Terrestrial Ecosystems of Northern Asia, Global Change and Post Kyoto Developments

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Abstract. The paper considers the impacts of global change on environment, current state and dynamics of terrestrial ecosystems (with a special emphasis to forest) of Northern Asia. Implementation of post Kyoto mechanisms and carbon management, mitigation and adaptation strategies are an obligatory feature of transition to sustainable use of renewable natural resources. Future (after the first commitment period) activities within the UNFCC require new scientific and economic decisions.

Key words: Northern Asia, terrestrial ecosystems, global change, Kyoto protocol

Introduction

Northern Asia (NA), a land mass of the continental scale, bounded by 60° and 180 e.L. and by 50° s.lat., plays a substantial role in the global climate machine through complex interactions among atmospheric circulation patterns, temperature regimes, permafrost behavior, river discharge, specifics and functioning of terrestrial ecosystems, and sea ice formation. NA substantially impacts the Earth system as a whole, and, particularly, its climatic and hydrological components. The most dramatic climatic change over the globe is expected in this region. While these territories comprise the largest over the globe indigenous ecosystems, significant part of the region is under the destructive and insufficiently regulated anthropogenic impacts.

Ongoing global change is an integral and inherent feature of the dynamics of NA ecosystems. The NA vegetation more and more becomes socio-ecological systems. This is revealed in the sophisticated interplay and mutual conditionality of impacts, responses and feedbacks of natural, economic and social components, environment and human society. An important feature of the region is fragility of ecosystems which evolutionary developed under a rather stable cold climate. Ecological thresholds and buffering capacity of ecosystems under substantial warming have no analogues and are poorly understood. This generates major challenges for understanding the current and future state, vitality and resilience of ecosystems of high latitudes.

The region has a huge potential for mitigation of climate change, as well as implementation of economic mechanisms introduced by the Kyoto Protocol and following decisions of the Conferences of Parties (COP). About two-thirds of its area covered by forests and wetlands - ecosystems of maximal potential to maintain or increase carbon stock in the long run [IPCC, 2007]. However, the regional specifics, insufficient governance of natural resources, high intensity of expected climatic change and some peculiarities of the Protocol require special consideration of a number of issues, particularly those, which would be relevant after the first commitment period (2008-2012) as part of the future Russian national strategy of climate change adaptation and mitigation.

The current paradigm of interaction of humanity and nature in the contemporary world is transition to sustainable development. One of most important prerequisites of sustainable development is maintenance of regional stability of the biosphere (in particular, balancing major biogeochemical cycles within ecological regions). In many countries (including Russia) this transition is declared as a background of national and regional policies of nature resources management. However, the reality is far from such declarations. The ecological and environment situation in large regions of NA could be characterized as the ongoing severe ecological crisis initiated by the unregulated anthropogenic pressure on nature and explosive increase of production and consumption of fossil fuels. All together, this results in the decreasing quality of major components of the environment - air, water, soil, and vegetation. NA is a typical and illustrative example of these negative processes.

Current developments of industry, man-made changes of environment and ecosystems, as well as ongoing and expected climate change across NA generate many risks. The region is one of the most vulnerable vast territories of the planet. The impacts of global change on the NA environment and human health, as well as on the social and economic safety of human well-being there, are very likely in the short-term impacts, and are crucial in assessing the long-term consequences.

This report aims at a brief description of ongoing and future global change in NA, its impacts on the state and dynamics of environment and ecosystems, and, consequently, on the sustainable use of natural resources. We discuss an urgent need of development of a special program of adaptation of natural landscapes and ecosystems to, and mitigation of, the negative consequences of climate change. Within this context, relevant policies and economics of future activities related to the UN Framework Convention on Climate Change (UN FCCC) are discussed.

Ongoing and expected climate change

A substantial increase of temperature is a distinctive feature of climatic change in NA during the second half of 20th century: the warming trends was estimated at above 0.2°C/10 years and in some "hot spot" regions - up to 0.5°C/10 years; these hot spots are mostly located in East Siberia. The process is spatially heterogeneous: maximal warming take place in continental regions, less - in maritime regions, over the Arctic coast [Gavrilova, 2007; Onuchin, Burenina, 2008]. The average warming in high latitudes was 1.5 fold higher than in Southern Siberia and 3 fold higher than in Mongolia. The highest rate of warming is

Table 1

Linear trend of temperature (°C/100 year) by NA regions during 1976-2002

Region	Year	Winter	Spring	Summer	Autumn
Western Siberia	3.7	6.8	8.5	1.2	-1.3
Centra] Siberia	5.3	7.3	7.7	5.9	0.5
Baikal Region	6.3	8.3	9.5	7.5	0.2
North-East of Asian Russia	4.4	-0.8	8.2	4.4	5.5
Russian Federation	4.9	6.7	7.1	4.6	1.6

Source: Gruza et al., 2002

indicated in central Siberia: during the last century winter temperature increased by 10 °C in Jakutia, 7°C in Pribaikalie, and 5°C in Mongolia with the increase of the annual average temperature in the range of 2-3.5°C. The growth period (with daily temperature > 5°C) increased by 1-2 weeks over the region, more in the south than in the north, less in more humid climate than in dry climate. After the 1970s, the intensity of warming was 1.5-2 times higher than during the first half of the 20th century (Table 1).

Trends of the annual and seasonal amount of precipitation had different direction by seasons: there is a positive trend in winter (of 2-5 mm/10 years) and a negative one in summer (about - 2 to -7 mm/10 years). The annual amount of precipitation, particularly, in continental regions of Middle and East Siberia had a tendency to decrease (e.g., of -4.1mm/100 years for areas around the Lake Baikal). The increase of snow depth in some regions of East Siberia shifts to the south. It may indicate a weakening of the Siberian anticyclone. The runoff of large Siberian rivers increased. In spite of a large spatial heterogeneity of climate change over the region, the increase of temperature in major continental parts of NA was not compensated by the change of precipitation. It leads to increasing aridity of climates, particularly in the continental regions [Vaschuk, Shvidenko, 2006],

All climatic models predict a substantial acceleration of the above tendencies during the 21st century: while the increase of annual average temperature is expected in the range of 4-10 °C, the water supply of vast areas likely will be unsatisfactory. Table 2 contains predictions of changes of temperature and precipitation obtained by an ensemble of 16 coupled atmosphere-ocean GCMs models using the IPCC Scenario A2 for Asian Russia [Meleshko et al., 2008], The changes are given in comparison to the base climatic period from 1980-1999. Another examination of a number of GCMs (HadCM3, CSIRO, NCAR-PCM, ECHAM4, CGCM2, GFDL and CCSRNIES) for the 21st century within IPCC Scenarios A1F1, A2, B2, B1 for two regions - Arctic land (between 67.5 and 90 N lat.) and Northern Asia (50 and 67.5 Nlat.) gives similar results [Ruosteenoja et al., 2003]. Although the diversity of forecasts by individual models is high,

Table 2

Forecast of changes of temperature and precipitation by an ensemble of GCMs for the 21st century

Region	2011-2030		2041-2060		2080-2099	
	Winter	Summer	Winter	Summer	Winter	Summer
Surface temperature (^oC)						
West Siberia	1.4±0.7	0.8±0.5	3.4±1.0	2.0±0.8	7.2±1.8	4.4±1.4
East Siberia	1.5±0.6	0.8±0.4	3.6±1.0	1.7±0.7	7.7±1.7	3.9±1.4
All territory of Russia	1.4±0.7	0.8±0.4	3.4±0.8	1.9±0.7	7.2±1.7	4.2±1.3
Precipitation (%% to the current climate)						
West Siberia	7±4	1±1	16±8	4±3	39±11	7±6
East Siberia	10±3	3±3	19±7	6±4	45±14	14±7
All territory of Russia	6±3	2±1	14±5	4±3	34±8	8±5

Source: Meieshko et al., 2008

some trends are consistent and clearly recognized: (1) the maximal increase of temperature is predicted for most cold months (December-February); the maximum increase - for about 10°C - is predicted by end of the century towards the north; (2) the minimal increase of temperature is expected for spring and summer (March to August) - on average from 4 to 4.5 °C by 2100; (3) increase of precipitation is expected mostly during wintertime; (4) summer increase of precipitation will not compensate the increase of temperature; increasing climate aridity is expected, particularly in the southern continental regions.

Observations and climate models show that the present-day changes in the radiation forcing affect the surface heat, moisture budgets and hydrological regimes of vast territories. Permafrost and seasonally frozen ground in most regions (and, especially, in high latitudes) show large changes in recent decades. Permafrost temperature increased approximately at 1°C at the depth between 1.6 and 3.2 m from the 1960s to the 1990s in East Siberia, and about 0.3 °C to 0.7 °C at the depth of 10 m in northern West Siberia. Long-term monitoring of the permafrost active layer has shown that over the period 1956 to 1990, its depth exhibited a statistically significant increase of about 21 cm. Results of permafrost monitoring provided by the Institute of the Cryolitozone (Yakutsk) in 1989-2002 indicated that under present-day warming trends, fast degradation of the upper part of ice-rich soils of both undisturbed and disturbed permafrost landscapes with 5-30% losses of ground ice resources is observed, and the degradation on disturbed sites is most intensive [Gavriliev, 2003]. Modeling studies on permafrost behavior in 21st century predict decreasing the total area of permafrost by 10-18%; 15-30% and 20-35% by 2030, 2050 and 2080, respectively [Anisimov *et al.*, 2003], Intensive development of thermokarst, gully formation, landslides, solifluction, floods, paludification (or aridity depending on geographical distribution and landscape peculiarities) is expected for large areas, especially for those continuing ice-rich soils (which cover about 35% of Yakutia and 35- 40% of north-eastern part of Russia). Due to predictions made by the Institute of Cryolitozone in Yakutsk, lake and swamps cover may increase (at 1.3-3 times for a future moderate warming by +3°C), differently in different regions of NA. If the observed warming trend $At_0 > 0.06\text{-}0.09°C\ yr^{-1}$ sustains, the unprecedented changes in geocryological, landscape and ecological conditions are very likely in high latitudes of NA [Ivanov, Maximov, 2003], The warming will likely provoke an explosive increase of emissions of carbon stored in permafrost, wetlands and alas territories (of the total amount of 500-700 Pg) [e.g., Desjatkin, Desjatkin, 2007], There are visible changes of the intensity of river runoff and its seasonal redistribution [Shiklomanov, Georgievsky, 2007], and this tendency will be accelerated in the 21st century [Meleshko et al., 2008].

In spite of substantial differences in modeling predictions of future climates, major tendencies with respect to the climate change impacts on terrestrial ecosystems could be aggregated as following: (1) geographical and landscape changes of areas suitable for the growth of certain plant, particularly tree species (shift or disappearance of some productive species); (2) increase or decrease of stability, vitality and productivity of agricultural and forest ecosystems; (3) increasing summer aridity of climate very likely will provide mostly negative impacts on ecosystems, particularly in the south; (4) a substantial increase of instability of regional weather (increasing length of dry summer periods, or intensity of precipitation during wet days etc.) will generate risks of droughts and floods, as well as negatively impact productivity of ecosystems; (5) alteration of ecosystem ecological functions (e.g., impacts on biogeochemical cycles; impacts on biodiversity); (6) increase or decrease in nutrient retention and turnover; (7) changes in species' reproduction cycles, regularities of succession dynamics, and changes in environmental and social services (e.g., changing values of forest ecosystem as a tourist attraction); (8) thawing of permafrost would generate diverse negative impacts on ecosystems.

Man-made impacts and changes are widespread in the region. They are mostly connected to extraction and exploration of fossil fuel (oil, gas, coal) and use of other natural resources (wood, metals etc.). Some regions of NA were and are impacted by different types of industrial pollution and contamination. It impacts the environment, gene pool and health of population, particularly of indigenous Northern populations. There are already significant statistical trends of increasing sickness rate - chronic, allergic and oncological ones.

Current realities of social and economic development of NA which are accompanied by the destructive anthropogenic impacts on the environment and natural landscapes may substantially accelerate the negative consequences of climatic change. Existing today methods of industrial exploitation of northern territories do not present any optimistic background for future interactions of the industry and environment in NA. The level of atmospheric pollution and soil contamination in major regions of intensive oil and gas extraction has exceeded all acceptable limits. The rate of contamination of some regions (West Siberia, north of Krasnoyarsk kray) has been increasing. The quality of river water, particularly in regions with maximal density of population does not correspond to the norms of water use for drinking and fisheries.

The governance of natural resources (in particular, forests), and the control of the use of natural resources are below a critical level [e.g., Musin, 2007], The impacts of toxic anthropogenic water contamination, the decline of the human immune system, increasing stresses, impacts of many negative social phenomena connected, among others, to intensification of migration processes, with a high probability will accelerate the negative impacts of climatic change on standards of life and health of the population, as well as enforce undesirable feedbacks.

Impacts of global change on terrestrial vegetation and renewable natural resources

It is expected that the warming trend will support productivity of agriculture and forests in major parts of the region [Sirotenko, Abashina, 2008]. Climatic models predict that bioclimatic potential for agriculture will increase by 20% in the Russian Far East and up to 50% in West Siberia. However, analyses of extreme climate events predict that main food producing regions in the south will experience an increase in the number of poor harvests - it will double by 2020 and triple that number by the 2070 [Alcamo et al., 2003].

Current state of agricultural land of NA is far from satisfactory. Substantial territories of arable land are not used, e.g., 45% of arable land has not been cultivated in 2003 in Far Eastern Federal Okrug (under 32% over the Russian Federation). Above 20% of irrigated agricultural lands are not used in Asian Russia [Gordeev et al., 2006]. About 25% arable land is affected by water and wind erosion in West Siberia, and -10 million ha are prone to desertification in steppe zone of Siberia. About 90% of this is caused by insufficient use of natural resources.

In spite of many negative impacts and processes, terrestrial ecosystems of the region, particularly forests, still demonstrate the impressive stability and vitality. Due to official forest inventory data, the area of forests in Asian Russia increased at 10.9% in 1961-2003 (from 546.5 to 605.8 x 10^6 ha). The region's ecosystems play a noticeable role in global climate regulation. Live biomass of the forests is estimated at 25.15 Pg C (74.4% of live biomass of all Russian forests) and Net Primary Production comprises at 1.68 Pg C year[1] (72.6%). Rather consistent assessments of the impacts of terrestrial ecosystems on major global biogeochemical cycles that were provided by different methods, show that terrestrial ecosystems of NA during the last two decades served as a net carbon sink - from 300 to 500 Tg C per year [e.g., Nilsson et al., 2003] that substantially contributes to attenuation of the greenhouse effect. However, in some regions forests served as a carbon source: e.g., the total amount of live biomass of larch forests of four north-eastern regions of Russia (Yakutia, Magadan, Chukot and Korjak regions) has decreased during 1993-2003 at 219 Tg C due to large areas of stand-replacing fires there [Schepaschenko et al., 2008]. Importantly, boreal forests are also a significant source of aerosols.

Bioclimatic models predict enormous changes in vegetation cover by end of this century. So, the forest area of Central Siberia is predicted to be two-fold shrank; the border between forests and steppes would shift 10 degrees north of its current position; the steppe area in southern Siberia will increase at 30% with 2-fold extension of desertified steppes (Tchebakova et al., 2003).

Natural disturbances impact terrestrial ecosystems in a clearly negative way. The warming during last two decades presented impressive examples of possible acceleration of disturbances in NA. Due to satellite assessments, the annual area of vegetation fires exceeded 10 million ha in 1997-2005. The areas of wild fire on forest land in 1998 comprised about 12 million ha in 1998 and 17 million ha - in 2003. The amount of consumed fuel and severity of fire were very high. Carbon emissions were estimated at 160-210 Tg C in 1998 and about 270 Tg C in 2003 [e.g., Kaiji et al., 2003].

The irreversible character of changes in forest ecosystems and transformation of historically stabilized ecological processes becomes evident after so-called *catastrophic fires* [Yefremov and Shvidenko, 2004], Such fires provide irreversible (for the period more than several hundreds years) change of ecotopes, as well as the long-term environmental impacts on natural landscapes as a whole, dramatically impact major biogeochemical cycles, and often cause "green desertification" over large territories. There are evidences that frequency and severity of catastrophic forest fires in different regions of NA increased during the last decades 2-3 folds. These fires have a dramatic impact on biodiversity [Kulikov, 1998]. Climate change is a major reason of that, but there is a clear link between the increased magnitude of catastrophic fires and enhanced anthropogenic impacts.

Generally, the long-term environmental consequences of catastrophic forest fires became apparent in diverse aspects: (1) a significant (up to several times) decrease of the biological productivity of forest lands due to the destruction of the indigenous ecotopes and replacement of indigenous vegetation formations; (2) irreversible changes in the cryogenic regime of soils and rocks; (3) change of long-term amplitude of hydrothermal indicators beyond natural fluctuation; (4) changes of multi-year average hydrothermal and bio-chemical indicators of aquatic and sediment runoff, as well as of hydrological regimes and channel processes of water streams; (5) accumulative impacts on atmospheric processes resulting in acceleration of global climate change; (6) promotion of large scale outbreaks of insects and disease; (7) irreversible loss of biodiversity including rare and threatened flora and fauna species; (8) long-distance transfer of pyrogenic products; and (9) change of historical migration routes for migratory birds, ground and water animals.

There is a clear statistical link between deforestation of lands and a forest fire occurrence rate. On average, a 1% increase in a forest fire occurrence rate will cause at 6-10% decrease in the percentage of forest cover for the taiga regions. By estimates, over the last 50 years, catastrophic or recurrent forest fires increased the total area of deforested lands in Asian Russia by -20 million ha. Such lands comprise up to 70% of bogs, 15% of grass-shrub lands, 10% of open woodlands, and up to 5% of stone fields and stone outcrops [Sheingauz, 2001; Yefremov, Shvidenko, 2004], Fires of that magnitude should be viewed as a pyrogenic disaster beyond a regional context, with century-long biotic, environmental, and socio-economic consequences.

Climate change is linked to the profound transformations of biotic processes. In particular, recently Khabarovsk Kray faced an intensive outbreak of gypsy moss (*Limantria dispar)* on an area of some 8 million ha. There is evidence that this phenomenon is an aftereffect of the pyrogenic disaster of 1998. It is worth to note that the synergism of fire and biotic disturbances is typical for whole Northern Asia. The outbreak of Siberian moth *(Dendrolimus superans sibiricus*) impacted from 8 to 10 million hectares of larch stands in 2001-2002 in NA territories where such outbreaks have never been observed earlier (north of Zabaikale, Saha Republic).

Overall, risks for terrestrial ecosystems, for agriculture and forestry initiated by climate change and anthropogenic activities could be categorized as following: (1) negative processes connected to permafrost destruction including physical destruction of sites, thermokarst, solifluction; (2) loss of soil fertility due to water erosion, soil compaction, desertification, lack of nutrients, salinization, increasing water table and other changes of water regime, soil contamination; (3) impoverishment of soil biota, decline of productivity of lands; (4) lack of water resources in arid regions; (5) damage of agriculture lands in river valleys due to increase of inundation; (6) anomalous outbreaks and spatial distribution of traditional and new insects and microorganisms; (7) alteration of forest fire regime; (8) loss of biodiversity; (9) "green" desertification; and (10) impacts of air pollution, soil and water contamination.

Adaptation, mitigation and ecological safety

In order to minimize the mentioned above challenges and risks, an anticipatory strategy of adaptation of landscapes and ecosystems to, and mitigation of, negative consequences of global change should be developed and implemented. Technical aspects of this process are well recognized. For instance, four major groups of relevant options to reduce emissions by source and to increase removals by sinks in the forest sectors include maintaining or increasing (1) the forest area through reduction of deforestation and forest degradation and through afforestation and reforestation; (2) the stand level carbon density; (3) the landscape-level carbon density; and (4) off-site carbon stock in wood products [IPCC, 2007], This defined corresponding types of management practices: afforestation and deforestation, biofuel plantations and substitution through wood products, reduction of emissions from deforestation, improvement of forest management, and forest restoration within a degraded forest land [Robledo et al., 2008].

However, these and other activities are closely tied with the overall problem of sustainable management of natural resources, economic and social development of the territory, and ecological safety of population. In essence, climate change should be one of cornerstones of regional strategies of social and economic developments with inherently implemented global issues and links, starting, *inter alia,* from the following major issues:

- development of a concept of sustainable development of regions of high latitudes; such a concept should base on unified ecological policy-ecological safety over all boreal and polar regions under expected climatic, social and economic changes; an important initial stage of transition to sustainable development is a system of activities which would allow to overcome the current ecological and nature management crises;
- development of integrated observing systems over the entire circumpolar polar & boreal biomes as an information basis of integrated land use management under global change; these systems should provide early warning of changes in the functioning Earth system and help to timely recognize undesirable "surprises", particularly in hot spot regions, e.g., on permafrost; integration of ground observation (monitoring stations), multi-sensor remote sensing concepts and relevant ecological models is a cornerstone of such systems;
- based on global change challenges, reconsideration of the existing and introduction of a new, relevant system of specially protected territories around of the polar circle with ecologically relevant regimes of nature management;
- taking into account that forest in northern regions is a major stabilizing element of natural landscapes, forest management paradigm requires substantial reconsideration - from a pure resource to multi-service use of forests with a clear emphasis to environmental and protective services. It requires a proper quantification of "global utility" of forests [Shvidenko et al., 2005] that would allow to understand a real cost of forests in the contemporary world;
- development of a new strategy, legislative and institutional background of forest fire protection; such a strategy should include relevant preparation of boreal landscapes to expected climatic change;
- all the problem of interaction of humanity and nature in northern regions requires new ways of thinking and principally new solutions in many

- aspects - education; institutions; capacity building; development and introduction of ecologically friendly methods, machinery and technologies of industrial development of northern territories;
- development of legislative and normative base of adaptation and mitigation is an urgent problem at both federal and regional level; with this respect the situation with post-Kyoto implementation in the region is clearly unsatisfactory;
- as comprehensive as possible use of the Kyoto ideology/ mechanisms in different aspects (for obtaining heat and energy by modern technologies; for full introduction of the biosphere in the post Kyoto international process etc.);
- management of major biogeochemical cycles (basically, carbon and nitrogen) should be considered as an inherent part of sustainable land use management (including agriculture, forestry, wetland management).

NA ecosystems and post Kyoto developments after the first commitment period

The Kyoto protocol and following decisions of the Conferences of Parties (COP) was an unprecedented effort joining the world community in attempts to mitigate climate change. However, the post Kyoto international process in its current form has substantial gaps and weaknesses. In essence - with respect to the biosphere - the Protocol introduced in an international practice a partial account of major GHGs in field of Land Use, Land Use Change and Forestry (LULUCF) limited to the so-called "managed biosphere". This contradicts the eventual goal of the UNFCCC because emissions of GHGs from the "unmanaged" part of the biosphere could be of the same level or even exceed industrial emissions, i.e., in tropics where annual deforestation accounts for 13 million ha per year and is responsible for annual emissions of-1.5 Pg C to the atmosphere [Shvidenko, 2008], or in the northern hemisphere where huge emissions caused by wild are currently observed.

The restriction of the process by the "managed biosphere" generates other negative consequences such as (1) exclusion of "climate friendly" investments in perspective fields of the biosphere; (2) a threat to the protection of some categories of "unmanaged" ecosystems, e.g. old growth forests; (3) an unsatisfactory consideration of large sources of emissions; and (4) the restriction of opportunities for many, particularly developing countries to participate in the international processes of climate change mitigation. As well, such a decision has a substantial methodological gap: any partial account does not allow any solid analysis of uncertainties due to the fact that considering the impacts on part of a system is not sufficient for assessing the responses and feedbacks of the entire system. Substantial problems also arise from the large difficulties (and often - impossibility) of strict definitions and unambiguous implementation of some key terms of the Kyoto language like managed land, anthropogenic impacts, base-lines and additionality, etc., that raises doubt concerning some incentives and results. Thus, introduction of the *full* GGA in international practice is an important *political and economic problem*, specifically for future - after the first commitment period - activities within the UN FCCC.

In this context, the *full* GGA assumes assessing all fluxes of major greenhouse gases ($C0_2$, CH4, CO, VOC, NO_x, N_20) and aerosols that are produced by the biosphere including all ecosystems and all processes continuously over time [Steffen et al., 1998]. However, uncertainties of previously reported estimates of the role of terrestrial ecosystems in the global biogeochemistry are high [e.g., Shvidenko et al., 2008] that hinders a solid scientific understanding of the problem and impacts important political and economic solutions. "Hot air" should be excluded from the post-Kyoto process. With this respect, level of uncertainties becomes an important economic indicator. Thus, we come to a need of a *verified* FGGA, i.e., the methodology used for the account should (1) explicitly, reliably and comprehensively assess uncertainties of the intermediate and final results, and (2) present an effective tool for uncertainties' management, which should not exceed a predetermined threshold. Designing, methodology and modeling development of the verified full GGA at the national level is an important *fundamental scientific challenge.* Implementation of a verified FGGA would allow to substantially improve and logically extend the Kyoto economic mechanisms.

However, this would require substantial improvements of the accounting methods and changes of some international agreements. The FGGA at a national level is a large, dynamic and very complicated and underspecified (fuzzy) system that comprises a sophisticated interplay of many stochastic elements/ processes (Shvidenko et al., 2003, 2008). In practical implementation, such systems cannot be directly verified due to the need of very expensive and resource consuming experiments. In essence, none of the four major methodologies of greenhouse gas accounting - landscape-ecosystem inventories; flux measurements; inverse modeling; and process-based vegetation models - if applied independently - are able to provide a comprehensive and reliable assessment of the uncertainties. An application of the FGGA that has been recently developed by the International Institute for Applied Systems Analysis together with Russian and other institutions is based on advanced information technologies including a multi-sensor remote sensing concept, model-data fusion principles, integration of approaches of different nature as indicated above, and multiple constraints of intermediate and major results in connection with corresponding uncertainties. The methodology includes a number of new solutions and models which substantially change previous estimates [Shvidenko et al., 2007, 2008]. This methodology has been applied over a large Siberian region and demonstrated the great potential for wide implementation.

Knowledge of the FGGA generates a solid basis for management of major biogeochemical cycles and development of relevant adaptation and mitigation strategies. Sustainable development and climate change policies in many cases can have a large number of synergies, which implies that reduced greenhouse gas emissions and climate change adaptation can be integrated into more general development policies.

The post-Kyoto developments face a principal methodological problem here. Carbon management, as well as planning of adaptation and mitigation strategies are an ill-defined and quasi-manageable task [Martens and Rotmans, 2002] or, in other terminology, a "full complexity problem" (FCP), i.e., it is (1) structurally, functionally and dynamically *intricate*, (2) non-separable from context, observation and interest, (3) multi-objective/subjective, and (4) uncertain due to fragmentary knowledge and insufficient validation process [Schellngruber, 2003],

Complexities of the situation are evident: need to take decisions for underspecified dynamics systems under uncertainties; relevancy to consider dual strategy that integrates mitigative and adaptive measures, particularly under no-regret and win-win considerations; necessity to derive minimum mitigation standards from the limits of adaptation; inevitability of non-linear responses and feedbacks and probability to meet surprises in the biosphere's behavior; etc. It defines a need for development of new philosophy of cognition and policy making by using open, iterative, distributed-modular systems based on shared pools of models, tools libraries, and data sets. Special requirements should be put to initial information (considering so-called 5R information). The overall relevant tool is a system application of integrated modeling which is based on a "data-model-policy fusion" platform. Integration is a key word - successful management cannot be done under the separation (in space, time and function) of causes and effects, pilots and passengers, and costs and benefits [Schellngruber, 2003].

An important and not trivial question deals with relevant accuracy of the FGGA. Elaborating and minimizing a function of losses due to an uncertain account is a relevant but complicated recommendation. The potential cost-effectiveness of carbon sequestration or global warming potential of the entire ensemble of major GHG seems presumably to be a major criterion. However, corresponding methodologies are still not developed. Large difficulties are evident; the biggest problem stems from the fact that any solution requires defining the "boundary of the effects" that are relevant to be included in the consideration. This comprises a complicated mixture of economic and political components.

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