i, forests might have the possibility to recover with (1) the absence of repeated disturbances; and (2) implementation of forest management mitigation efforts with increased resources for the most severe cases. However, if the recent tendencies of fire weather continue, the survival of the forest biome in its present boundaries is not possible (Tchebakova et al. 2009).

In 2008, smoke and related emissions from early season fires associated with agricultural/clearing in the country of Kazakhstan, in the Transbaikal region, and the Russian Amur Oblast (oblast is a large administrative division in Russia) were observed in the Arctic. On reaching the Arctic, this early season ash deposition could result in more rapid snow and ice melting, further altering albedo impacts on the ice sheet (Warneke et al. 2009). In 2010, the Moscow region experienced a 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 $3.6 \times 10^9$ \$US (by other estimates up to $10 \times 10^9$ \$US) and the death of nearly 56,000 people (Guha-Sapir 2010). In the spring of 2015, anomalous weather caused extensive and severe fires in Siberia that destroyed 1200 houses in 42 settlements and resulted in 36 deaths and hundreds of injuries in the Republic of Khakassia (Valendik et al. 2015). Similarly, fires in the Transbaikal region resulted in the loss of more than 240 houses in 18 settlements, the death of 11 people, and more than 30 people injured (Kukavskaya et al. 2016).

Wildfires are uncommon in Eastern Europe and European Russia (Krylov et al. 2014), but anthropogenic fires in agricultural areas, including croplands and pastures, are widespread (Soja et al. 2004; Dubinin et al. 2011; McCarty et al. 2017; Derevyagin 1987). Romanenkov et al. (2014) noted that a peak of satellite fire detections occurs 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. Agricultural burning is a source of short-lived climate pollutants like black carbon (McCarty et al. 2012) and methane (McCarty et al. 2017). However, prescribed fire in forests, grasslands, or croplands is either illegal or not reported by national agencies in Lithuania, Belarus, or Russia (Narayan et al. 2007). Efforts to organize reliable monitoring of such fires from space are warranted.

**Research focus 3: retreat of the cryosphere**

The cryosphere in the montane regions of Northern Eurasia is represented by three components: (i) seasonal and perennial snow pack; (ii) glaciers; and (iii) permafrost. The cryosphere retreat has a continent-wide spatial scale with temporal scales that vary from the century to millennia 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: a) continental energy balance changes due to decreases in surface albedo, increases in heat flux into the upper surface layers, and earlier spring onsets and longer growing seasons; b) the 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 c) large-scale biosphere changes (Figure 4) especially prominent in regions where the cryosphere is intrinsically linked with the survival/dominance of major species within biomes (e.g., larch forest over the permafrost areas in northern Asia).

The most prominent snow cover changes are observed in the late spring (Figure 7a) while the total duration of seasonal snow on the ground is decreasing, there are days/periods, when snow maximum water equivalent and maximum snow depth have been increased over most of Russia (Bulygina et al. 2009, 2011, updated). Note that the strong systematic increase in spring temperatures in Northern Eurasia (Figure 3) was apparently enhanced by positive snow cover feedback.

**Figure 7.**

Changes in the extent and mass balance of glaciers are important primarily because of their impact on water resources. Yet, while there is extensive information about glacier area change, less is known about changes in glacier volume and mass, either observed or projected. Within the domain of Northern Eurasia, assessments of changes of glacier mass on a regional scale are available for the Tien-Shan mountain system using Landsat and Corona satellite imagery which provided data on volume change (e.g., Pieczonka and Bolch 2015) and Gravity Recovery Satellite Experiment (GRACE) data (e.g., Farinotti et al. 2015). The latter provides data on changes in ice mass and is therefore directly relevant to the assessment of water resources. Yet for regions other than the Tien-Shan, the uncertainty of measurements using GRACE remains very high and often exceed the measured signal (Jacob et al. 2012). In other regions, changes in the mass and volume of ice are characterized using traditional glaciological surveyors' pole measurements of mass balance at the benchmark glaciers (World Glacier Monitoring Service 2015). Geodetic mass balance for smaller areas is based on using *in situ* geodetic measurements, aerial photography and high-resolution satellite imagery (e.g. Shahgedanova et al. 2012), and ground-penetrating radar (GPR) measurements performed both *in situ* and from the air (e.g. Kutuzov et al. 2015). This last method appears to be promising, particularly in combination with ice thickness modeling, e.g. the recently developed Glacier Base Topography Model, 2nd Version (GLABTOP2; Linsbauer et al. 2012).

Within Northern Eurasia, the contemporary glaciation reaches its maximum extent in the mountains of Central Asia. In the Tien-Shan alone, according to different estimates, glaciers occupy between 15,400 km$^2$ and 16,400 km$^2$ (Sorg et al. 2012). The Altai Sayan Mountains and the Caucasus Mountains are other important centers of contemporary montane glaciation with a combined glacier area of approximately 1,550 km$^2$ (Aizen 2011) and 1350 km$^2$ (Shahgedanova et al. 2014) respectively. Smaller centers of contemporary glaciation occur in the Polar Urals, mountains of eastern Siberia (e.g. Kodar, Chersky, and Suntar-

Kayata), and Kamchatka (Khromova et al. 2014). Across all these regions, with the exception of the coastal glaciers of Kamchatka (Khromova et al. 2014), glaciers are retreating although regional variations in retreat rates are observed both between and within the mountainous systems (Kutuzov and Shahgedanova 2009; Narama et al. 2010; Sorg et al. 2012; Shahgedanova et al. 2010). When observations allow, the retreat of glaciers can be documented at the century scale (cf., Figures 7c and 7d). In the first decade of the 21st century, the retreat rates increased to 1% $yr^{-1}$, e.g., across most of Tien-Shan and Djungarskiy Alatau (Severskiy et al. 2016; Sorg et al. 2012; Farinotti et al. 2015; Pieczonka and Bolch 2015). In addition to glaciers, the ongoing climate warming has already affected the ground ice of these mountain ecosystems (Jin et al. 2000, 2007; Marchenko et al. 2007; Wu et al. 2013).

Across the Caucasus, the glaciered area has been shrinking at a slower rate of 0.4–0.5 % $yr^{-1}$ (Shahgedanova et al. 2014). Changes in the extent of glaciers of north-eastern Siberia and the Urals are often more difficult to quantify because of the small size and cloudy summer weather which make it difficult to obtain suitable satellite imagery. However, analysis of glacier change in the Kodar Mountains shows both a strong loss of glacier area, as high as 0.9 % $yr^{-1}$ between the 1960s and 2010 (Stokes et al. 2013), and a strong loss of glacier volume and negative mass balance (Shahgedanova et al. 2011). Glaciers of the Polar Urals have lost nearly half of their area since the 1950s and exhibited negative mass balance (Shahgedanova et al. 2012).

It is difficult to believe that the temperature increases over montane areas of Central Asia and Caucasus will not affect the extent of the regional cryosphere unless there is a concurrent two-digit percentage increase in regional precipitation. Analyses of cyclonic activity over Central Asia do not show sizeable changes in the total cyclone numbers, and there are some increases in their variability. Furthermore, the number of deep cyclones, which are already rare here, has decreased in the last decade (Figure 8). Thus, the countries comprising this region should be prepared to confront potential problems with water availability for montane agricultural fields and pastures.

**Figure 8**.

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) to buffer the loss of glacial mass. The impact of a declining cryosphere on water resources varies among the regions. While the impact is predicted to be moderate in the northern Caucasus, which receives ample precipitation (Lambrecht et al. 2011), it is likely to be stronger in arid regions such as southern Caucasus and Central Asia. In particular, the mountains and plateaus of Central Asia have been in the spotlight of cryosphere research because they are a major regional source of fresh water for surface runoff, groundwater recharge, hydropower plants, community water supply, agriculture, urban industry, and wildlife habitat. Central Asia is categorized as a water-stressed area where projected climate change could further decrease streamflow and groundwater recharge (Core Writing Team 2007).

It is anticipated that under the current climate warming trend, the recession of glaciers in Central Asia will accelerate, leading to a temporary increase of runoff during the dry season. The studies of the observed and projected changes in discharge suggest that the peak flow might have already been reached and will continue for the next decade (Hagg et al. 2006, 2013; Shahgedanova et al. 2016). However, on longer time-scales (> 50 years), the crucial dry season glacier runoff will be substantially reduced, as glaciers will lose most or all of 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. Currently few projections of future climate using regional climate modelling exist for Central Asia (Mannig et al. 2013; Shahgedanova et al. 2016). While all existing simulations project an increase in air temperature for the region, there is substantial disagreement among the models on the future trends in precipitation.

In the last 30–40 years, observations have indicated 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 and North America 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, 2017). 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. In the regions where permafrost surface is already "warm" (i.e., where its temperature is close to the freezing point: Arctic shelf seas, riverbeds, edges of the present permafrost boundaries), such warming causes multiple changes in the terrestrial hydrological cycle, land cover, and man-made infrastructure (Pokrovsky et al. 2012; Shvidenko et al 2013; Shiklomanov et al. 2017). 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 (see Research focus 7: changes in infrastructure). Figure 7b shows the number of newly emerging thermokarst lakes in West Siberia which indicate the rate of degradation there of the upper layer of the permafrost.  A main aim of the future NEFI efforts related to permafrost is to evaluate its vulnerability 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 a potential source or sink of an additional amount of carbon in the Earth system.

During the NEESPI studies of the past decade, the cryosphere retreat and its major manifestations were documented (Figure 7) and it was shown that this process plays a critical role in environmental changes across Northern Eurasia.

**Research focus 4: changes in the terrestrial water cycle**

The mountains of Northern Eurasia cut its landmass off from the major sources of water supply from 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 cryospheric storage. The rest of the water is provided through unstable atmospheric circulation (e.g., cyclones). Changes caused by global warming can decrease and/or redistribute water supplies from the cryosphere, increase the vegetation period, and affect the water vapor transport from the oceans into the continental interiors where both absolute changes and variation in the water vapor transport are of great consequence. 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; Khromova et al. 2014), (b) an already unstable water source (atmospheric circulation) becoming even more variable (Schubert et al. 2014), and (c) a longer and warmer period for vegetation growth ("greening") increasing the biospheric water demand (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.**

There is ample evidence of changes in the terrestrial water cycle across Northern

Eurasia (AMAP 2011; Barros et al. 2014; Figure 9), including reduced snow cover (Brown and Robinson 2011; Callaghan et al. 2011a; AMAP 2011, 2017), intensifying spring melt (Bulygina et al. 2011), increasing river flow (Shiklomanov and Lammers 2009, 2013; Georgiadi et al. 2011, 2014a, 2014b; Georgiadi and Kashutina 2016; 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 others.

River flow is a dynamic characteristic that integrates numerous environmental processes and aggregates their changes over large areas. River runoff plays a significant role in the fresh-water budget of the Arctic Ocean and its 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. 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 a new historical maximum in 2007 (Figure 10; Shiklomanov and Lammers 2009; Holmes et al. 2015).

River discharge into the Arctic Ocean is a highly effective conveyor in transporting continental heat across Eurasia (Nghiem at al. 2014) under a warming climate with increasing temperatures (Figure 2). Eurasian rivers with immense watersheds, particularly the Severnaya Dvina, Pechora, Ob, Yenisei, Lena, and Kolyma Rivers, provide a massive flux of warm waters into the Arctic Ocean or peripheral seas contributing to melt sea ice in spring and summer. The massive river energy flux to the Arctic Ocean carries an enormous heating power of 1.0 × $10^{19}$ J/yr for each 1°C of the warm river waters above freezing, which is equivalent to the power release from detonation of 2.5 ×$10^{9}$ ton of trinitrotoluene (TNT) per °C per year (Nghiem et al. 2014). With increased water temperatures (Lammers et al. 2007) and longer ice-free periods of the Arctic rivers (Shiklomanov and Lammers 2014), the role of river heat input is increasing and must be incorporated in sea ice prediction and projection models. These changes of river discharge in Northern Eurasia have a predictive potential to force Arctic change at interannual to decadal timescales and beyond (Richter-Menge et al. 2012).

**Figure 10.**

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, 2006; Yang et al. 2004; Adam et al. 2007; Shiklomanov and Lammers 2009; Zhang et al. 2012a), 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; Groisman et al. 2014).

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 (Barros et al. 2014). The air temperature rise leads to significant changes in the regional cryosphere including spring snow cover retreat, 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 permafrost thaw (Davydov et al. 2008; Woo 2012; Streletskiy et al. 2015b), glacier melt (Bennett et al. 2015), less thickness of seasonally frozen soil (Markov 1994, 2003; Frauenfeld et al. 2004; Frauenfeld and Zhang 2011; Shiklomanov et al. 2017), and river ice on river runoff generation (Gurevich 2009; Shiklomanov and Lammers 2014). However, 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 and the freshwater flux to the ocean. There is also considerable uncertainty about how these local changes will scale up to regional and continental scale impacts.

Terrestrial evaporation and transpiration (evapotranspiration) are the components of the terrestrial hydrological cycle that are the most difficult to measure given few direct observations (Speranskaya 2011, 2016). Near-surface air temperatures are increasing, and one can expect that the evaporation from wet land surfaces should increase. However, the near-surface wind speeds over the entire territory of Russia have been decreasing in the past several decades (Bulygina et al. 2013 updated to 2016; such studies have not been completed for other parts of Northern Eurasia), and this may reduce the air-surface water vapor exchange. Furthermore, most Northern Eurasian land surfaces are not “wet” so 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). Thawing of permafrost and less seasonally frozen ground can significantly change underground hydrological pathways. This will lead to an increase in ground flow, higher runoff during the cold season and, correspondingly, to a decrease in total evapotranspiration. Finally, future ecosystem shifts can dramatically change the vegetation composition (Figure 4) and the transpiration rate of the new communities can induce further fundamental 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 the atmosphere, soil, and biosphere. Large-scale geochemical and geophysical runoff changes (biological and inorganic matter transports) also should be considered.

Recently, there were a number of assessments of trends in the discharge from glaciered catchments of Central Asia. A detailed review of changes in river discharge in the Tien-Shan has been provided by Unger-Shayesteh et al. (2013) who reported contrasting trends for its different sectors including increasing summer runoff in the northern and inner Tien-Shan, and decreasing summer runoff in the central and western Tien-Shan and at the lower elevations in the inner Tien-Shan. More recently, Shahgedanova et al. (2016) reported an increase in discharge from the glaciered catchments unaffected by human activities in the northern Tien-Shan using homogenized long-term records. Positive trends in the discharge from the headwater catchments of the Tarim River were reported by Duethmann et al. (2015), Krysanova et al. (2015), and Kundzewicz et al. (2015) who also attributed these changes primarily to the increasing glacier melt, but highlighted their inability to quantify water withdrawal and its contribution to the long-term trends as a limitation of these studies.

It is important to recognize that the increases in discharge due to glacier melt (if any) have been a temporary relief for water resources in the interior regions of Central Asia and Caucasus. In these regions, water stored in the cryosphere is limited and, if the current tendencies of the cryosphere depletion persist, they will result in severe water deficits in future decades. Therefore, it is time to begin preparations to mitigate and/or adapt to these deficits beforehand by developing management routines for water preservation and responsible consumption as well as by modifying agriculture and pastoral practices accordingly.

Accelerated climate- and anthropogenic-induced changes in the hydrological cycle raise societal concern 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.

Presently, changes of the hydrological regime in Northern Eurasia are producing more and more freshwater input to the Arctic Ocean. The changes in river dscharge, along with the sea ice decline, and higher 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, we should expand our knowledge to better understand these hydrological processes, to better project possible extreme events, and better adapt to ongoing and upcoming environmental changes.

**Research focus 5: changes in the biosphere**

Ecosystems in Northern Eurasia are subjected to the impacts of climate change and human activities over the entire sub-continent. In the northern part on sites with permafrost, anthropogenic changes are primarily due to oil and gas exploration and extraction, mining, and infrastructure development. Further south, timber harvest (along with oil/gas) is predominant in the boreal and temperate forest zones, as are agricultural and pastoral activities in the forest-steppe and steppe zones. Industrial development often leads to the physical destruction of landscapes, changes of the hydrological regime, and widespread contamination of air, soil and water (Derome and Lukina 2011; Baklanov et al. 2013). Climate-induced changes in terrestrial ecosystems transform important ecosystems and their services, which in turn, require an adjustment in business planning, nature conservation, forest management, agricultural practices and regional economic policies to mitigate or adapt to these changes. The Siberian Taiga and Far East zones together comprise the largest part of the world's most intact remaining boreal 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).

In the long term, terrestrial ecosystems function in a dynamic balance with the states of climate, water resources, the lithosphere, and cryosphere. When these four driving forces change, ecological systems also begin to change. Currently, significant changes in forest area and composition are predicted to occur within a few future decades (see Figure 4 and discussion). Ongoing climate change already impacts the ecosystems of Northern Eurasia and may provide hints for projecting future changes. These impacts are manifold and relate to diverse features of ecosystem states and behavior like health, productivity, resilience, change of natural disturbance regimes, major biogeochemical cycles, among many others (Kharuk et al. 2017b).

Forests disturbed within the last 30 years account for approximately 75 x $10^6$ ha (9%) of Russian forests (Loboda and Chen 2016). Dendrochronological data show that fire frequency has been increasing in different parts of Russia throughout the 20th century

(Voronin and Shubkin 2007; Kharuk et al. 2016). Recent satellite-based assessments show that the rates of forest disturbance have increased further since 2000 compared to the pre-2000 era across all forest biomes with the largest increase from 1.2 to 2.2 $x 10^6$ ha $year^{-1}$ in Eastern Siberia associated with an increase in fire occurrence (Loboda and Chen 2016). The average extent of burnt area during the last 15 years over Russia is estimated at 10–13 $x10^6$ ha $year^{-1}$ with the post-fire forest mortality rate of 1.76 $x10^6$ ha $year^{-1}$ (Krylov et al. 2014; Bartalev et al. 2015). In the future, the frequency and extent of a fire occurrence in boreal forests are expected to rise further under the projected scenarios of climate change by anywhere from 25–50% (Flannigan et al. 2000, 2013) to 300–400% (Shvidenko and Schepaschenko 2013; Abbot et al. 2016) with an accompanying 50% increase in fire weather severity. These, in turn, are likely to result in large scale ecosystem shifts. For example, an increase in fire frequency is expected to lead to the disappearance of the pure Siberian pine stands in southern Siberia and the replacement of Siberian pine forests by Scots pine stands in the northern regions (Sedykh 2014). Repeated disturbances have resulted in substantial decreases in fuel loads and led to soil erosion, overheating, the absence of nearby seed sources, and the proliferation of tall grasses. As a result, the lack of natural post-fire regeneration of forests has led to their conversion to steppe vegetation (Kukavskaya et al. 2016; Figure 6). Based on the analysis of satellite vegetative indices combined with ground-based data, repeated fires have been found to have the most negative impact on reforestation, forcing the failure of post-fire regeneration in more than 10% of the forested area in the south-western part of the Transbaikal region (Shvetsov et al. 2016). Furthermore, Flannigan et al. (2013) project that cumulative fire severity would increase three times and fire season length could increase by 20 days by 2091 for Northern Eurasia. Thus, 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 (climatic, forest-vegetation, social, technical, and economic).

While productivity of forests at the continental level has increased during the last few 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. This mirrors the general condition 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) resulting in increased 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 visibly 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 — first of all, the exchange rates of water vapor and carbon dioxide between plant ecosystems and the atmosphere. When ecosystems respond to changes in ambient temperature and moisture conditions, the direct response can be quite 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 (Bohn et al. 2013; Olchev et al. 2013a, 2013b).

Sustainability of the forest carbon sink under changing climate is a serious concern, given the huge task of limiting the growth of atmospheric greenhouse gases (GHG) concentrations to levels adopted under the Paris Agreement of 2015 (http://ec.europa.eu/clima/policies/international/negotiations/paris_en). The global growth of $CO_2$ in the atmosphere is significantly compensated by the terrestrial biosphere sequestering 2 to 4 Petagrams of carbon every year as evidenced globally from atmospheric composition measurements (Le Quéré et al. 2015). Atmospheric inverse models (Dolman et al. 2012) estimate the sink, which amounts to less than 4% of global net primary production, to be disproportionally allocated to high and mid latitudes of the Northern Hemisphere, including Northern Eurasia. This result is especially convincing when atmospheric observations over Northern Eurasia are used (Stephens et al. 2007; Maksyutov et al. 2013; Jiang et al. 2012, 2016; 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 during the past few decades that are driven by rising temperatures and atmospheric $CO_2$ concentrations. Maintaining the size of the carbon sink in Northern Eurasia into the 21st century under the negative impacts of increased droughts and fires requires basically the same measures as those needed for sustaining forestry, namely fire protection and efficient forest management (Hurtt et al. 2002, 2011; Shvidenko et al. 2013). Despite the high level of natural and human-induced disturbances, the ecosystems of Northern Eurasia currently serve as a net sink of carbon up to 0.5 – 0.6 Pg C $yr^{-1}$ (Dolman et al. 2012) with about 90% of this sink occurring in forested landscapes. However, Figure 11 shows that large areas of disturbed forests, basically on permafrost, have already become a carbon source.

**Figure 11**.

Current biosphere models predict diverse responses based on the acceleration of the carbon cycle by future climate change. A significant change is expected for ecosystems on permafrost, but 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 may increase by 75% (Gustafsson et al. 2011). The carbon loss from wildfires may increase substantially (Shvidenko et al. 2013). The expected changes of ecosystems in permafrost regions include forest decline over large regions from changes in the hydrological regime and increasing water stress (Figure 4). Still, it is not clear whether northern forest ecosystems will reach a tipping point, but this is very likely under regional warming above 7$^{o}$C (Gauthier et al. 2015; Schaphoff et al. 2015). The uncertainty of such a 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 which warming scenario is used. Purposeful forest management could substantially slow down this process (Abbot et al. 2016).

Logging is an important disturbance factor in many forest areas of Northern Eurasia (Achard et al. 2006; Gauthier et al. 2015). Logged sites are usually highly susceptible to fire due to a combination of high fuel loads in leftover debris and accessibility for human-caused ignition (Loboda and Csiszar 2007; Loboda et al. 2012). These sites typically experience higher severity fires than do unlogged forests, and these fires can spread to adjacent areas (Ivanov et al. 2011; Kukavskaya et al. 2013a). In the dry lands, clear-cut logging accelerates the conversion from forest or forest-steppe to steppe vegetation.

Throughout the Taiga zone, timber harvesting (Bergen et al. 2008) and possibly human-exacerbated forest fires (Kasischke et al. 1999) are major contributors to change in the ecological systems of Northern Eurasia. Forest harvest in Russia as a whole, and in particular in Siberia and the RFE has changed over the past fifty years with high harvest rates characterizing the late Soviet era (Peterson et al. 2009). After the dissolution of the former Soviet Union, these rates dropped to less than to $100{\times}10^6$ $m^3$ (Bergen et al. 2008) although more recently they have partially rebounded. The early Soviet era saw an emphasis on harvest from western Russia. Since the 1980s, the greater development of logging in Siberia and the RFE was spurred by declining western Russia reserves, incentives to establish industry in the eastern reaches of Russia and agreements with Japan (in 1968 and 1974) for forestry infrastructure development in Siberia/RFE. Most recently (and in the foreseeable future), trade in eastern regions is influenced by increasing demand from China (Figure 12), with significant potential to adversely impact the health and intactness of Siberian and RFE forests in particular (Bergen et al 2013; Newell and Simeone 2014).

**Figure 12.**

Predictions of the future distribution and state of ecosystems in Northern Eurasia vary considerably (Gustafson et al. 2011a, 2011b; Tchebakova and Parfenova 2012, 2013), with remaining large uncertainties in the vegetation dynamics. Progress in dynamic vegetation observations and modelling in North Eurasia has become more visible with the recent availability of high-resolution remote sensing data on topography, plant phenology, biomass, and soil wetness (Kharuk et al. 2017a; Tchebakova et al. 2016a, 2016b). However, more efforts will be needed to expand the new data capabilities into lowlands and tundra regions.

Study results from the region suggest that further global warming will put at risk the sustainability of forest and forest landscapes (Gauthier at al. 2015; Schaphoff et al. 2015; Figure 4). As mentioned earlier in this paper, models predict substantial shifts of vegetation to the north with forest steppe and steppe expected to be dominant across large southern territories of the present forest zone (Schaphoff et al. 2006; Tchebakova and Parfenova 2012). However, the changes in climatic conditions during the last several decades have occurred too rapidly for vegetation structure to completely adjust to the new conditions. The immediate response of vegetation cover to changes of climatic variables can be quite rapid, but the recovery can be characterized to occur over a longer time frame with significant delay. When the climate changes shift a region to conditions outside of the range of dominant species, the past and current seed dispersal rates (Udra 1988) are slower than the migration rate needed for vegetation to alter its composition to one appropriate to the predicted climate change.

A similar conclusion was reached based on comparisons 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 although the rate did reach 500 – 1000 m per year for pioneer species (birch and aspen). 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 analogues) for prediction of the possible changes of the vegetation cover due to the projected change of climate conditions in the 21$^{st}$ century. 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 21$^{st}$ 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 paleo analogue for the end of the 21$^{st}$ 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 risk, and the potential loss or decline of southern taiga forests will not be compensated for by increasing forest area beyond the current northern tree line.

Ecosystem changes in the present forest zone of Northern Eurasia may be quite rapid due to simultaneous effects of climate change that is among the largest over the planet (Figure 3; Blunden and Arndt 2015, 2016) and of anthropogenic factors such as logging (Figure 12), air, soil, and water pollution, and man-induced fires (see Research focus: frequency and intensity of extremes). First of all, the feedbacks from these changes directly affect the ecosystem services to societies of the region and, thus, their well-being. Secondly, the biogeochemical feedbacks of the carbon cycle changes in the forest and tundra zones of Northern Eurasia and its Arctic shelf seas may go far beyond the continent after the release of methane and $CO_2$ from large carbon storage in forest, wetlands, and frozen soil to the atmosphere due to biomass decomposition, fires, and thawing (Friedlingstein et al. 2006; Shvidenko et al. 2011, 2013; Gao et al. 2013; Gauthier et al. 2015; Shakhova et al. 2015; Ruppel and Kessler 2017). These types of feedbacks affect the rates of global Earth system change and, therefore, represent a global concern.

In Central Europe, air pollution has been recognized as a key threat for forest ecosystems since the second half of the 20$^{th}$ century. At the end of the 20$^{th}$ century, sulphur and nitrogen depositions in Europe connected with lignite combustion and the high concentration of industry reached their highest levels. Thereafter, the deposition of S 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 its monitoring remains an important task.

Norway spruce (*Picea abies*) is a tree species sensitive to air pollution. Thus, Norway spruce forests in the mountains of Central and Eastern Europe have been selected for regional studies of the interaction of climate and socio-economic drivers (Campbell et al. 2004; Mišurec et al. 2016; Kopačková et al. 2014, 2015). Since 1994, a network of 15 small forested watersheds (GEOMON) was established in Czechia to understand the forest response to air pollution. Since then, GEOMON has provided a testbed for exploration of element cycling on a watershed scale using modern remote and proximal sensing methods (Fottová 1995; Oulehle et al. 2008).

## Research focus 6: pressure on agriculture and pastoral production

The temperate and steppe zones of East Europe are a breadbasket for a large part of Northern Eurasia (Swinnen et al. 2017). However, under pressure of growing population, the nations of these zones will need to invest in climate-smart agricultural techniques to sustain or continue to improve agricultural yields and livestock production given forecasted climate change. "Climate-smart" agricultural systems are resilient to climate change and offer carbon and GHG emissions mitigation potential without compromising productivity, food security, and the livelihoods of those working in the agricultural sector. So far, 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 by management strategies.

*Land abandonment and recultivation*

During the past quarter-century, land abandonment in the Northern Eurasia region has been associated with fundamental changes in agricultural production and land use caused by the breakup of the Soviet Union in 1991 (Lerman et al. 2004). The guaranteed markets and subsidized production from the Soviet era, particularly in the livestock sector and less productive agricultural land, were lost. This caused an unprecedented drop in fodder-crop production, plummeting livestock numbers (Schierhorn et al. 2014a), decline in grain yields (Trueblood and Arnade 2001), increased fallow periods (de Beurs and Ioffe 2014) and widespread agricultural land abandonment (Alcantara et al. 2012, 2013; Prishchepov et al. 2012; Griffiths et al. 2013; Lieskovský et al. 2015). According to official statistics, approximately, 59 Mha of farmland were abandoned from 1991 to 2000 across the post-Soviet countries (Figure 13). A large portion of this change occurred in Russia. Two generalized trajectories of change resulted from this perturbation of 1991 and its subsequent effects up to the present: 1) some former agriculture lands have been taken out of production and have become reforested, and 2) others were temporarily taken out of production but have been later recultivated and/or otherwise put back into production under different ownership, management or other socio-economic processes.

With regards to the first trajectory, overall, the abandoned agricultural fields in Eastern Europe and Russia are driving an increase of forest cover, and have become a terrestrial carbon sink at the global scale over the late 20th and early 21st centuries (Kuemmerle et al. 2011b; Schierhorn et al. 2013; Kurganova et al. 2014, 2015). By 2010, approximately 5 Mha of new forests were observed on former agricultural fields in Eastern Europe that were cultivated during the Soviet era (Potapov et al. 2015). In the temperate zone, abandoned fields are often slowly but steadily encroached by shrubs and forests. Varying levels and timing of abandonment of agricultural lands were observed at the landscape level in three Landsat scene case study sites over the period 1975–2001 in the Siberian Taiga zone (Bergen et al. 2008), with most consistent decreases in agricultural land areas after 1990.

After the dissolution of the Soviet Union and subsequent cessation of the state subsidies for collective agriculture, large areas of less productive croplands were either abandoned (Alcantara et al. 2012, 2013; Prishchepov et al. 2012) or the 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. 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.

**Figure 13.**

The second trajectory which centers on land recultivation is more complex. First, agriculture abandonment rates varied across all of the former-USSR countries and were mediated by national and regional policies regarding support of agriculture (Prishchepov et al. 2012), as well as access to new markets (de Beurs and Ioffe 2014). One of the lowest rates of abandonment was observed where land reforms were successfully completed in a short period (Poland) or, in an alternate case, where they were absent (Belarus). Strong regional differences were also observed within countries. For example, 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, the agricultural activity now appears to be sustainable, albeit on a somewhat less extensive spatial scale than in the past.

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). However, recultivation rates have been compensated by ongoing agricultural land abandonment—reaching 60 Mha by 2013 for three largest post-Soviet agricultural nations (Figure 13). From 2000 to 2010, grain yields increased (Trueblood and Arnade 2001; Liefert et al. 2010). In southern Russia where the physical attributes, location, and human resources are best positioned to support agricultural activity (e.g., in Stravropol' Krai), there is growth potential for agriculture (Kattsov et al. 2012). Here there is evolving specialization of former socialized farms in response to market conditions. In Stavropol', this involves a shrinkage of animal husbandry and a consequent release of surplus labor, increased levels of absentee (corporate) ownership of farmland in the more favorable locations, decoupling of the economic fate of successful large farms from deficient local municipal budgets, and an expansion of non-Russian ethnic communities in the countryside (Ioffe et al. 2014).

Dynamics of cultural landscapes in European countries of the former Soviet Bloc can also be characterized by two opposite processes – intensification and extensification (Fjellstad and Dramstad 1999; Bičík et al. 2015). Intensification occurs when cropping intensity or livestock stocking increases on some land. This may 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 1950s 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 from European national land resource statistics.

The combined abandonment-reforestation and abandonment-recultivation trajectories potentially provide future options for both biofuel production and cropland expansion. The Northern Eurasian region represents a great potential to boost agricultural production (Schierhorn et al. 2014b), and also to 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). 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 (2017), limiting recultivation of abandoned lands. Adverse demographic conditions in Eastern Europe associated with an exodus of the rural population (Nikodemus et al. 2005; Prishchepov et al. 2013) and the depopulation of rural areas in China (Liu et al. 2010) may trigger additional land abandonment. Because of limited institutional and economic ability to adapt to changing weather patterns, the increase of weather extremes represents a real threat for future agricultural production in Northern Eurasia. This may reduce 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 diminish yields.

With respect to the above, the importance of socio-economic factors in land use is paramount. For example, the level of institutional suppression in two major crop-producing nations of the former Soviet Union, Ukraine and Russia, during the last 60 years of the Soviet period was so high, that the former Soviet Union imported grain in the last two decades of its history. Conversely, in recent years, even after the massive land abandonment in the 1990s, these two nations have become the second and third major wheat exporters globally.

*Agriculture and pastoral production in the DLB*

Spanning 25–125° E and 24–55° N across 17 countries (Figure 1), the DLB is the largest contiguous dryland in the extratropics. The region has served as the historical trade route between the Chinese East and the Mediterranean West, combining the Persian Royal Road and the Silk Road. The Silk Road was and is an important international trade route between China and the Mediterranean. Historically, the Silk Road has experienced major expansions and geopolitical conflicts among cultures and religions, political and institutional shifts including the collapse of the Soviet Union (Hostert et al. 2011). Especially in the last millennium, resource extractions (e.g., oil), rapid land use change (e.g., urban and agricultural expansion), climatic change, and natural disturbances (e.g., dust storms) have driven change in the region. The increased demand for meat and dairy products have produced strong pressure on agro-pastoral lands where transitional economies with frequent institutional shifts, water resource scarcity and climate conditions interact to alter DLB ecosystems and societies. The geopolitical systems are diverse, but most countries in the region are either developing or transitional economies with great demands for meat and dairy production (Ojima and Chuluun 2008)

While climate projection models agree that the DLB will become much warmer over the rest of the century, there is little agreement and considerable uncertainty about future precipitation patterns for the region. The Fifth IPCC Assessment Report (AR5; IPCC 2014) stated with high confidence that the Coupled Model Intercomparison Project Phase 5 (CMIP5) generation of models could project temperature distribution at a regional scale better than the previous generation of models. However, the AR5 report states with "a medium confidence" that there had been no improvements in model performance for precipitation. Moreover, global and regional climate models are seriously challenged by the rugged terrain found in much of the DLB (Parfenova et al. 2013; Lu et al. 2009a; John et al. 2013b, 2016).

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 East Asian part of the DLB, have increased more rapidly resulting in greater pressure on agricultural and pastoral lands (Qi et al. 2012a, 2012b; Kraemer et al. 2015). Second, there have been profound institutional shifts in the agricultural sector, primarily in post-Soviet Central Asia where the newly independent states have disparate natural resource endowments. To balance food security with commodities for export, these new nations have shifted their agricultural priorities (for example, replaced high water demanding cotton by wheat) that have altered regional water demands — resulting in agricultural abandonment in some locations and intensification in others (Wright et al. 2012; de Beurs et al. 2015; Kraemer et al. 2015).

Observations and biosphere models suggest that climate change is producing shifts of the ecotones in the drylands of Asia (Groisman and Soja 2009; Tchebakova et al. 2016a). The northward movement of the tree line and the changing dynamics of cover types, such as shrublands and savannas in the grassland matrix, alters feedbacks to carbon, water, and energy balances. Warming trends along with land-use and land-cover change (LULCC) could substantially modify the carbon balance and biodiversity of the Eurasian Steppe. Natural and anthropogenic factors act in concert amplifying one another. Consequences of reckless land use and general drying of the continental interiors include water scarcity, lowered water quality, soil salinization from agriculture intensification, and the disappearance of lakes/rivers due to reduced snow packs, glacier loss, and aggressive fresh water extraction (Klein et al. 2012).

The region has also experienced a rapid transformation in land cover. Grasslands have been converted to croplands in Central Asia and in portions of East Asia. Changes from cropland to vacant land have accompanied the collapse of the Soviet Union as farms were abandoned *en masse* (Lioubimtseva and Henebry 2009; Chen et al. 2015b; Figure 13). The net gain in carbon sequestration due to abandonment of croplands is offset by grassland degradation from the increased grazing pressures following dramatic increases in land privatization (e.g., herding policy on the Mongolia Plateau, Chen et al. 2015b), and increased food demands (Qi et al. 2012b).

**Figure 14.**

LULCC has simultaneously occurred at an alarming scale across the DLB. A transition matrix based on the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Product (MCD12Q1) between 2001 and 2012 revealed that shrublands and savannas (i.e., steppe) show a high degree of turnover across the entire region, at 38% for shrublands and 73% for savannas, respectively (Figure 14). Regionally, shrublands and savannas showed a greater turnover (77% and 89%, respectively) during the decade, with East Asian and Central Asia at 47% and 88%, respectively, and the Middle East at 39% and 54%, respectively. Similarly, croplands and cropland/natural vegetation mosaics have high turnover in East Asia (53% and 72%, respectively), in Central Asia (49% and 66%, respectively), and in the Middle East (25% and 73%, respectively). Barren and water cover types represent about 35% and 1% of total land area, respectively, but showed a 15% and 18% turnover across the region, respectively. Intensive use of exposed barren areas has escalated dust storms, drought severity, and water shortages (e.g., Xuan et al. 2000; Chen and Liu 2014). Worse yet, in the Fifth IPCC Report, Barros et al. (2014) predicts that this water-limited region will experience a warming trend significantly higher than the global mean, which would alter summer and winter precipitation patterns and increase the frequency of extreme climate events with longer, more intense, and more frequent summer heat waves. Cook et al. (2016) reports that, since 1998, the drought in the eastern Mediterranean Levant region (Cyprus, Israel, Jordan, Lebanon, Palestine, Syria, and Turkey) is the worst drought of the past nine centuries. Furthermore, the LULCC in DLB is expected to be significantly higher in the upcoming decades than now (Kelley et al. 2015; Chen et al. 2017), jeopardizing the regional stability and sustainability of the DLB. All of these factors along with its landlocked geographic location make DLB a hotspot for the scientific community concerned with negative consequences of ongoing global change.

By shifting C stocks in soils and vegetation, both abandonment and intensification strongly impact the regional carbon budget. 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). 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 can drive increases in grasslands-based livestock production (Chen et al. 2015a, 2015b).

A regional land-use change analysis using MODIS data suggests differential land-use change across the DLB (Figure 15) with cropland abandonment in the west (zoom windows at the bottom) and expansion in the east (zoom windows at right) are driven primarily by shifts in governance and economic development. Therefore, the DLB has seen increasing demands for food quantity and quality as well as decreasing food production, resulting in unbalanced pressure on agricultural and pastoral lands (Chen et al. 2015a, 2015b).

**Figure 15.**

From the perspective of cultural and social norms, the Asian part of DLB shares similarities in history of nomadic herding lifestyles and in geographic proximity. Totaling 8.82 million $km^2$, Central Asia, Mongolia and Northern China includes the largest land-locked countries (Kazakhstan and Mongolia) and has been influenced by some of the most severe geopolitical, biophysical, and socioeconomic disturbances affecting societies and simultaneously their livestock, a major source of food in the region. The region's total livestock of 209.16 million animals in 1992 increased to 278.3 million in 2011 (33.1% increase). However, livestock in Kazakhstan and Kyrgyzstan decreased substantially (by 43.8% and 34.1%, respectively) likely due to the collapse of the Soviet Union. Empirical relationships among ecosystem production, population density, gross domestic production, and land use remain intrinsically connected even with major policy shifts (such as the collapse of the Soviet Union or the new status of China within the World Trade Organization (Chen et al. 2015a, 2015b). The underlying mechanisms responsible for these consistent relationships, as well as their dynamics remain unknown.

Food security in the Central Asian part of the DLB 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 countries started taking practical measures by constructing reservoirs in order to ensure their economic development. These actions will have short-term benefits, but estimates of contemporary and future water resources that will originate from the high mountain cryosphere at the regional scale are needed to develop long-term adaptation and mitigation strategies. These estimates will be used for socio-economic vulnerability assessments of the benefits to 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 the blending of geosciences with social sciences to evaluate the role of high-elevation ice storage in permafrost and glaciers for levels of vulnerability and the resilience of mountain and downstream ecosystems along with their inhabitants.

**Research Focus 7: changes in infrastructure**

In the previous sections we mostly describe environmental and climatic changes in Northern Eurasia in recent decades. They have affected infrastructure of the region. In particular, the Arctic and Siberia have been substantially affected by the permafrost changes and its impact on man-made infrastructure (e.g., buildings, factories, mines, bridges, roadways, and pipelines). In the boreal zone, gradual onset of drier climate conditions accompanied with more frequent wild fires endangers human settlements, silviculture, and agriculture. In the DLB, a general depletion of already scarce water resources affects the general well-being of all population groups, and all aspects of human activity. These climate-related impacts on the infrastructure have been compounded by the marked social, economic, and institutional changes over Northern Eurasia during the past three decades. Therefore, this section is devoted mostly to the socio-economic changes attributable to the dramatic political and economic transformations that have affected infrastructures of Northern Eurasia.

In Russia, these transformations have been most pronounced in its Arctic regions where regional welfare critically depends upon the well-being of the entire country (e.g., Stammler 2005; Forbes et al. 2009; Kumpula et al. 2011; Pelyasov 2011; Hitztaler and Bergen 2013; Andrew 2014). Here, several socio-economic processes are major anthropogenic drivers of environmental change since the 1960s. These include 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 may be economically beneficial (e.g., decrease in climate severity and associated heating costs, longer navigation season), other changes negatively impact the natural environment, both traditional and nontraditional sectors of the economy, and the regional socioeconomic conditions. Overall, these climatic-induced changes in natural conditions exert additional pressure on the marginal environments of Eurasian Arctic, which are already stressed by human activities (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; Polishchuk and Polishchuk 2013, 2014). Communities, urban environments, and industrial infrastructure built on ice-rich soils can be catastrophically affected by thawing permafrost (Streletskiy et al. 2012; Shiklomanov and Streletskiy 2013;

Shiklomanov et al. 2017). Simultaneously, permafrost thawing, caused by both climate and infrastructure changes, 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 Arctic regions (Walker and Pierce 2015). Due to unprecedented levels of urban and industrial development, this problem is most pronounced for the Arctic regions of Northern Eurasia.

The Taiga ecoregion of Northern Eurasia has also seen dramatic pendulum-like shifts in population, infrastructure and forest resource use between the late Soviet, early post-Soviet, and the present-day eras. Over this time span, additional changes in the ecosystems driven by climate factors have also been accompanied by multiple severe wildfire years. Siberia's population expanded by 9 million people (23.5 to 32.5 million) between the years 1959 to 1989; a similar trend occurred in the RFE. This was due in large part to state incentives encouraging settlement of these eastern reaches of the Soviet domain. Thus in these 'peripheral' regions away from the 'center' (Moscow and St. Petersburg), population growth was strongly a product of in-migration and not intrinsic population growth.

With the relatively sudden withdrawal of State-supported programs, this situation precipitated significant shifts in population and natural resource use in the immediate post-Soviet era (Voinova et al 1993; Bergen et al. 2013). Driven by significant economic hardship, subsequent population out-migration began ~1990, which pervaded East Siberia and the RFE and has only recently been lessening. In addition to high rates of migration out of the regions altogether, residents also migrated within the regions from rural areas to the few main cities, resulting in a more urban population.

During the final three decades of the Soviet era, the forestry sector sustained high rates of timber production in Siberia. Some of this timber was exported to Japan based on official agreements with Japan in 1958 and 1974 (Mathieson 1979) and, in the last decades, to China (Figure 12). This brought investments in infrastructure. Despite the otherwise successful commitment of the Federal Forest Service to scientific forestry including the creation of forest inventory and an exceptional scientific knowledge (Kukuev et al. 1997), late Soviet-era forest harvest itself was surprisingly inefficient (Shvidenko and Nilsson 1994). Immediately after political dissolution in 1991, total harvest volumes significantly declined across Russia to approximately 175 million $m^3$ compared to approximately 400 $m^3$ in 1989 (Bergen et al. 2013). Significant growth did not occur again in the forest industry until approximately 2009.

As governance and institutions have regrouped after the early post-Soviet transition era, new or renewed developments in forest and energy sectors have emerged. Resource use in the taiga of Siberia and the RFE is influenced by its proximity to China, Japan and Korea. These countries have (a) some of the world's highest human population density numbers, (b) either naturally limited or depleted forest resources, and (c) far-reaching global-industrial and trade conglomerates (Crowley 2005; Bergen et al. 2013). Thus, in Russia, the geographic location of forest exploitation is shifting to eastern reaches that can easily supply and transport logs to the growing Asian market (Newell and Simeone 2014). This occurs both through legal forest management and harvest but also through illegal harvest (Vandergert and Newell 2003).

Siberia and the RFE Taiga regions are also rich in oil, gas and minerals, i.e., natural resources which are of great current economic and strategic importance. Within Russia there may be a greater shift in oil and gas extraction to East Siberia and the RFE given that the historic large oil reserves of western Siberia are thought to be approximately 75% tapped (Dienes 2004). The Eastern Siberia-Pacific Ocean pipeline has recently been completed, along with a spur directly into northern China. Most significantly, Russia sees its energy sector as a strategic central pillar to its re-establishment as a global economic power (Dienes 2004; Hashim 2010). Thus, it is likely that energy extraction and associated infrastructure will increase.

Communities in the Asian part of DLB are poised between dry and cold weather conditions. Their position is precarious in the face of multiple forces: climatic variations, extremes, and their changes; environmental degradation and loss of ecosystem services; globalization of markets; rapid population growth and changes to demographic structure; out-migration of the young and able segments of society with the subsequent brain drain and remittances to the left-behind families. Rural dryland communities in Central and East Asia face further challenges and opportunities due to the lingering consequences of the institutional upheaval and uncertainty following the end of the Soviet Union, China's market reforms and increasing regional influence of China. The DLB region has a low population, but the population is rapidly increasing. The total population in Central Asia and Mongolia in 1992 was 54.05 million. In 2011, it increased to 67.09 million, a 24.1% increase over the 20 year period. As might be expected, this population increase is coupled with rapid urbanization, agricultural development, and desertification (caused by heavy grazing) across Central and East Asia. The average regional increase of urban population from 1992 to 2011 was 27.3% with the largest increases occurring in China and Tajikistan (both of ~50%) and the lowest increase occurring in Kazakhstan (6.4%). In contrast, there is a 10.1% decrease in urban population in Mongolia.

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

**Figure 16**.

A crucial infrastructure factor in these DLB regions is a rapid rate of urbanization (Koch and Valiyev 2015). In particular, real estate development in the decade of the 2000s has led to major lateral expansion as well as vertical build-up that have transformed small cities into major metropolises. For example, in Kazakhstan, the extent of the Almaty urban agglomeration has increased substantially as observed by the Dense Sampling Method (DSM) (Nghiem et al. 2009) using NASA satellite scatterometer data in 2000–2009 (Figure 16). With the capability to track urban change in three dimensions (Nghiem and Small 2016), DSM results also reveal the significant vertical build-up as observed in the Almaty urban core area with a fast growth rate of approximately 7% per year in terms of the total volume of building structures in the 2000s (Figure 17). Such an overheated urbanization rate may result in an excessive building supply that surpasses the building occupancy rate, and thereby may turn the real estate boom into a bust.

In northern China, tremendous urban development quadrupled Beijing urban extent observed by DSM in the 2000s and brought along severe air pollution as a consequence (Jacobson et al. 2015). Similarly, in the DLB cities such as the complex of Xiangfang, Nangang, and Harbin have experienced multi-fold lateral expansion and significant vertical build up shrouded in smog due to soaring air pollution from coal combustion and the petrochemical industry (Huang et al. 2016). Mongolia has also undergone rapid urbanization similar to that of many cities in northern China, resulting in serious air pollution problems caused by automobiles and industrialization (Batmunkh et al. 2013). In any case, the rapid urban transformation exerts a high demand for rapid infrastructure development, such as road networks not only for intra-urban but also for inter-urban connectivity to support the commercial and industrial activities for the increasing population.

**Figure 17**.

Complex interactions among a rapidly changing climate and the continuously evolving social, economic, and political systems in Northern Eurasia require an integrative approach for studying the cumulative effects of infrastructure and climate change on high-latitude social-economic and natural systems. This research should focus on assessing the vulnerability of communities, industries, and ecosystems and should aim at developing adaptation and mitigation strategies and plans for the sustainable development of the Arctic infrastructure. The high latitudes of Eurasia, the largest and most dynamically complex northern region, can serve as a basis for developing effective climate mitigation policies and adaptation measures for global circumpolar North. The observed disparity of changes among the DLB countries hints that the socioeconomic factors define the resilience of these countries to ongoing changes and not so much the climatic factors.

**Research focus 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. Nowadays, 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.

**Figure 18**.

Planning is also now beginning to be practiced to reduce the adverse impact of disasters associated with environmental changes and increase the 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 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 globally (Figure 18) and also regionally (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 and dykes may increase flood peaks. Curbing industrial development may negatively impact human well-being and 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 and integrated assessment models (see the next section of this Paper).

**Research focus 9: quantification of the role of Northern Eurasia in the global Earth and socioeconomic system**

Northern Eurasia is a key part of the global Earth and socioeconomic systems. It occupies a substantial portion of the land surface of the Earth (19%) and 60% of land surface north of 40°N. Northern Eurasia is where some of the largest climatic, environmental, and socio-economic changes have occurred during the past century. In many aspects, changes here presage the rates of global change including global temperature rise (cf., Figure 3 versus Figure 2). The 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 7; Romanovsky et al. 2010a, 2010b; 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), and atmospheric pollution from industrial development (Lu et al. 2010) and from boreal forest fires (Soja et al. 2007) affect the global climate and environment. Large areas of natural and anthropogenic land-cover change are closely related to the interaction of the cryosphere and terrestrial hydrology change (Tchebakova et al. 2009; Zhang et al. 2011, Mátyás and Sun 2014; Figure 4) with human activities (Qi et al. 2012a, 2012b; Chen et al. 2013, 2015a; Horion et al. 2016, Figures 12 and 15). The importance of these changes and associated impacts on Northern Eurasia and potential feedbacks to the global Earth and socioeconomic systems may be quantified using models.

## Global change modeling for Northern Eurasia

As discussed in the previous sections, Northern Eurasia is comprised of a complex and diverse set of physical, ecological, climatic and human regional systems, which interact among themselves and can have potentially important feedbacks on the evolution of the global Earth and human systems. At the same time, the region has experienced dramatic climate, environmental and socio-economic changes, which leads us to argue that studying the fate of Northern Eurasia needs to be placed in the context of global change modeling (i.e. the modeling of the coupled human and Earth systems at the global scale) and include interactions with other regions of the globe. In this section, we review past and ongoing modeling studies over Northern Eurasia and provide new approaches for integrated modeling for Northern Eurasia.

**Past and ongoing modeling studies over Northern Eurasia**

Many models have been developed and used to study various components of the Earth system with a focus on Northern Eurasia. Monier et al. (2017) provides an overview of recent and ongoing modeling studies over Northern Eurasia and identifies the many ecological and geophysical processes comprising Earth system dynamics (i.e. the hydrological cycle, soil thermal dynamics, wildfires, dust emissions, carbon cycle, terrestrial ecosystem dynamics, climate and weather, sea ice) and the human dimensions (i.e. demography, risk management addressed, agriculture, forestry, water management) addressed by the Northern Eurasia modeling community. Because of the major role of Northern Eurasia in the global land system, they find that most studies focus on the land processes (i.e. land and water carbon cycle, energy balance) or on the fate of the land system under climate change (permafrost thawing, agriculture, wildfire). They also find that most studies focus on a single component of the Earth system, with generally little attention placed on interactions and feedbacks, and with climate change being imposed. Nonetheless, Monier et al. (2017) identify a few studies that try to integrate various aspects of the Earth system, in terms of scale, teleconnection or global feedbacks, and processes, as well as other studies focusing 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, 2011b; Kuemmerle et al. 2011a, 2011b, 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 into more coordinated and multidisciplinary research projects by NEESPI scientists along with the development and integration of models that can interact with each other, including weather and aerosol physics, permafrost and terrestrial hydrology with water management, the carbon and water cycles, land carbon and atmospheric transport modeling, and biospheric and climate information (Table 1).

**Table 1.**

Modeling studies focusing on a specific component of the Earth system have provided valuable insight into processes controlling their behavior and the direct impact of climate change. Meanwhile more integrated modeling studies have been useful for identifying and quantifying potential interactions and feedbacks among various components of the Earth system and societal activities associated with environmental changes over Northern Eurasia. However, most studies of climate change impacts rely on standard socio-economic and climate change scenarios, thus limiting the possibility of conducting integrated studies. A common experimental design for these studies is to prescribe climate change and to examine the varied response of a particular component of the Earth system (Rosenzweig et al. 2014). In such an approach, many potential global and regional feedbacks that can have major implications for the climate system, both in Northern Eurasia and globally, are overlooked. The development of effective climate mitigation and adaptation strategies for Northern

Eurasia depends on understanding how environmental conditions may evolve in the region within the context of global change, including the influence of feedbacks and potential thresholds (i.e., "tipping points"). Fortunately, modeling frameworks have already been developed to study these issues (see the next section) and they could be improved to better represent the important aspects of the Earth system that are unique to Northern Eurasia.

**New approaches to integrated modeling for Northern Eurasia**

Earth System Models (ESMs; Brovkin et al. 2006, 2013; Friedlingstein et al. 2006; Arora et al. 2013; Eby et al. 2013; Zickfeld et al. 2013; Koven et al. 2015; Zaehle et al. 2015**)** have been developed by coupling together unique Earth system component models (e.g., atmosphere, land, cryosphere, oceans). These provide an ideal modeling framework to investigate interactions and feedbacks among these components as well as the impact of changes in Northern Eurasia on the global Earth system. For example, in an ESM, carbon emissions from land-use change in Northern Eurasia may increase atmospheric carbon dioxide concentrations to influence climate, the uptake of atmospheric carbon dioxide by oceans to influence ocean acidification, and the uptake of atmospheric carbon dioxide by land vegetation in the future. ESMs provide tools to investigate the response of the system to changes in external forcings that not only affect each of the components individually but also the interactions among them. For example, climate change impacts cannot be examined without considering the role of human activity. In current ESMs, however, there is a simple representation of the influence of human activity on earth system components. Anthropogenic effects related to industrial, residential, and agricultural activities may be represented by simply prescribing an input of greenhouse gases into the atmosphere. More sophisticated ESMs might also use prescribed changes in land use across the globe to simulate the effects of spatial and temporal variations in albedo, sensible and latent heat fluxes, and greenhouse gas fluxes on regional and global energy budgets. In these ESM studies, the simulated human activity is determined solely by prescribed policies without any consideration about how feedbacks from changing environmental conditions might modify these activities in the future. For example, the land-use change prescribed in CMIP5 simulations is driven solely by socio-economic considerations and does not account for climate change impacts on land productivity (Hurtt et al. 2011).

Because ecological and social systems are interdependent and constantly co-evolving, their non-linear behavior is difficult to predict. Taking into account 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 (Jones et al. 2013; DeLucia 2015). For this reason, another major effort has been put into the linkage between models of human activity, including the global economy, global trade, demography, technologies and user preferences—which are essential to study the potential impacts of humans on the environment—to models of the physical climate system, generally simplified compared to ESMs. These models are known as **Integrated Assessment Models** and allow economic decisions to respond to changing environmental conditions to support mitigation and adaptation efforts (**IAMs**; Rotmans et al. 1990; Alcamo et al. 1994; Weyant et al. 1996; Prinn et al 1999; Sokolov et al. 2005, 2009; van Vuuren et al. 2006, 2007; Riahi et al. 2007; Hijioka et al. 2008; Melillo et al 2009, 2016; Wise et al. 2009; Reilly et al. 2012; Hallgren et al. 2013; Prinn 2013; Nelson et al. 2014a, 2014b; Sue Wing et al. 2015).

IAMs have been at the core of the Representative Concentration Pathways (RCPs, van Vuuren et al 2011), a set of socio-economic and emissions scenarios, including socio-economic change, technological change, energy and land use, and emissions of greenhouse gases and air pollutants, developed for the climate modeling community in support of the IPCC AR5.

More recently, major efforts have focused on developing models with a detailed representation of all components of the coupled Human-Earth system, by coupling IAMs with ESMs, or essentially replacing the simplified representation of the climate system in IAMs with ESMs. Such models can provide novel insights into the complex issue of global change by accounting for an exhaustive number of feedbacks among the components of the Earth system and of the human system.

Figure 19 shows an example of a coupled human-Earth system model, with three pathways for feedbacks between the two systems. The first pathway includes the human activity model providing emissions of greenhouse gases, aerosols and other precursors of atmospheric pollution, thus providing the footprint for both future climate change and air quality, with a feedback on the human system through health impacts. The second pathway centers on land, with the human activity model making decisions on land use change based on natural ecosystem productivity and crop yield. Finally, the third pathway centers on water, with the Earth system model computing basin-wide geophysical water resources and the irrigation demand from crops, and the human system model making economically based decisions on water availability for irrigation, with competition from municipal and energy use. The global and regional climate would in turn be affected by land use and land cover change and irrigation, through both emissions of greenhouse gases, changes in albedo and in the hydrological cycle.

**Figure 19**.

At the frontier of integrated assessment modeling, a number of issues have emerged that can be better examined with the ongoing development of coupled human-Earth system models for Northern Eurasia (Monier et al. 2017) and include the following:

- The food-energy-water (FEW) nexus. While the FEW is a global issue and major efforts are underway to improve its representation in models of the coupled human-Earth system, it also has unique characteristics over Northern Eurasia that require specific improvements for such models to be useful, including thermokarst dynamics, permafrost degradation, scarcity of human infrastructure, varied levels of agricultural development and management practices, locally diverse hydrological conditions associated with complex biomes and climate interactions.
- The air quality and health nexus. In addition to the traditional anthropogenic precursor emissions associated with the industry, energy and transportation sectors, or biogenic emissions of precursors, Northern Eurasia experiences varied and complex sources of air pollution, including wildfires, crop residue burning and dust. Accounting for these sources of pollutants, specific to Northern Eurasia, along with the transport of pollutants to and from surrounding countries, to quantify the economic impact of future changes in air pollution in the region can prove key to accurately inform policy responses for Northern Eurasia.
- The new transnationalism of natural resources. The more porous international borders that have emerged after the dissolution of the former Soviet Bloc have considerable implications for Northern Eurasia's natural resources. In particular, forest resources but also oil and gas, are at the nexus of regional demand due to uneven distributions within the countries of Northern Eurasia. Understanding and developing levels of sustainable use will have implications ranging from local human livelihoods to the global carbon budget. Integrated models will need to include local, regional and, now, even international drivers and consequences of these coupled human-natural systems pertaining to natural resources.

- The opening of new Arctic trade routes. New trade routes emerging as the result of the shrinking of Arctic sea ice extent could result in the ability of the timber industry and energy exploration to reach remote areas like Siberia. The development of infrastructures to respond to these new economic opportunities, including potential population migration within Northern Eurasia and from neighboring regions, will face challenges such as with climate-driven permafrost degradation or the disappearance of temporary roads constructed over frozen lakes and rivers. Investigating the fate of Northern Eurasia as these new trade routes emerge will require a detailed regional coupled human-Earth system model.

As with any model activity, the representation of interactions and feedbacks among Earth system components and societal activities in Northern Eurasia can be improved within models, in order for these models to address such emerging issues. Insights gained from previous and ongoing efforts by the NEESPI/NEFI research community, such as those on the unique features and processes of Northern Eurasia described above, could be incorporated to guide these model improvements to create a new generation of coupled human-Earth system models to study the role of Northern Eurasia on global change. For example, most ESMs do not have a representation of permafrost dynamics, which is important for Northern Eurasia as the presence of permafrost affects the availability of soil moisture and the timing and magnitude of runoff (which are important for the FEW nexus), the ability to support buildings and other infrastructure (which is important for the socio-economic development of remote regions in Siberia as Arctic trade routes open up after the sea ice retreat), and vegetation primary production rates and decomposition rates of organic matter (which influence the ability of the landscape to provide food, energy and timber and impact the timing, extent and severity of wildfires, which in turn, impact air quality and health). In addition, the degradation of permafrost might also be associated with several important tipping points including those related to water availability and the release of land carbon to the atmosphere. The representation of permafrost dynamics in ESMs could strongly benefit from an improved representation of soil thermal dynamics, as influenced by water, ice, organic matter and soil texture in the soil profile, and of the surface insulating layer and its modification by snow cover, moss, litter or wildfires. Furthermore, we suggest that to improve key processes relevant to Northern Eurasia in ESM and IAM, like permafrost degradation, a stronger involvement of the Northern Eurasia modeling community and local stakeholders is needed.

# Concluding comments

The major goal of this paper is to introduce the reader to the present challenges in Northern Eurasia and to outline the pathways forward to address these challenges in the coming decades. In doing so, we have provided the reader with a sample of exemplars of NEESPI's accomplishments. The science questions of the "*Northern Eurasia Future Initiative*" or NEFI derive from an urgent need to incorporate and expand our knowledge of the consequences of human and social dimensions in assessing current and future change in Northern Eurasia. Across this region, the future strongly depends upon this incorporation and the amelioration of environmental change, the effects of these changes on human societies, and bridging the considerable gaps in research procedures, capacity for prediction, and in time- and space-scales that complicate the integration of human dynamics with environmental dynamics.

When the embryonic NEESPI project began over a decade ago, there were concerns that a program spanning Eurasia involving scientists from multiple disciplines based in a score of nations with complex and sometimes opposing diplomatic missions could have been a failure. However, there were several significant factors that brightened and opposed such a dark forecast. Truly interdisciplinary interactions among engaged scientists who tackled a shared problem are a remarkable glue for holding research projects together, and they proved that 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 many scientists 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 environmental and socio-economic change in Northern Eurasia that may spread well beyond its boundaries have been simply too dire to leave them unstudied and, generally speaking, unknown. NEESPI was born to reverse the situation by elucidating both negative and beneficial aspects of these changes to inform societies and, thus, better prepare them for resilient future development. An objective of NEFI is that this development must now be secured by science-based strategies provided to regional decision makers at different levels that will lead their societies to prosperity.

Northern Eurasia has undergone significant environmental change, having experienced warming in the past few decades that already exceeds the 1.5ºC to 2.0ºC warming limits adopted as a target at the United Nations Climate Change Conference (30 November –12 December 2015, Paris, France). Several aspects of this warming are manifested in changes in the regional energy and hydrological cycles, which affect and interact with the biosphere and with socio-economic activities. These changes are multifaceted. Some of them seem and are inevitable (e.g., ecosystems’ shift, glacial retreat and permafrost thawing, increased fire regimes, the new state of the regional environment); however, it is imperative they are acknowledged and comprehended. Some of these changes, particularly if their consequences are adverse for human well-being, can be reversed, moderated or mitigated — hopefully to levels that will completely or substantially negate their undesirable impacts. These latter instances include proactive and sometimes quite expensive interventions in water management, forestry and agricultural practices, environmental protection, infrastructure and urban planning and resource consumption. In any case, the scientist's duty is to propose and justify strategies for resilient future development in the region. "To justify" is a key word here. Scientists must strive to know the Earth system in its functional entirety to develop the tools necessary to project the future state in response to natural and societal impacts, as well as to estimate the overall consequences of the realization of these scenarios on human wellbeing.

To these ends, we have formulated three major science questions to be answered by NEFI:

*1). How can we quantify and project ecosystems dynamics in Northern Eurasia when these dynamics may be internally unstable, are controlled by components that have been systematically changing, and have a potential to impact the global Earth system with unprecedented rates of change over the next few decades?*

*2). 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?*

*3). 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 disentangling restrictive institutional legacies?*

To address these science questions, nine research foci are identified and their selection has been briefly justified in this paper. These research foci are: (1) Global change influence, particularly warming in the Arctic; (2) Increasing frequency and intensity of extremes and changes in the spatial and temporal distributions of inclement weather conditions; (3) Retreat of the cryosphere; (4) Changes in the terrestrial water cycle; (5) Changes in the biosphere; (6) Pressures on agriculture and pastoral production; (7) Changes in infrastructure; (8) Societal actions to mitigate the negative consequences of 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. The socio-economic research challenges are integral to and a top priority for these research foci.

Taking into account the numerous powerful feedbacks between the Earth and human systems in Northern Eurasia, we propose to employ Integrated Assessment Models (IAMs) at the final stage of this global change assessment. The purpose of these IAMs is to couple Earth system component models with the result being a functioning integrated Earth System Model. Simultaneously, models of the human system that represent the global economy, global trade, demography, technologies and user preferences will be incorporated. These will provide support to economic and societal decision-makers, so they are able to thoughtfully respond to changing environmental conditions to support mitigation and adaptation efforts. Development of IAMs which include detailed representation of all components of the Human-Earth coupled system to account for the exhaustive number of feedbacks among these components, is the overarching goal of NEFI global change research. These models will provide information and guidance to decision makers in their efforts to secure sustainable and prosperous societal development and resilience-based ecosystem stewardship in Northern Eurasia.

Finally, Northern Eurasia presents a range of complex human and environmental systems varying from modern industrial societies to traditional indigenous cultures, all undergoing significant social and environmental change. Certainly, the continuing transformation of the former USSR, China, Mongolia, and Eastern Europe represents one of the largest and most profound social changes of recent decades. Through NEFI, the work in Northern Eurasia is moving to more effectively address shared goals with interdisciplinary programs at the global level. The research record that will stand as the basis from which to launch NEFI is a logical consequence of the accomplishments of NEESPI. This situation and the need for progress is critical. Now is the time to press forward with this opportunity. The challenge lies before us.

## Abbreviations

| | |
|---|---|
| ACIA | Arctic Climate Impact Assessment |
| AMAP | Arctic Monitoring and Assessment Programme |
| AR5 | The Fifth IPCC Assessment Report |
| BP | Before present |
| CGCM3.1 | Canadian Centre for Climate Modelling and Analysis Model, 3rd Version |
| CMIP5 | Coupled Model Intercomparison Project Phase 5 |
| DLB | Dry Land Belt of Northern Eurasia |
| DSM | Dense Sampling Method |
| ERA-interim | Global atmospheric reanalysis developed at the European Centre for Medium-Range Weather Forecasts |
| ESM | Earth System Model |
| GCM | Global Climate Model |
| GHG | greenhouse gases |
| GLABTOP2 | Glacier Base Topography Model, 2nd Version |

| | |
|---|---|
| GPR | ground-penetrating radar |
| GRACE | Gravity Recovery Satellite Experiment |
| GTN-P | Global Terrestrial Network for Permafrost |
| GTOS | Global Terrestrial Observing System |
| HadCM3 | UK Hadley Centre Climate Model, $3^{rd}$ version |
| IAM | Integrated Assessment Model |
| ICSU | International Council for Science Union |
| IPCC | Intergovernmental Panel on Climate Change |
| IPCLCM4 | Institute Pierre Simon Laplace Climate Model, $4^{th}$ Version |
| LC/LU | Land Cover/Land Use |
| LCLUC | Land Cover and Land Use Change |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| NEESPI | Northern Eurasia Earth Science Partnership Initiative |
| NEFI | Northern Eurasia Future Initiative |
| RFE | Russian Far East |
| RubCliM | Large-Scale Bioclimatic Envelope Model |
| SibCliM | Siberian Bioclimatic Model |
| SIE | Sea Ice Extent |
| WMO | World Meteorological Organization |

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The authors declare that they have no competing interest.

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## Authors' contributions

PG, HS, GG, SM, and SG proposed the topic, conceived and designed this overview. They wrote the Introduction part of the Manuscript. Other major contributors to the Introduction Section are NS, ASo, and JQ. Major contributors to Section on Three Unique Features of Northern Eurasia of Global Concern and Their Related Major Science Questions are PG, NT, JQ, HS, NS, GH, KB, TL, AP, and DK. Each author of the paper has contributed to the Major Research Foci Section of the paper. EM and DK are the major contributors to Section devoted to Global Change Modeling in Northern Eurasia of the paper. HS and PG were the major contributors to the last (Concluding Comments) Section. All authors read and approved the final manuscript. All Authors suggested numerous editorial corrections to the manuscript. In addition to scientific contributions, the language editorial service was provided by the authors, who are the native English speakers: HS, DK, GH, KB, KdB, ASo, and JM.

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# Figure legends

**Figure 1.** 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. On this map, green corresponds to vegetated lands. Light brown and yellow indicate sparse vegetation and arid areas, respectively (Groisman et al. 2009). Major city names within the NEESPI domain (shown in Groisman et al. 2009) are removed. During the NEESPI studies, we expand the study domain occasionally to address the ecosystem in its entirety beyond the strict lat/long boundaries (e.g., taiga and tundra zones in Fennoscandia or barren and semi-desert areas in China. The Dry Land Belt of Northern Eurasia is sketched on the map by a dashed white line.

**Figure 2.** Global annual surface air temperature anomalies (°C) derived from the meteorological station data for the 1957–2016 period (Lugina et al. 2006, updated). 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). The reference period used for calculations of anomalies is 1951–1975. Dotted ovals in the figure show (a) this reference period, (b) the new state of the global Earth system (+0.3° to 0.4°C of the global temperature) with shift during the late 1970s and early 1980s, that manifested itself in biospheric, oceanic, cryospheric, and atmospheric variables around the World (Reid et al. 2016), and (c) the last period (since circa 2001) , when impacts on the Earth system (e.g., retreat of the cryosphere, Arctic warming, increasing dryness of interior of the continents) still need to be completely documented.

**Figure 3.** Seasonal temperature anomalies over Northern Eurasia (the NEESPI study domain) for the 1881–2016 period. The reference period used for calculations of anomalies is 1951–

1975. The annual anomaly for 2016 is +2.0°C. Linear trend estimates shown by dash lines are provided for demonstration purposes only. Data source: archive of Lugina et al. (2006 updated).

**Figure 4.** Vegetation distribution under present climate conditions and equilibrium vegetation distribution under future climate conditions (scenarios) over Northern Eurasia in current climate and by the year 2090 as calculated by the RuBCliM ecosystem model (developed by modifying the SibCliM ecosystem models, Tchebakova et al. 2009, 2010, 2016a) using an ensemble of Canadian (CGCM3.1), UK (HadCM3) and French (IPCLCM4) GCM outputs for the B1 and A2 scenarios for the IPCC Fourth Assessment Report (Core Writing Team 2007), where greenhouse gases induced global warming of 3 –5°C and 6 – 8°C, respectively, by 2090 (Tchebakova et al. 2016a).

**Figure 5. Left.** Annual surface air temperature anomalies (°C) area-averaged over the 60°N - 90°N latitudinal zone (Lugina et al. 2006, updated). **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; date of retrieval; Dec. 30, 2015). For possible change in 2016, see Gannon (2016). Linear trend estimates shown by dash lines are provided for demonstration purposes only.

**Figure 6.** Examples of fire-induced forest transformations in the light-coniferous (Scots pine and larch) forests of southern Siberia when logging and plantation are done: (a) unburned forest; (b) forest burned by low-severity fire with high trees survival; (c) forest burned by high-severity fire with high tree mortality; (d) repeatedly-burned forest with all trees killed and almost all organic layer consumed; (e) logging after post-fire tree mortality; (f) repeatedly burned and logged forest site, with little to no tree regeneration, dominated by tall grasses; (g) plantation of Scots pine on a repeatedly-disturbed site with no natural regeneration; (i) burned

plantation; (j) the “question” mark indicates sites where management activities may alter these disturbance trajectories in unknown ways (Kukavskaya et al. 2016).

**Figure 7.** Manifestations of the cryosphere retreat: **(a)** Spring snow cover extent anomalies over Eurasia (Blunden and Arndt 2016); **(b)** Number of newly emerging thermokarst lakes in West Siberia during the 1973–2013 period (Polishchuk et al. 2015); **(c-d)** Altai Mountains on the boundary of Russia, China, and Mongolia; Kozlov glacier in 1906 and 2013, respectively (Syromyatina et al. 2015).

**Figure 8.** Annual number of deep cyclones with sea surface atmospheric pressure in its center less than 980 hPa entering sector [45°N – 50°N; 60°E – 90°E] that encompasses Central Asia according to ERA-interim reanalysis (Archive of Tilinina et al. 2013, updated).

**Figure 9.** Changes in the surface water cycle over Northern Eurasia that have been statistically significant in the 20$^{th}$ century; areas with more humid conditions **(blue**), with more dry conditions (**red)**, with more agricultural droughts (**circles and ovals**), and with more prolonged dry episodes (**rectangles**) (Groisman et al. 2009, updated). In the westernmost region of this map (Eastern Europe), blue and red rectangles overlap indicating “simultaneous” (although in different years) increases of heavy rainfall frequency and of occurrences of prolonged no-rain periods.

**Figure 10.** Top panel: Annual precipitation and surface air temperature in Siberia (east of the Ural Mountains, excluding Chukotka) from 18 Siberian 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 (source of the sea ice extent data: U.S. National Snow & Ice Data Center, Boulder, Colorado, USA web-site, http://nsidc.org/data).

**Figure 11**. Carbon sources and sinks by 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).

**Figure 12.** Major export markets for Russian forest products 1960—2009 (archive of Newell and Simeone 2014; data source European Forest Institute 2014).

**Figure 13.** Changes in sown areas across the former Soviet Union (Russia, Ukraine, and Kazakhstan) from 1990 to 2013; areas of abandoned sown areas for this period are: 40 Mha in Russia (Rosstat 2016); 5.4 Mha in Ukraine (Ukrstat 2014); and 13 Mha in Kazakhstan (Kazstat 2014).

**Figure 14.** Land cover change from 2001 to 2012 based on MODIS LC products for the three regions within DLB.

**Figure 15**. Land-use and land-cover change in the Asian part of the DLB without steppe regions of Siberia from 2001 to 2012 (Qi et al. 2012a, 2012b updated). Two zoomed windows show the land-use and land-cover changes between 2001 and 2012 in (A) the Central Asia around the Uzbekistan and (B) southern border of the Gobi Desert around Lanzhou, China.

**Figure 16**. Almaty urban region in Kazakhstan from DSM satellite observations in 2000 (left) and 2009 (right), translucently draped over 3D topography. Red represents main urban areas, transitioned into orange for urban area with less development, then to yellow for suburban, and finally to green for rural/natural/wilderness areas. Blue indicates surface water (lakes, reservoirs, etc.). Astounding expansion of the Almaty urban extent occurred between 2000 and 2009.

**Figure 17**. Dramatic increase in the total building volume corresponding to the real estate boom since 2000 in an area of ~6 $km^2$ centered in the urban extent of Almaty in 2009 seen in red in the right panel of Figure 16. Error bars show the accuracy of regional averaged values

(columns) and incorporate together errors of the observation and area-averaging methods used. The linear trend line indicates the mean rate of the building volume increase during the study period and its comparison with error bars shows that the changes are clearly seen beyond the noise generated by observations and the averaging procedure.

**Figure 18**. The frequency of and monetary losses from 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).

**Figure 19**. An example schematic of an Integrated Assessment Model (IAM) that couples a human activity model and an Earth system model (ESM) with a focus on three feedback pathways: health, land-use change, and water resources (from Monier et al. 2017). See text for details.

**Table 1**

Non-exhaustive list of modeling studies with a focus on Northern Eurasia. The list is sorted by specific aspects of the Earth and human systems. Some studies are listed under several aspects of the Earth and human systems. From Monier et al. (2017 updated).

| **Specific aspects of the Earth and human systems** | **References to modeling studies with a focus on Northern Eurasia** |
|---|---|
| Agriculture (crop modeling, economics) | Dronin and Kirilenko 2010; Gelfan et al. 2012; Iizumi and Ramankutty 2016; Magliocca et al. 2013; Peng et al. 2013; Schierhorn et al. 2014a, 2014b; Tchebakova et al. 2011 |
| Air quality (aerosols, ozone, pollen, dust…) | Baklanov et al. 2013; Darmenova et al. 2009; Lu et al. 2010; Siljamo et al. 2013; Sofiev et al. 2013; Soja et al. 2004; Sokolik et al. 2013; Xi and Sokolik 2015a, 2015b |
| Carbon (in land and water) | Bohn et al. 2013, 2015; Cresto-Aleina et al. 2015; Dargaville et al. 2002a, 2002b; Dass et al. 2016; Dolman et al. 2012; Gao et al. 2013; Glagolev et al. 2011; Gustafson et al. 2011a; Hayes et al. 2011a, 2011b, 2014; John et al. 2013a; Kicklighter et al. 2013, 2014; Kim et al. 2011; Koven et al. 2011; Kuemmerle et al. 2011a, 2011b; Kurganova et al. 2014, 2015; Lu et al. 2009b; McGuire et al. 2010; Mukhortova et al. 2015; Narayan et al. 2007; Olchev et al. 2009a, 2013a; Rawlins et al. 2015; Rossini et al. 2014; Sabrekov et al. 2014, 2016; Saeki et al. 2013; Schaphoff et al. 2015; Schierhorn et al. 2013; Schulze et al. 2012; Shakhova et al. 2013, 2015; Shuman and Shugart 2009; Shuman et al. 2013a; Yue et al. 2016; Zhang et al. 2012b; Zhao et al. 2009; Zhu et al. 2013, 2014; Zhu and Zhuang 2013; Zhuang et al. 2013 |
| Climate | Anisimov et al. 2013; Arzhanov et al. 2012a, 2012b; Miao et al. 2014; |

| | |
|---|---|
| | Monier et al. 2013; Onuchin et al. 2014; Shahgedanova et al. 2010; Shkolnik and Efimov 2013; Volodin 2013; Volodin et al. 2013; Zuev et al. 2012 |
| Cryosphere (snow, glaciers, sea ice…) | Callaghan et al. 2011a, 2011b; Farinotti et al. 2015; Hagg et al. 2006; Klehmet et al. 2013; Loranty et al. 2014; Mokhov et al.. 2013b; Pieczonka and Bolch 2015; Shahgedanova et al. 2010; Shakhova et al. 2015; Sokratov and Shmakin 2013; Sorg et al. 2012 |
| Demography | Heleniak 2015 |
| Energy balance | Brovkin et al. 2006; Gálos et al. 2013; Loranty et al. 2014; Olchev et al. 2009b; Oltchev et al. 2002b; Tchebakova et al. 2012 |
| Hydrological cycle | Bowling and Lettenmaier 2010; Cresto-Aleina et al. 2015; Gelfan 2011; Georgiadi et al. 2010, 2014a; Hagg et al. 2006; Karthe et al. 2015; Khon and Mokhov 2012; Kicklighter et al. 2013; Klehmet et al. 2013; Kuchment et al. 2011; Liu et al. 2013, 2014, 2015; McClelland et al. 2004; Motovilov and Gelfan 2013; Novenko and Olchev 2015; Olchev et al. 2009a, 2013a; Oltchev et al. 2002a, 2002b; Osadchiev 2015; Rawlins et al. 2010; Serreze et al. 2006; Shiklomanov et al. 2013; Shiklomanov and Lammers 2013; Shkolnik et al.. 2017; Sorg et al. 2012; Streletskiy et al. 2015b; Troy et al. 2012; Zhang et al. 2011 |
| Land-use change | Blyakharchuk et al. 2014; Chen et al. 2017; Griffiths et al. 2013; Gustafson et al. 2011a; Hayes et al. 2011a; Hitztaler and Bergen 2013; Kicklighter et al. 2014; Kraemer et al. 2015; Kuemmerle et al. 2009; Meyfroidt et al. 2016; Peterson et al. 2009; Prishchepov et al. 2013, 2017; Robinson et al. 2013; Schierhorn et al. 2013, 2014a, 2014b; Smaliychuk et al. 2016; Zhang et al. 2015 |
| Infrastructure | Shiklomanov and Streletskiy 2013; Shiklomanov et al. 2017; Stephenson |

| | |
|---|---|
| | et al. 2011; Streletskiy et al. 2012 |
| Nitrogen | Kopáček et al. 2012; Kopáček and Posch 2011; Oulehle et al. 2012; Zhu and Zhuang 2013; Zhuang et al. 2013 |
| Permafrost | Euskirchen et al. 2006; Gao et al. 2013; Gouttevin et al. 2012; Hayes et al. 2014; MacDougall and Knutti 2016; Marchenko et al. 2007; Shakhova et al. 2013, 2015; Shkolnik et al. 2012b; Streletskiy et al. 2012, 2015b; Zhang et al. 2011 |
| Terrestrial ecosystems characteristics | Cresto-Aleina et al. 2013; Kopačková et al. 2014, 2015; Lapenis et al. 2005; Lebed et al. 2012; Li et al. 2016; Shuman et al. 2013a, 2013b; Shuman and Shugart 2012; Ziółkowska et al. 2014 |
| Vegetation shifts | Gustafson et al. 2011a; Jiang et al. 2012, 2016; Khvostikov et al. 2015; Kicklighter et al. 2014; Li et al. 2014; Macias-Fauria et al. 2012; Novenko et al. 2014; Schaphoff et al. 2015; Shuman et al. 2015; Soja et al. 2007; Tchebakova et al. 2009, 2010, 2016a, 2016b; Tchebakova and Parfenova 2012; Velichko et al. 2004 |
| Weather (i.e. extreme events) | Barriopedro et al. 2011; Meredith et al. 2015; Mokhov et al.. 2013a; Schubert et al. 2014; Shkolnik et al. 2012a |
| Wildfire | Balshi et al. 2007; Dubinin et al. 2011; Gustafson et al. 2011b; Kantzas et al. 2013; Loboda and Csiszar 2007; Malevsky-Malevich et al. 2008; Narayan et al. 2007; Park and Sokolik 2016; Schulze et al. 2012; Soja et al. 2004; Tchebakova et al. 2009, 2012; Vasileva and Moiseenko 2013 |
| Zoology | Bragina et al. 2015; Kuemmerle et al. 2011a, 2014; Ziółkowska et al. 2014 |

Figure 1



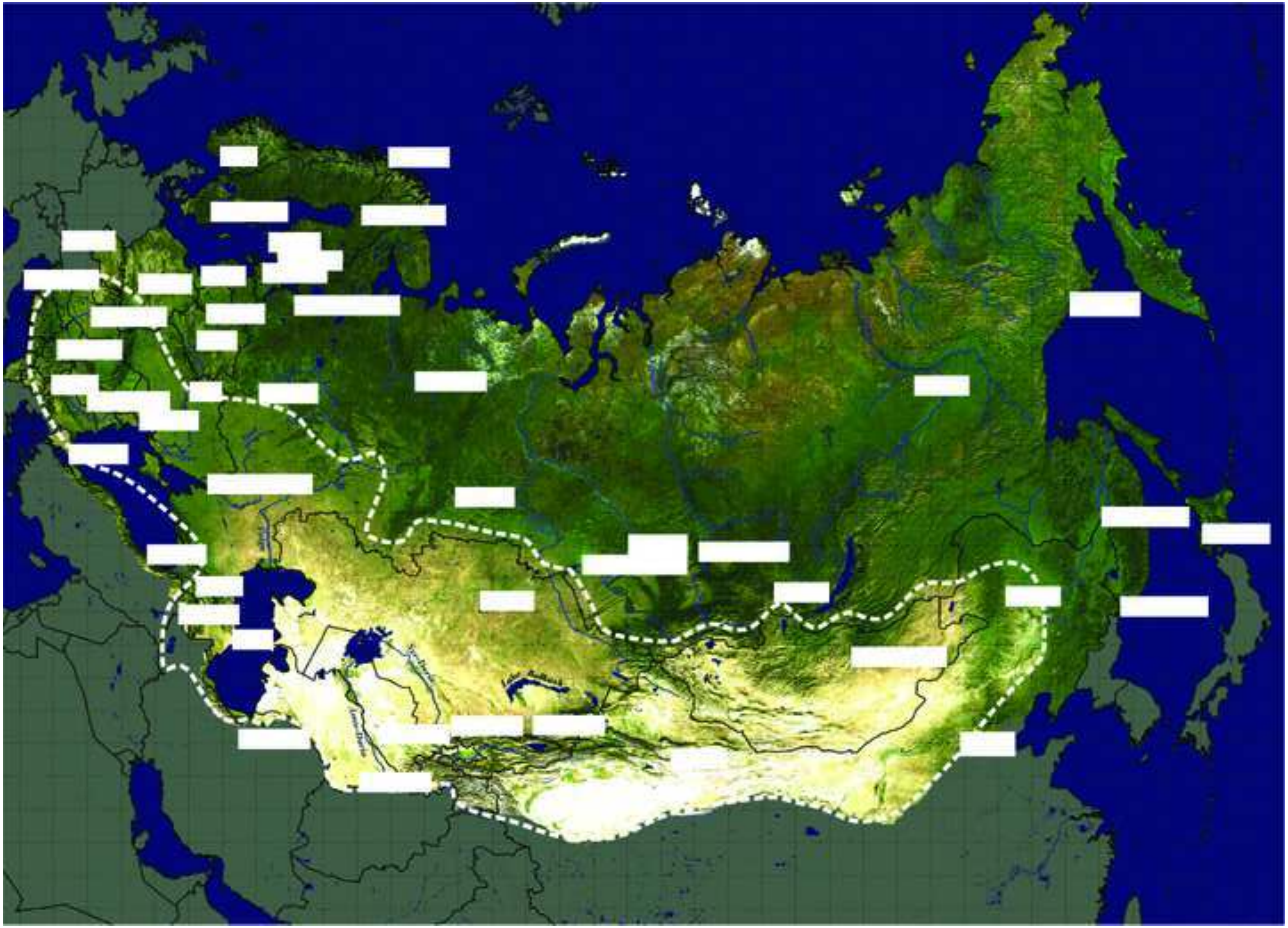

Figure 2

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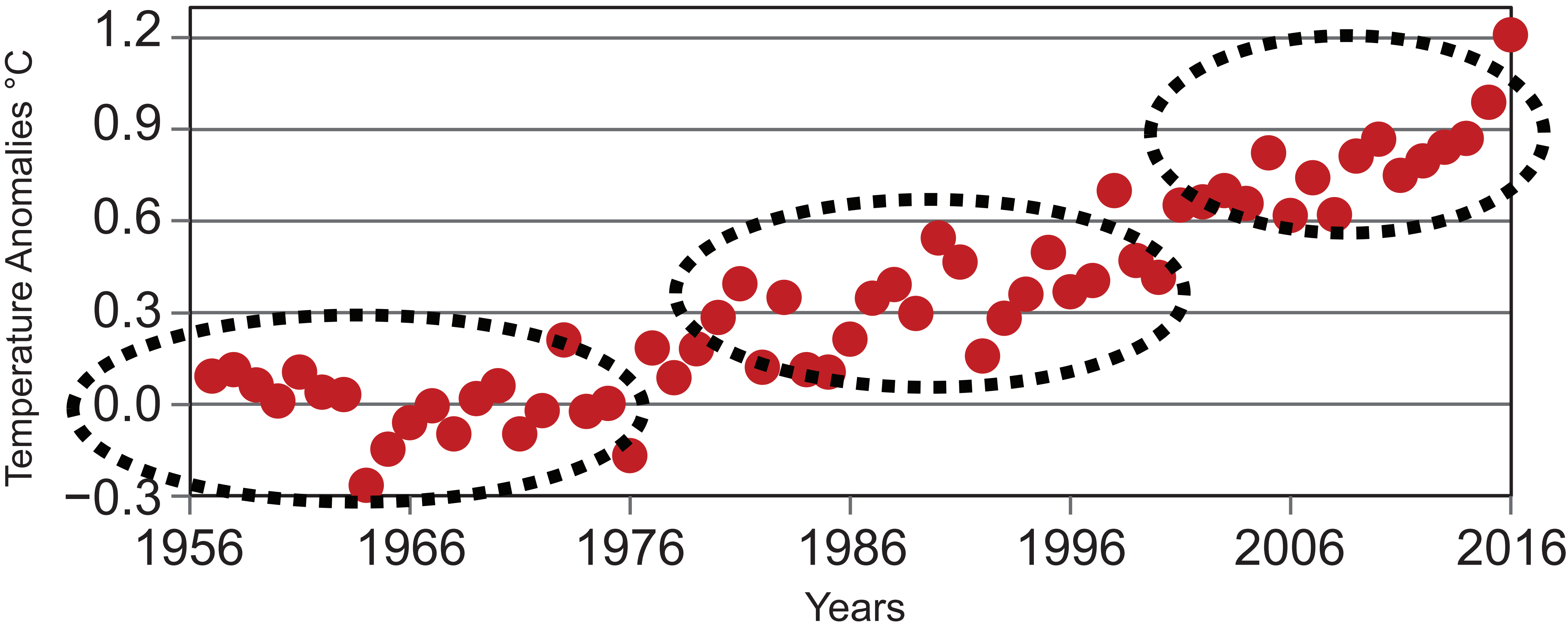

Figure 3

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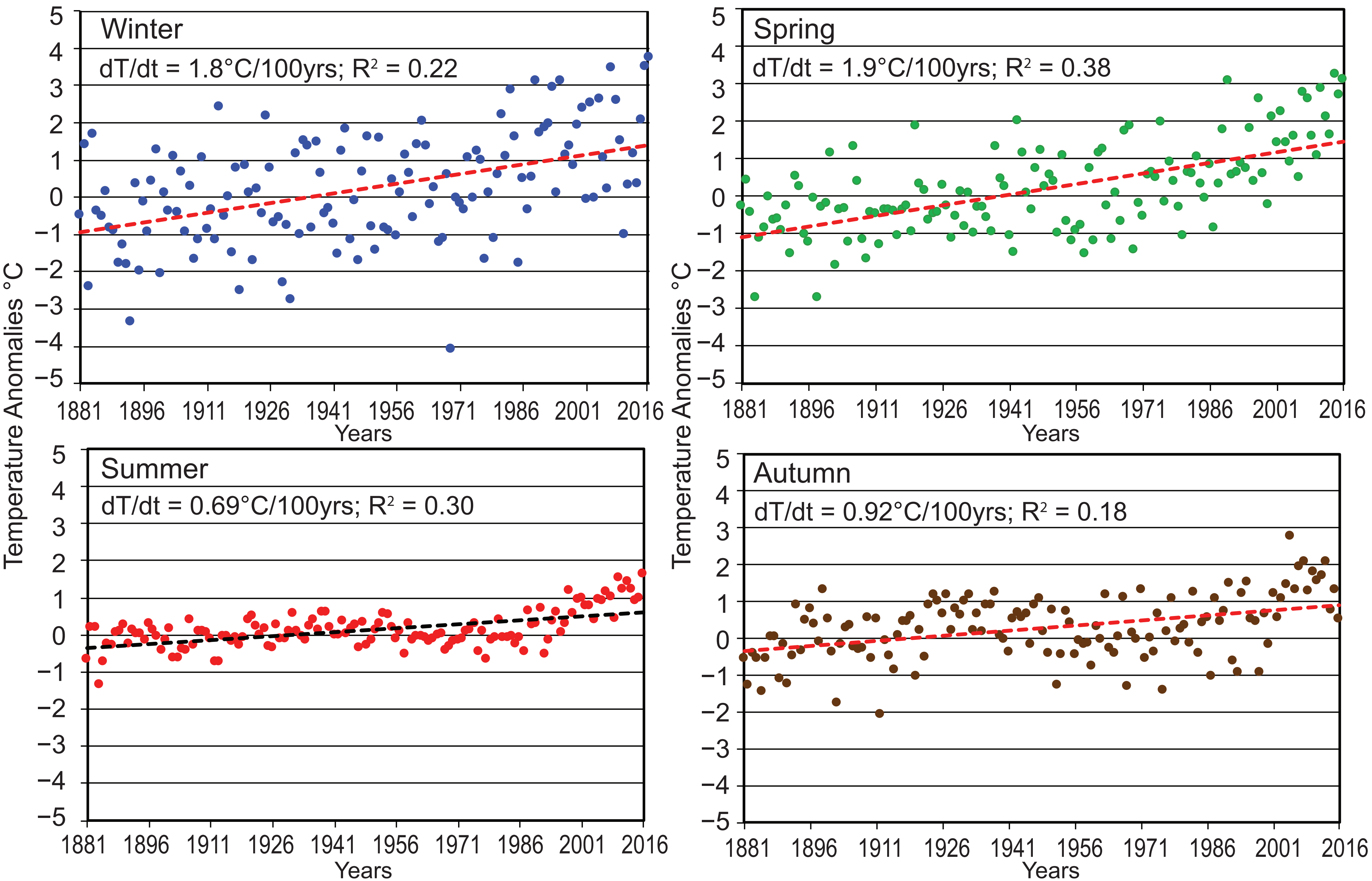

Figure 4

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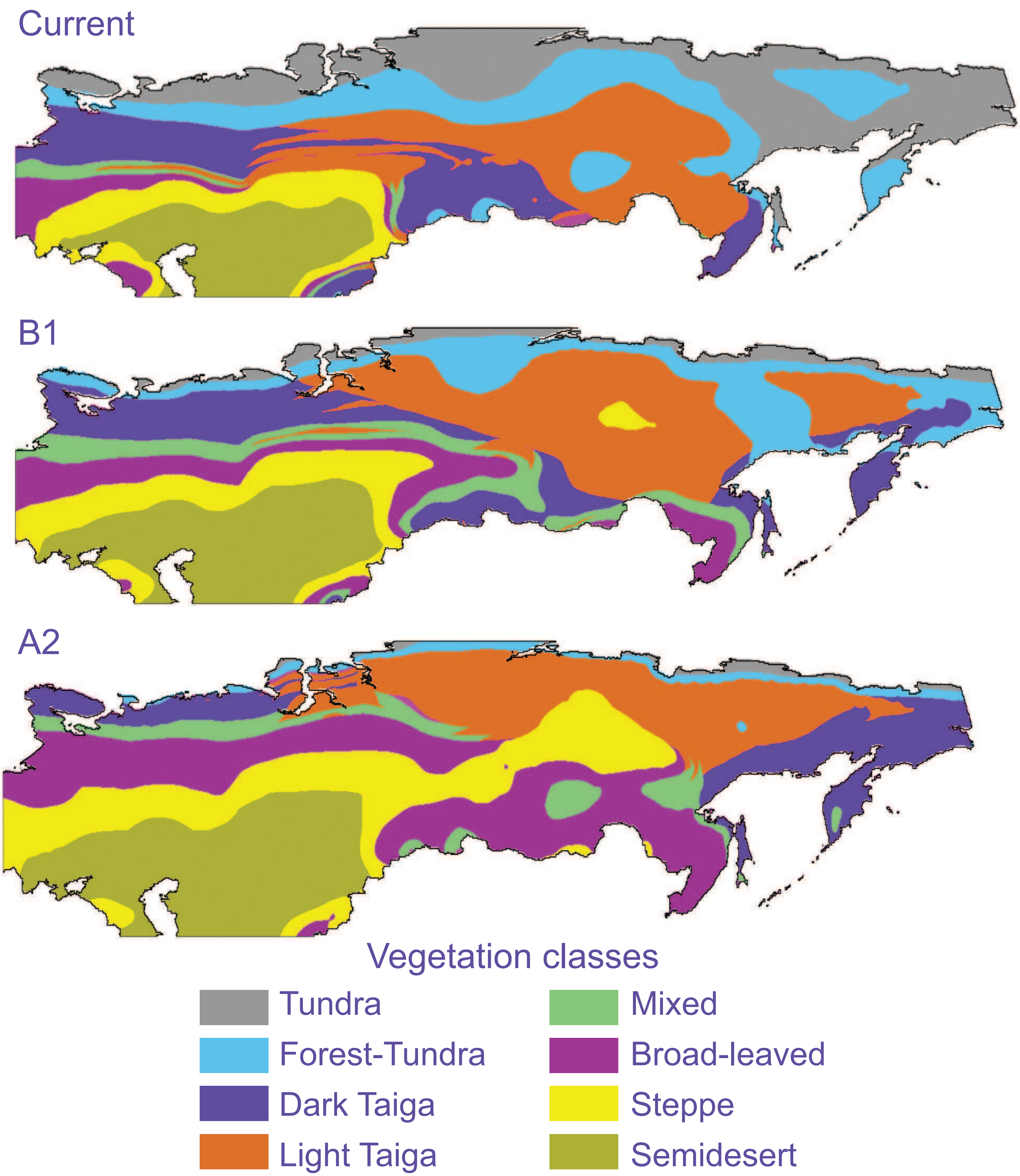

Figure 5

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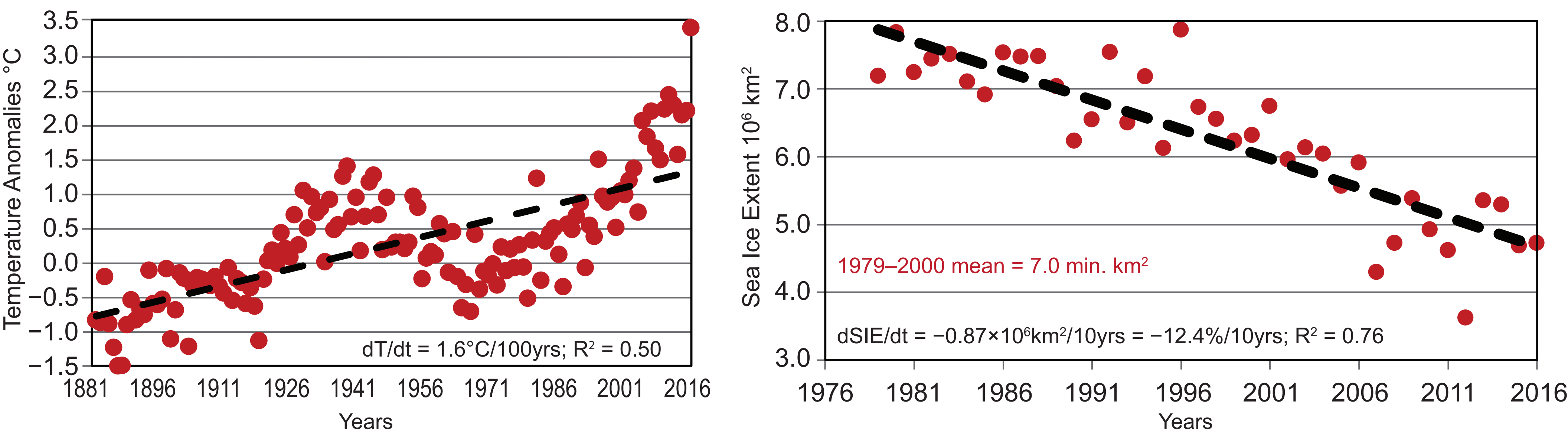
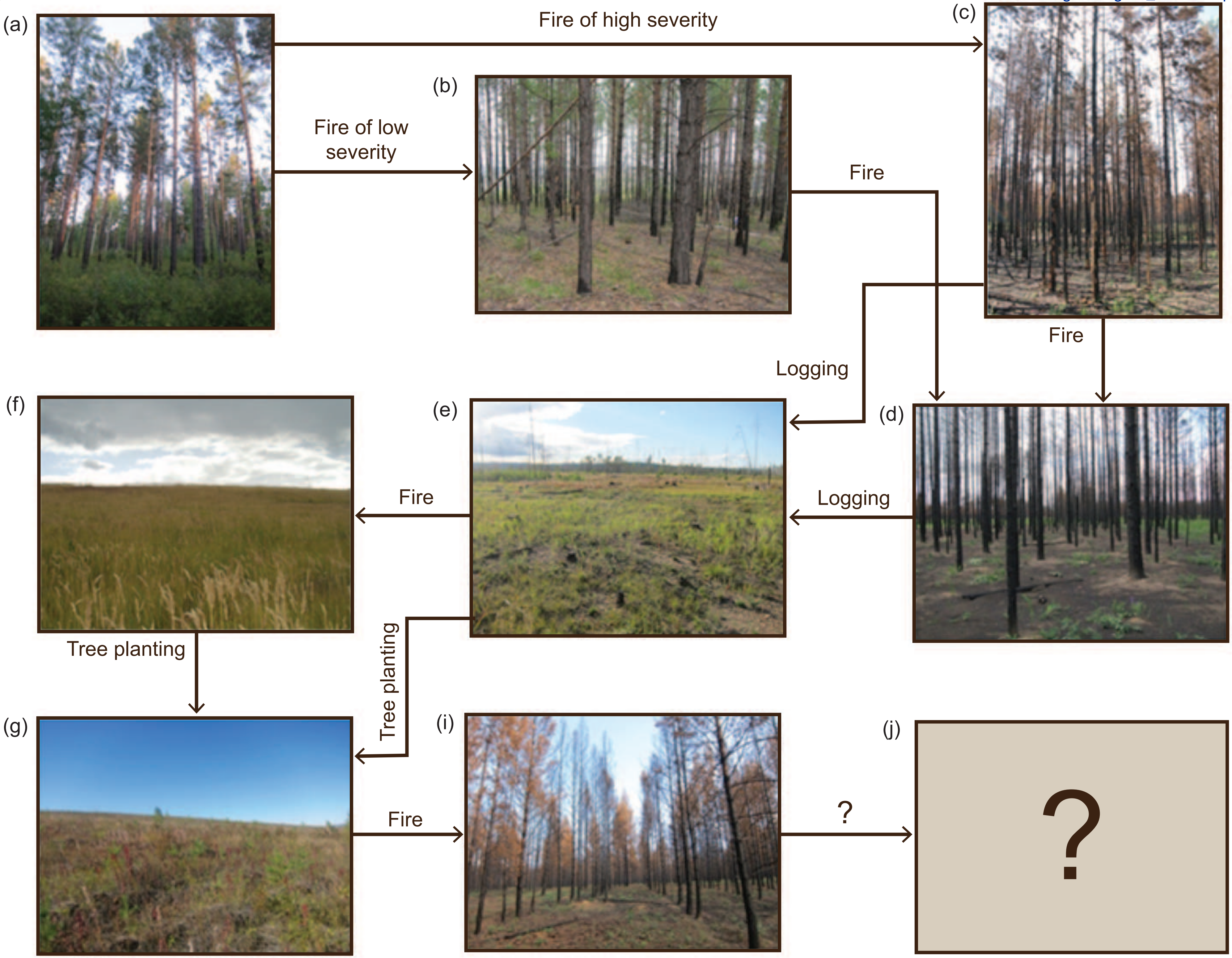


Figure 6





(a)
Fire of high severity
(c)
(b)
Fire of low severity
Fire
Fire
Logging
(f)
(e)
(d)
Fire
Logging
Tree planting
Tree planting
(g)
(i)
(j)
Fire
?
?

Figure 7

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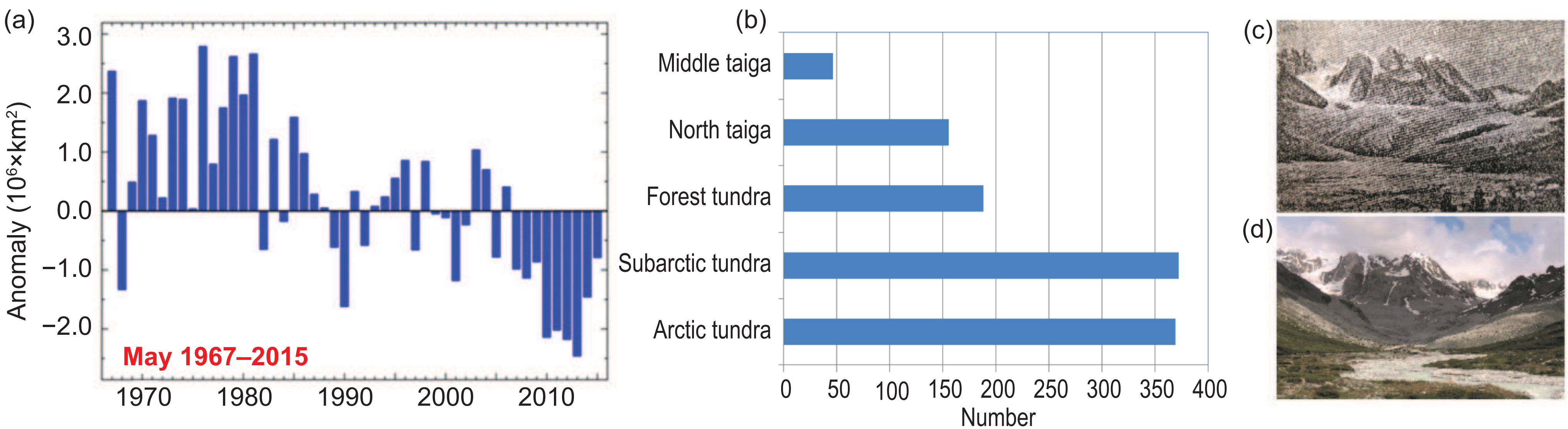

Figure 8

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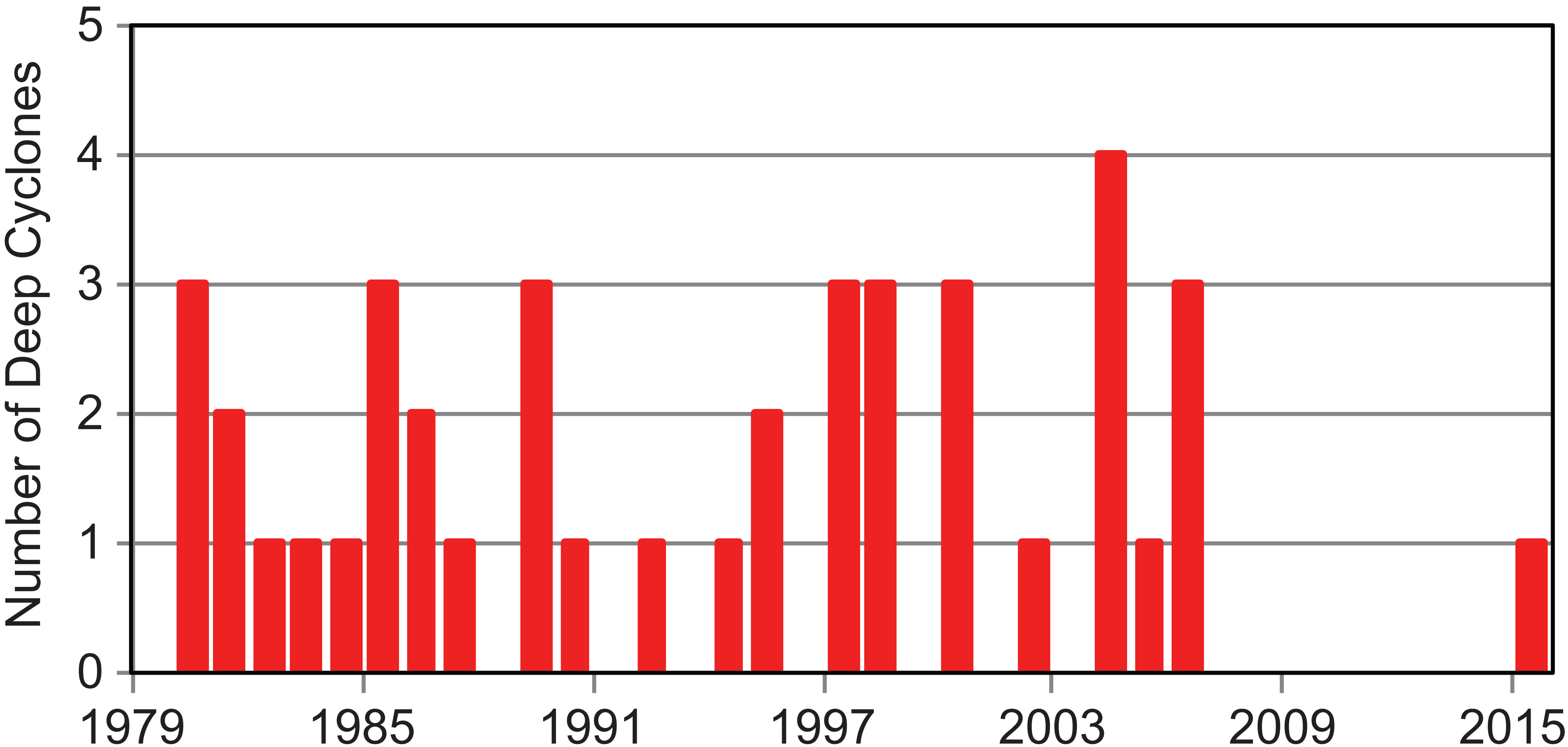

Figure 9

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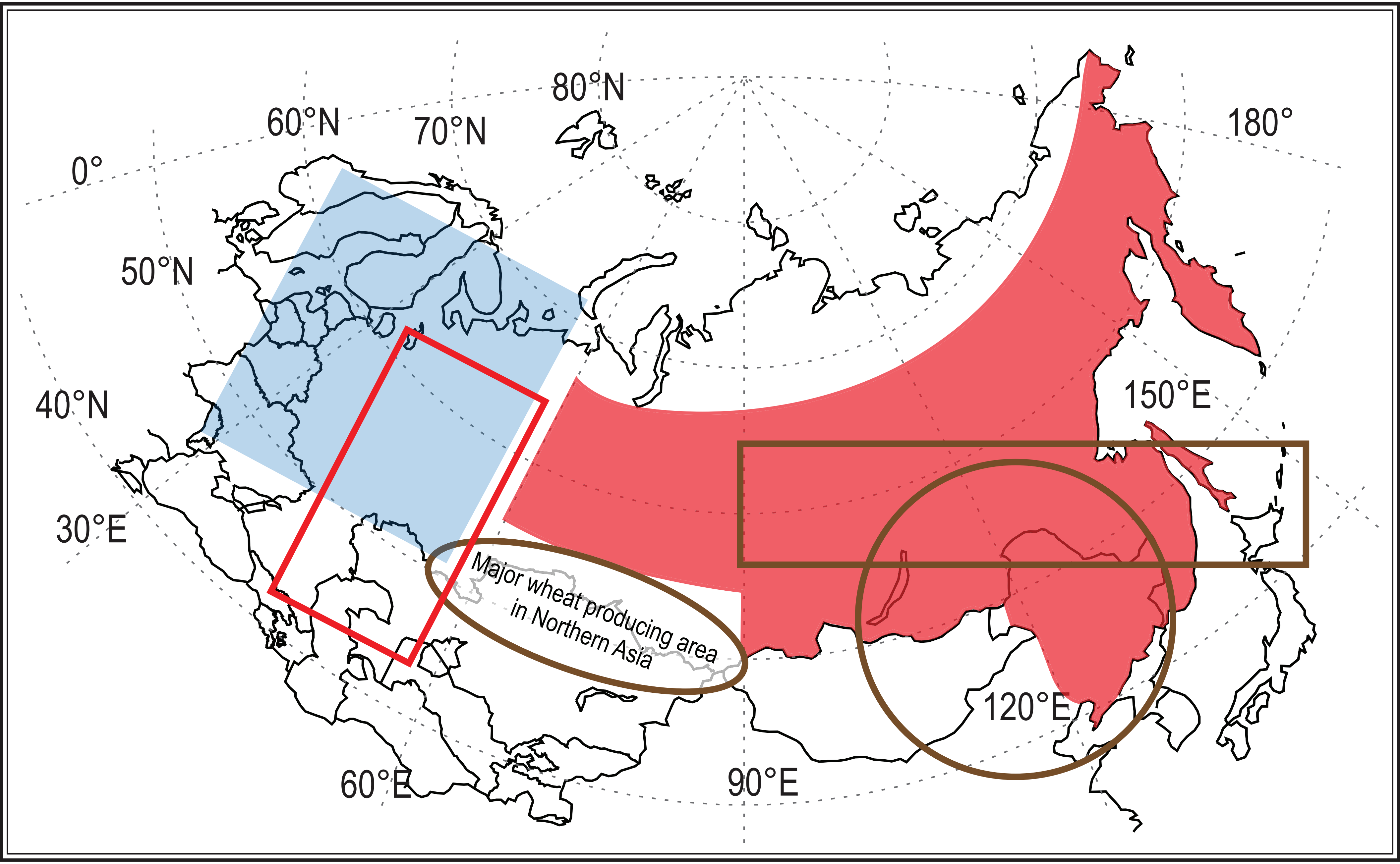

Figure 10

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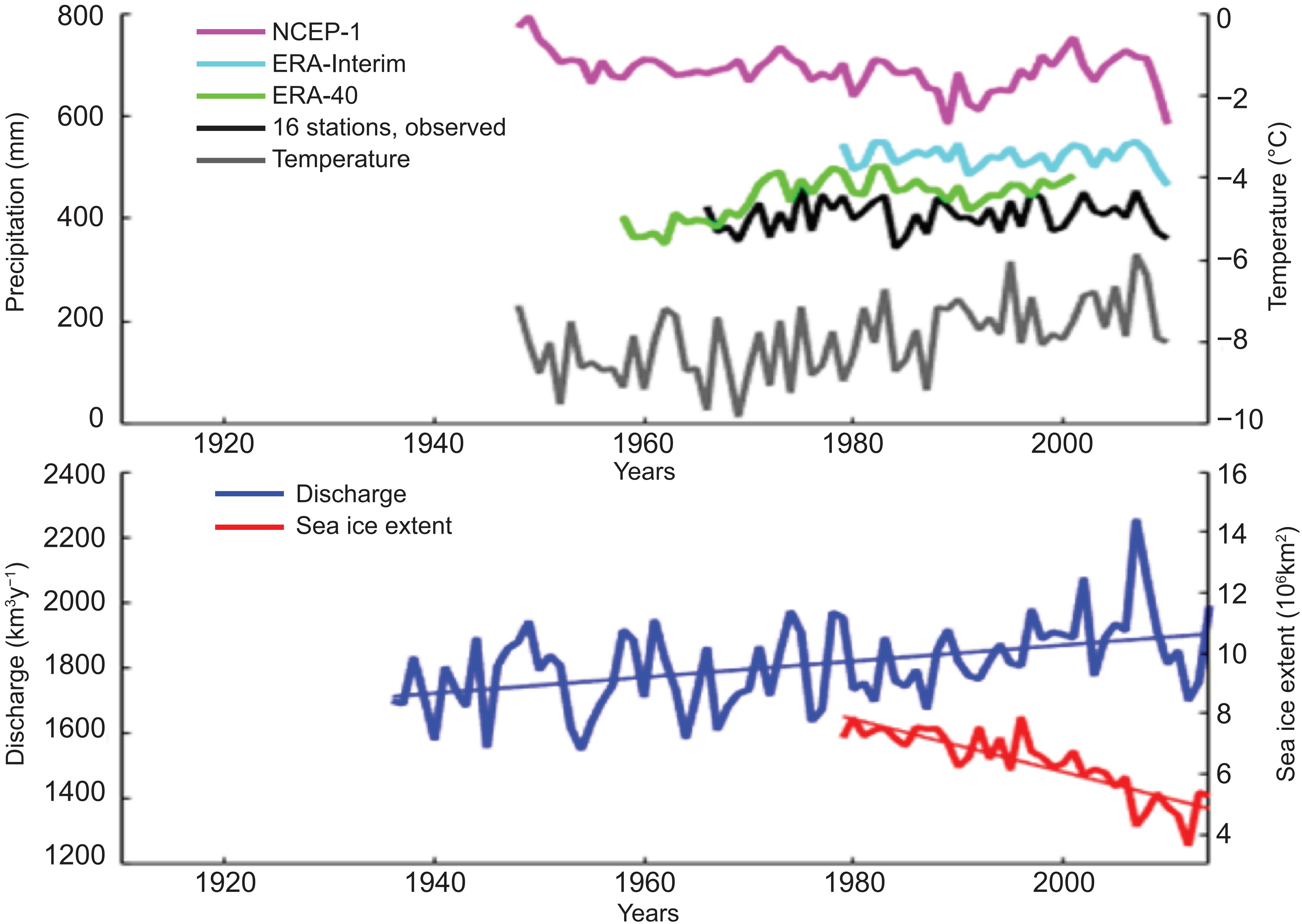

Figure 11

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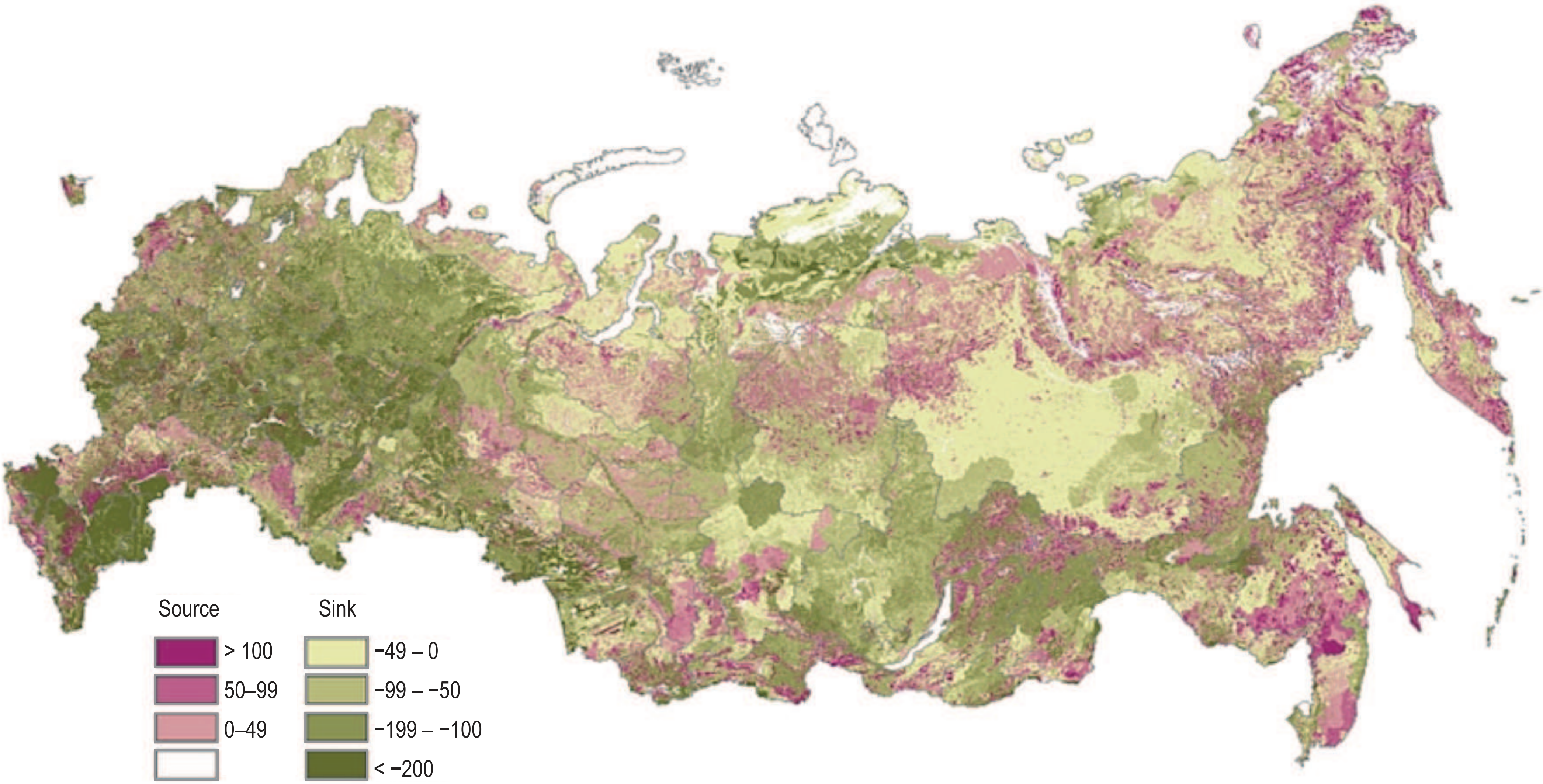

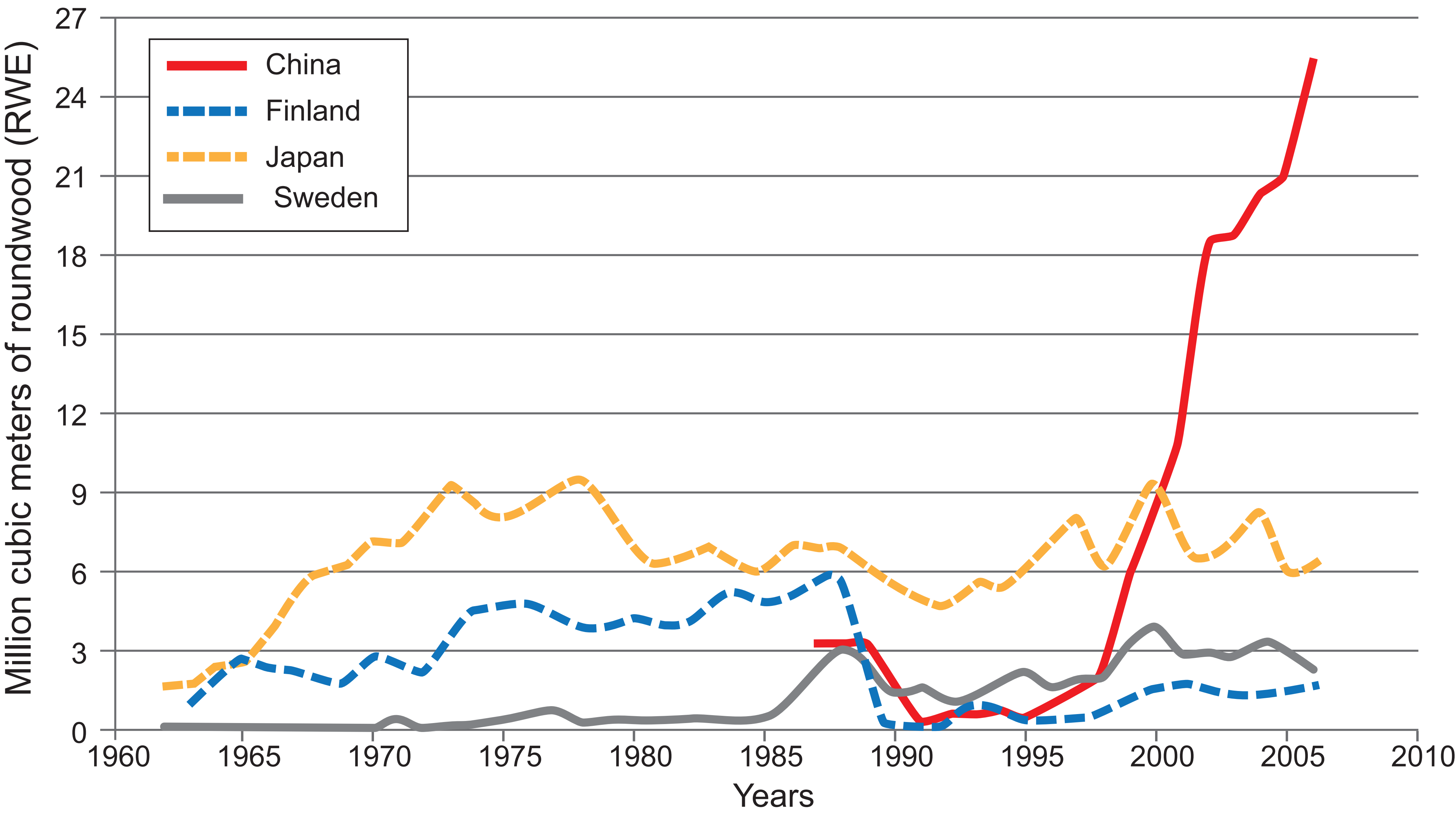
China
Finland
Japan
Sweden
Million cubic meters of roundwood (RWE)
27
24
21
18
15
12
9
6
3
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Years

Figure 13

Click here to download Figure Figure_13-improved.eps

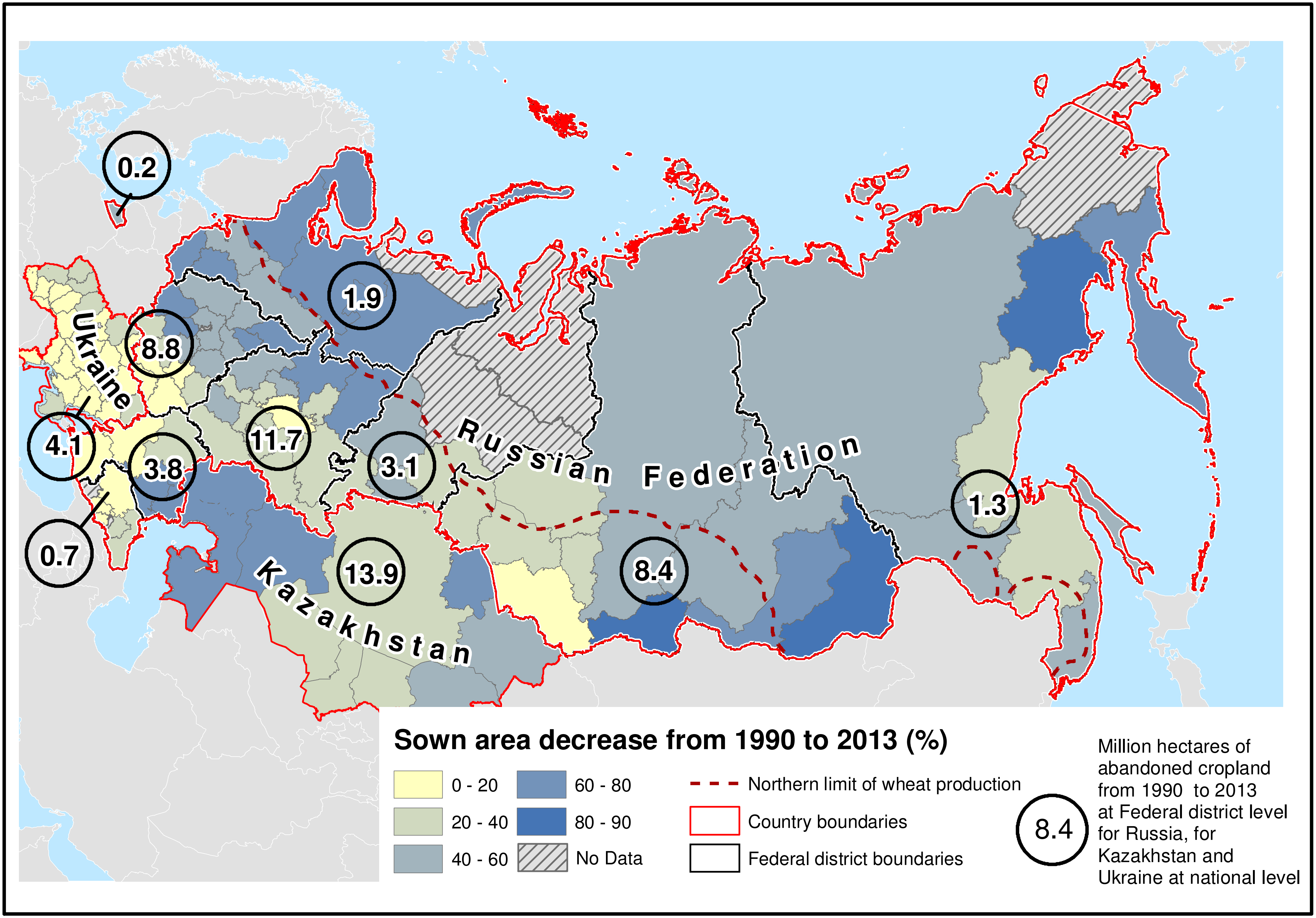

Figure 14

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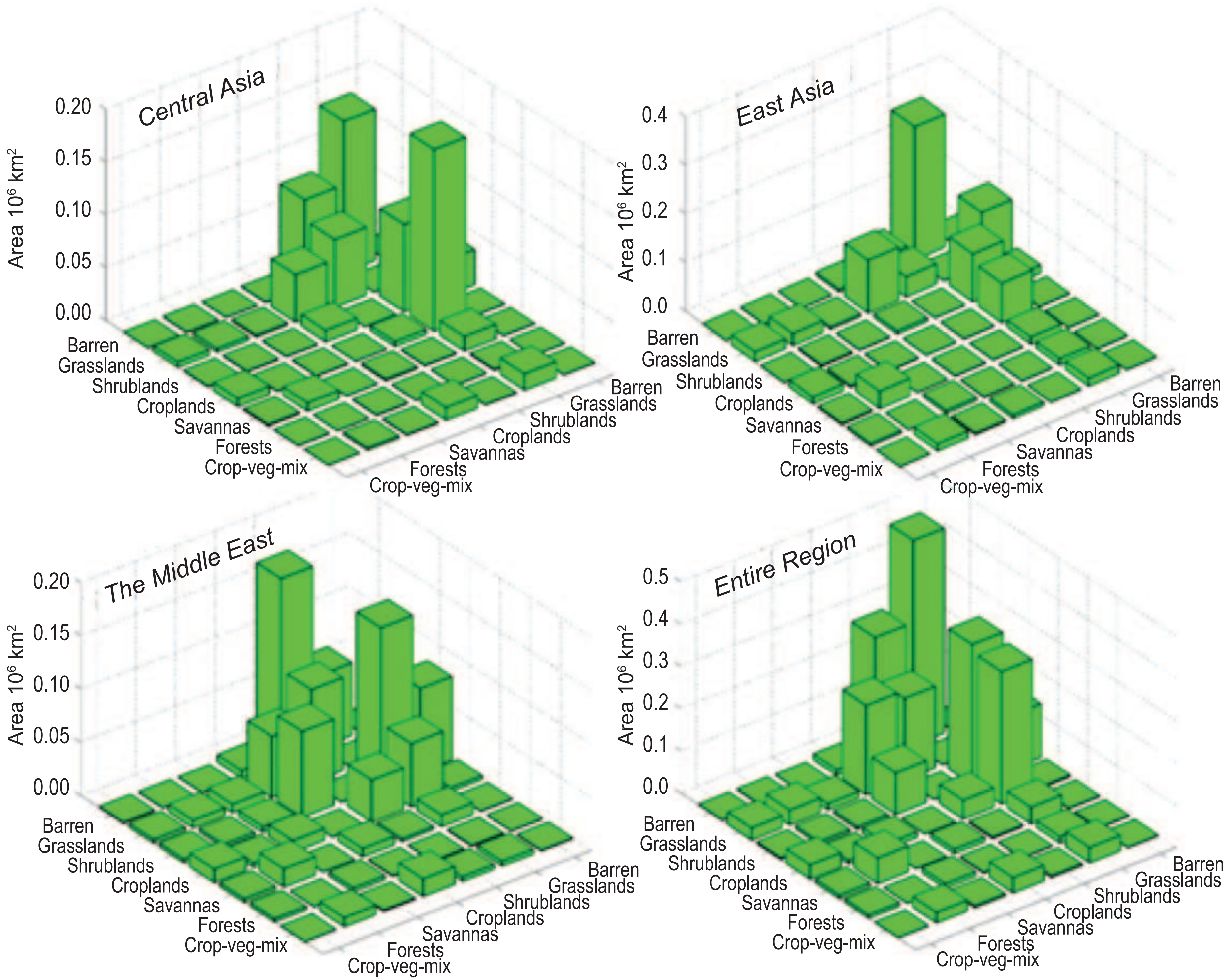

Figure 15

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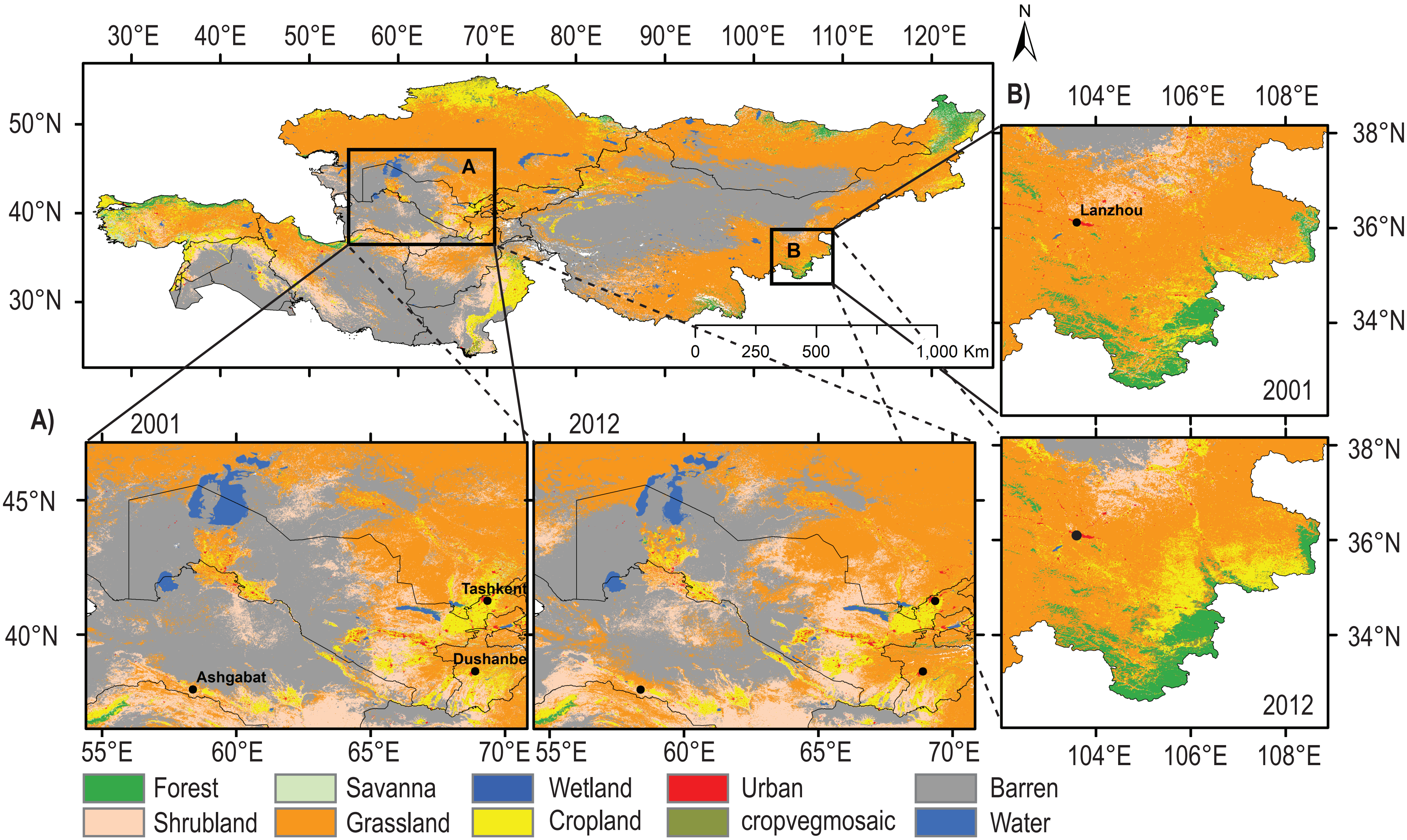

Figure 16

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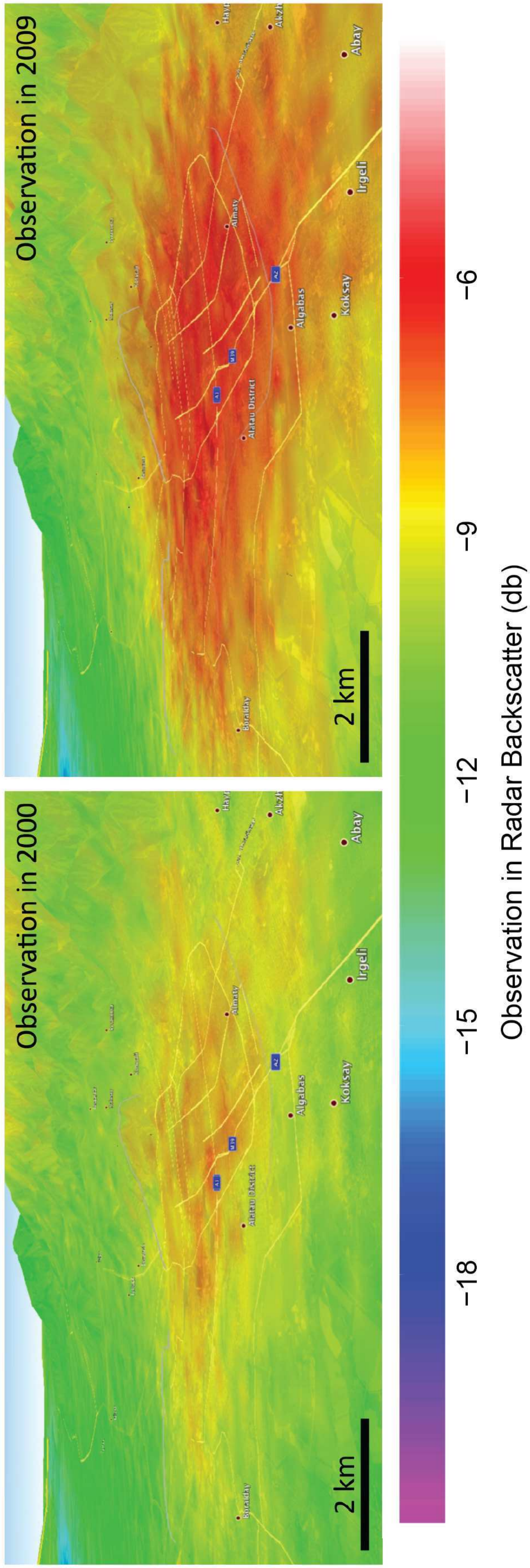

Figure 17

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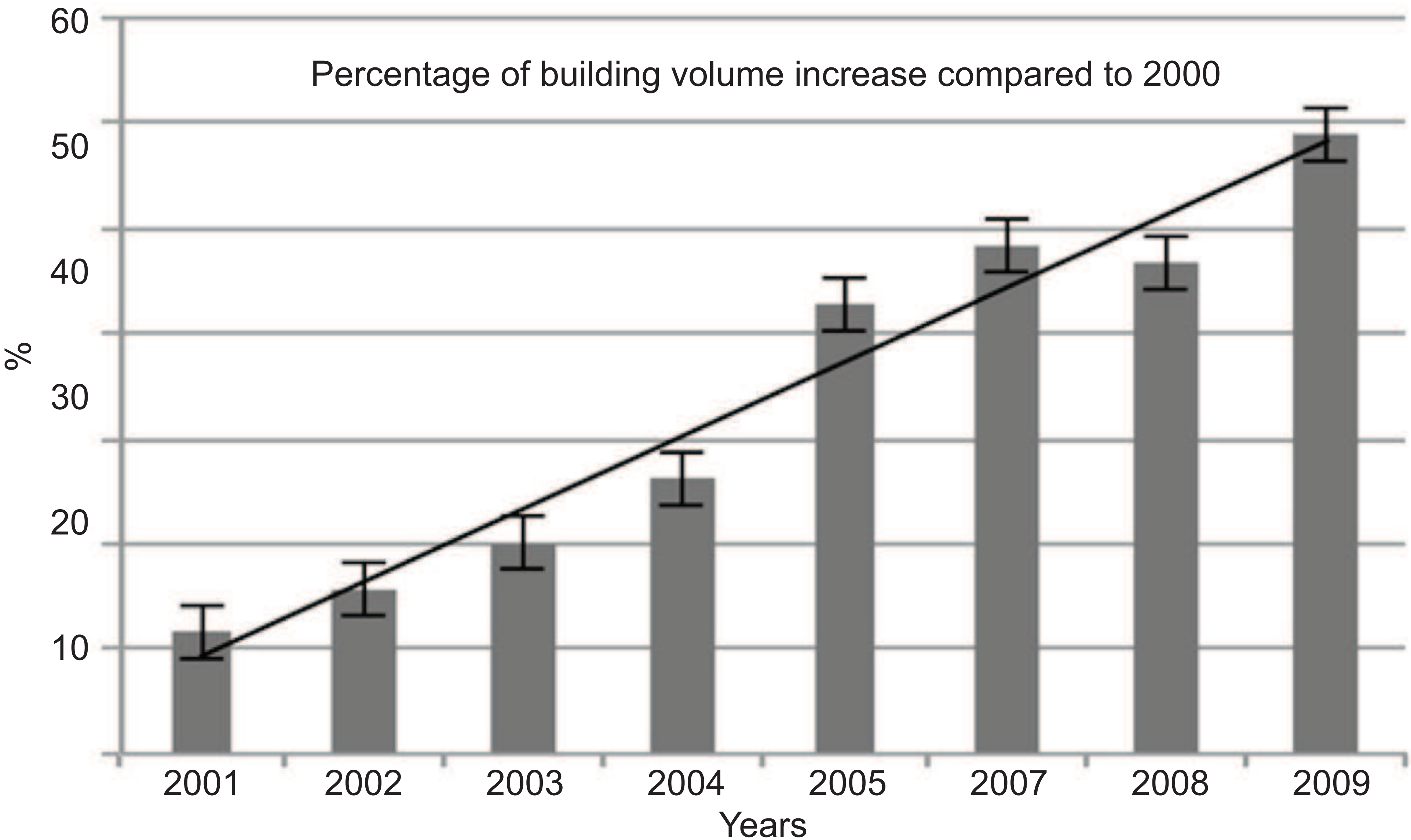
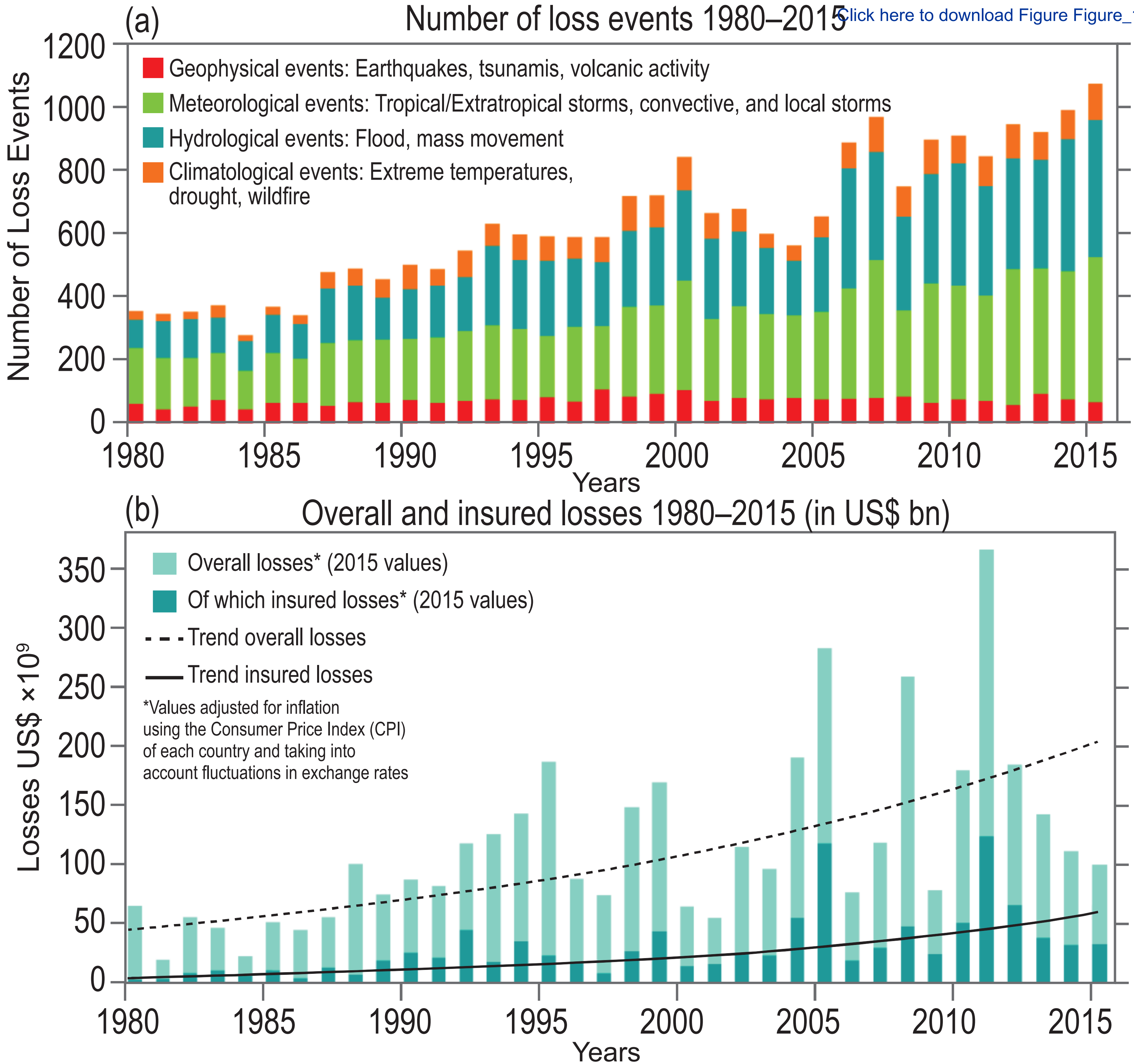


Figure 18

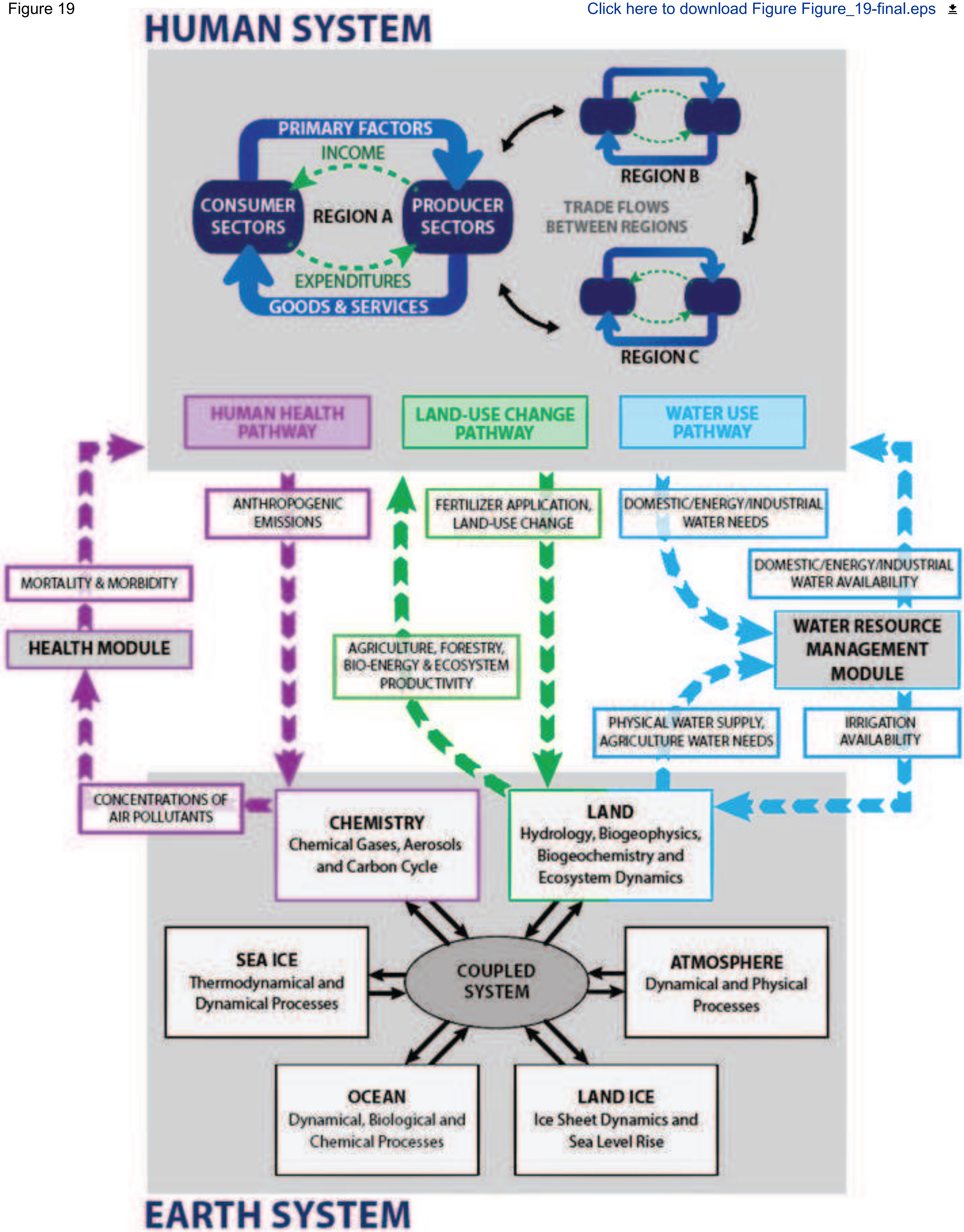




(a)
Number of loss events 1980–2015
Geophysical events: Earthquakes, tsunamis, volcanic activity
Meteorological events: Tropical/Extratropical storms, convective, and local storms
Hydrological events: Flood, mass movement
Climatological events: Extreme temperatures, drought, wildfire
Number of Loss Events
0
200
400
600
800
1000
1200
1980
1985
1990
1995
2000
2005
2010
2015
Years
(b)
Overall and insured losses 1980–2015 (in US$ bn)
Overall losses* (2015 values)
Of which insured losses* (2015 values)
Trend overall losses
Trend insured losses
*Values adjusted for inflation using the Consumer Price Index (CPI) of each country and taking into account fluctuations in exchange rates
Losses US$ ×10⁹
0
50
100
150
200
250
300
350
1980
1985
1990
1995
2000
2005
2010
2015
Years

Figure 19




HUMAN SYSTEM
PRIMARY FACTORS
INCOME
CONSUMER SECTORS
REGION A
PRODUCER SECTORS
EXPENDITURES
GOODS & SERVICES
REGION B
TRADE FLOWS BETWEEN REGIONS
REGION C
HUMAN HEALTH PATHWAY
LAND-USE CHANGE PATHWAY
WATER USE PATHWAY
ANTHROPOGENIC EMISSIONS
FERTILIZER APPLICATION, LAND-USE CHANGE
DOMESTIC/ENERGY/INDUSTRIAL WATER NEEDS
DOMESTIC/ENERGY/INDUSTRIAL WATER AVAILABILITY
MORTALITY & MORBIDITY
HEALTH MODULE
AGRICULTURE, FORESTRY, BIO-ENERGY & ECOSYSTEM PRODUCTIVITY
WATER RESOURCE MANAGEMENT MODULE
PHYSICAL WATER SUPPLY, AGRICULTURE WATER NEEDS
IRRIGATION AVAILABILITY
CONCENTRATIONS OF AIR POLLUTANTS
CHEMISTRY
Chemical Gases, Aerosols and Carbon Cycle
LAND
Hydrology, Biogeophysics, Biogeochemistry and Ecosystem Dynamics
SEA ICE
Thermodynamical and Dynamical Processes
COUPLED SYSTEM
ATMOSPHERE
Dynamical and Physical Processes
OCEAN
Dynamical, Biological and Chemical Processes
LAND ICE
Ice Sheet Dynamics and Sea Level Rise
EARTH SYSTEM

Graphical Abstract Image

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