Chapter 6
Terrestrial Ecosystems and Their Change

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Abstract This chapter considers the current state of Siberian terrestrial ecosystems, their spatial distribution, and major biometric characteristics. Ongoing climate change and the dramatic increase of accompanying anthropogenic pressure provide different but mostly negative impacts on Siberian ecosystems. Future climates of the region may lead to substantial drying on large territories, acceleration of disturbance regimes, deterioration of ecosystems, and positive feedback to global warming. The region requires urgent development and implementation of strategies of adaptation to, and mitigation of, negative consequences of climate change.

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6.1 Introduction

Siberian vegetation is mostly represented by unique ecosystems which evolutionary developed under stable cold climate (Khotinsky 1984). While the region is represented by a vast diversity of ecosystem types, amount of dominant plant species in all land classes is relatively limited (e.g., Lavrenko and Sochava 1956; Zhukov 1969; Scherbakov 1975; Popov 1982; Polykarpov et al. 1986). Plasticity of major forest-forming species is high, and they occupy wide ecological niches. These provided a rather high resilience of boreal forests which coped with stable disturbance regimes during last centuries (Bonan and Shugart 1989, 1990).

The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007a, b) concluded that for increases in global average temperature exceeding 1.5–2.5 °C, forests globally face the risk of significant, basically undesirable transformations. With this respect, boreal forests of Siberia could be especially affected due to (1) dramatic changes of heat and hydrological balances of northern landscapes over huge territories caused by permafrost thawing, (2) sensitivity of boreal forest ecosystems to warming and the high rates of expected warming in northern high latitudes, (3) different consequences of climate change impacts over the southern and northern ecotones of the forest zone – death and impoverishment of forests in the south and a very limited potential to move northward in the north, and (4) dramatic acceleration of disturbance regimes, particularly fires, outbreaks of insects and diseases, coupled with the tough anthropogenic impacts.

The expected warming generates dangerous risks and challenges for the ecosystems. If the global increase of annual temperature would exceed +3 °C by end of this

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century, the warming in vast territories of high latitudes of the region is expected to be in range of +7 to +10 °C. Based on an ensemble of 16 coupled atmosphere-ocean GCMs, the increase of temperature by 2080–2099 for entire Russia was predicted at +7.2 ± 1.7 °C and in summer +4.2 ± 1.3 °C (Meleshko et al. 2008). Such a level of warming has never been experienced before. The most likely scenario for the boreal forest, as a major ecosystem type in the region, is a nonlinear response to warming, resulting in the creation of previously nonexistent ecosystems and the extinction of species with limited capacity to adapt. The critical limit for large-scale forest dieback may be a rise of 3–5 °C (Lenton et al. 2008). Experts considered boreal forest dieback as one of nine possible global "tipping elements" (a sudden and dramatic response as global warming exceeds a certain threshold value, presumably 5–6 °C for boreal forests), supposing that the nonlinear response to global warming can happen during this century. The supposed mechanisms behind boreal forest dieback are increased water stress and higher peak summer heat causing increased mortality directly and also indirectly through higher vulnerability to disease and alteration of fire regimes. Once the critical threshold is passed, the process may be rather fast; the transformation of the boreal forest ecosystems may happen over a period of about 50 years (Lenton et al. 2008).

High vulnerability of Siberian ecosystems, particularly forests in south of the boreal zone and on permafrost becomes evident even under ongoing climate. It defines a high importance of understanding current and future behavior of Siberian ecosystems as a background of transition to adaptive ecosystem management.

This chapter has two main objectives: (1) to present a brief overview of the current state of Siberian ecosystems and (2) to identify major ongoing and future dynamic processes in ecosystems of a changing world. Taking into account that part of the available information on Siberian land and ecosystems is either biased or obsolete (e.g., official data on land cover, forest inventory data), the analyses rely on different information sources, particularly recent results of Earth observation from space (e.g., Schepaschenko et al. 2010; Santoro et al. 2011). All areas and biometric indicators in this chapter are defined based on the hybrid land cover 2009 (Fig. 1.1; Schepaschenko et al. 2010).

6.2 Resource and Ecological Services of Siberian Ecosystems

6.2.1 Brief Characteristics of Siberian Ecosystems

The vast expanse of Siberia (about 3,500 km in latitudinal and more than 6,000 km in longitudinal directions) ensures a large diversity of natural conditions, climate, soils, ecosystems, and landscapes. More than 50 % of the territory is mountainous, and about 85 % of the territory is covered by different types of permafrost. While there are vast territories which have been transformed into anthropogenic deserts, about half of the region's area is covered by practically untouched ecosystems.

Diversity of natural conditions of the region requires division of the vast Siberian territory in more homogeneous parts based on different criteria, with many attempts resulting in development of natural, climatic, soil, vegetation, agricultural, etc., divisions (regionalizations). One of the most common was ecological regionalization (Shvidenko et al. 2000), where major spatial classification units – ecoregions – were delineated based on the following major requirements: (1) homogeneity of the natural environment including similar climate, typical soils, and landforms at the level of bioclimatic (vegetation) subzones and large landscape units that led to separation of mountain and plain territories, permafrost regions, etc.; (2) similarity of character and intensity of anthropogenic pressure on ecosystems and landscapes that includes negative impacts (e.g., pollution) and homogeneity of land management (e.g., forest management); (3) similarity in levels of transformation of natural vegetation; and (4) comparable input of each ecoregion in major biogeochemical cycles (i.e., carbon, hydrological, and nitrogen). Ecoregions are combined in bioclimatic subzones and zones. A map and list of Siberian ecoregions is available at http://www.iiasa.ac.at/Research/Forestry/Downloaddata/. A quantitative description of ecoregions of Central Siberia is presented in Farber (2000) and West Siberia in Sedykh (2009). Here we present the most important aggregated characteristics of Siberian ecosystems by bioclimatic zones.

While almost all bioclimatic zones and major vegetation types of the Northern hemisphere are represented in Siberia, this region is usually associated with taiga – coniferous evergreen and deciduous forests of cold climates. Three subzones of taiga cover about 77 % of the total land of the region. Tundra (16.3 %) and steppe (4.7 %) are two other widely distributed zones. The remaining three zones (arctic desert, temperate forests, or sub-taiga, and southern semideserts and deserts) cover only ~2 % (Table 6.1).

Diverse climate, vegetation, and relief of the vast territory of Siberia resulted in the development of various soil types. The majority of the area is covered by typical forest soils: either sandy (*Podzols*) or loamy soils (*Albeluvisols, Cambisols*). Wetlands are also spread widely with *Histosols, Gleysols*, and some *Phaeozems*. Almost every soil type has permafrost signs, especially *Cryosols*. Agricultural area is generally represented by *Chernozems* in Southern Siberia. Weakly developed mountain soils (*Leptosols*) and river valley soils (*Fluvisols*) complete the range of soils of the region. Areas in Table 6.2 were calculated based on a digitized soil map (Fridland 1989, modified to scale 1:1M). More detailed data on Siberian soils are available at the above-mentioned IIASA FOR website.

Siberia is largely a forest territory – forest land (i.e., area covered by forest vegetation or destined for growth of forest) comprises 61.6 % of the total area of which about 20 % are sparse forests (woodlands) – generally in high latitudes, and disturbed forests. Forests (or forested areas, defined by the forest inventory manual of the Russian Federal Forest Service, RFFS 1995) are relatively simple in terms of species composition. They are dominated by seven tree genera – light coniferous larch (*Larix* spp.) 40.3 %, pine (basically *Pinus silvestrys*) 13.0 %, dark coniferous cedar (*Pinus sibirica* and *P. korajensis*) 6.8 %, spruce (*Picea* spp.) and fir (*Abies* spp.) 7.3 %. Softwood deciduous, mostly birch (*Betula* spp.) covers 12.0 % and

Table 6.1 Distribution of area by land classes and bioclimatic zones

	Area, $\times 10^6$ ha, by land classes								
Zone	Forest	Agricultural land	Burned forests	Wetland	Grassland	Open woodland	Unproductive	Water	Total
Arctic					0.3		3.3	0.3	3.9
Tundra	11.8	0.1	1.5	30.2	106.4	6.2	19.5	6.5	182.1
FT, NT & SpT[a]	103.3	0.1	2.9	24.4	22.6	24.2	0.3	2.2	179.9
Middle taiga	381.4	10.3	15.4	36.3	74.3	35.5	4.7	4.8	562.6
Southern taiga	89.5	11.2	0.5	12.5	3.4	0.7	0.0	0.9	118.8
Temperate forest	5.5	4.8	0.0	0.6	0.6	0.1	0.0	0.1	11.8
Steppe	9.7	36.4	0.1	2.8	2.5	0.1	0.2	0.9	52.6
SD & D[b]	1.1	4.2	0.0	0.6	0.6	0.0	0.3	0.4	7.2
Total	602.2	67.0	20.5	107.4	210.7	66.8	28.3	16.0	1,119.0

Notes: (1) Administratively, the accounted for territory is represented by the Asian part of Russia without several Far Eastern regions of the monsoon climate – Primorsky and Kamchatka *Krays*, Chukchi Autonomous *Okrug*, and the Sakhalin *Oblast* and Jewish Autonomous *Oblast*. (2) Areas by land classes are estimated based on the hybrid land cover of Russia (see Chap. 1). (3) Abbreviations:

[a] FT, NT and SpT – forest tundra, northern and sparse taiga zones

[b] SD and D – semidesert and desert zones

Table 6.2 Soil distribution by types and bioclimatic zones

	Area by bioclimatic zones, ×10⁶ ha								
Soil type by WRB[a]	Arctic	Tundra	FT, NT and SpT	Middle taiga	Southern taiga	Temperate forest	Steppe	Semidesert	Total
Albeluvisols			2.3	43.6	49.2	1.9	4.8	0.1	101.9
Cambisols		2.2	10.4	147.0	18.1	3.0	2.6	0.5	183.8
Chernozems				3.7	7.5	6.4	33.3	2.6	53.5
Cryosols	0.7	31.5	0.7						32.9
Fluvisols		12.8	15.8	22.1	7.6	1.2	2.4		61.9
Gleysols		71.0	66.6	53.8	6.1	0.5	0.7	0.3	199.0
Histosols		2.7	24.7	28.1	19.9	0.6	0.1		76.1
Leptosols		3.3	0.0	11.9	0.0	0.0	0.1	0.5	15.8
Phaeozems		7.6	25.5	53.2	4.6	0.5	0.5	0.7	92.6
Podzols		41.7	33.5	186.3	4.7	0.0	0.3	0.5	267.0
Solonchaks		0.4			0.1		1.0	0.3	1.8
Solonetz					0.4	0.4	5.1	1.0	6.9
Total	0.7	173.2	179.5	549.7	118.2	14.5	50.9	6.5	1,093.2

[a] *WRB* world reference base (FAO 2006)

aspen (*Populus tremula*), cover 2.4 %. Shrubs (accounted for as forests in regions where "high" forests cannot grow due to severe natural conditions) cover significant areas (12.4 % of the total forested area) in high latitudes. The rest (5.6 %) of the forested area is presented by hardwood deciduous species, mostly by stone birch (*Betula ermani*) in oceanic territories of Far East and oak (*Quercus mongolica*), ash (*Fraxinus mandshurica*), lime (*Tilia mandshurica* and *T. amurensis*), etc., in broad-leaved forests of the south of the Far East. Larch forests (presented mostly by *L. sibirica, L. gmelini,* and *L. kajanderi*) are represented by unique ecosystems occurring on permafrost over huge territories in high latitudes, forming the northern climatic tree line and the most northern forests on Earth (reaching 72°30′N).

The largest global bog-forest systems extend over large areas in West Siberia. Wetlands (defined as forestless territories with a peat layer >30 cm) comprise 107.4×10^6 ha (or 9.6 %). These territories are situated almost exclusively in northern bioclimatic zones. Approximately an area of the same magnitude of relatively shallow peatland is covered by forest. Grasslands (18.8 %) are represented by tundra and meadow vegetation, mostly located in high latitudes. Only 3.4 % of natural grassland occurs toward the south of the middle taiga zone.

Dynamics of major classes of land cover, particularly forests, are documented since 1961, when results of the first complete inventory of Russian forests were published. By January 1, 1961, official statistics reported the total forested area of the region at 505.4×10^6 ha with growing stock of 56.5×10^9 m^3 (FFSR 1962). Official data by 2009 reported the area at 594.7×10^6 with growing stock at 58.0×10^9 m^3. However, it has been shown that methods of forest inventory which were used during this period reported biased estimates of the growing stock volume. An attempt to eliminate the bias, update obsolete inventory data and clarify the area by remote sensing data resulted in the area of 602.2×10^6 ha and growing stock at 60.8×10^9 m^3 for 2009 versus the official 594.7×10^6 ha and 60.1×10^9 m^3, respectively. Taking into account that the unbiased estimate of growing stock in 1961 was 52.2×10^9 m^3 (Shvidenko and Nilsson 2002), we conclude that during the last five decades the forested area in the region increased by 96.8×10^6 ha and growing stock by 8.6×10^9 m^3. Such a large increase in area could be explained by several reasons: (1) improved accuracy and completeness of inventory data, (2) substantial decrease of unforested areas (at ~50×10^6 ha for Asian Russia), and (3) encroaching forest vegetation in previously nonforest land, particularly in the abandoned agricultural lands. Based on official statistics, the area of cultivated agricultural land in the region decreased by 8.7×10^6 ha during 1990–2009.

However, the dynamics of forested area in most populated regions with intensive forest harvest are substantially different. Typically an analysis of the dynamics of forests of Central Siberia (i.e., Krasnoyarsk Kray including territories of Republic Khakassia, Taimir and Evenkia Autonomous okrugs) generates the following results for 1961–2007 (Vtyurina and Sokolov 2009): (1) forested areas decreased by 5.1×10^6 ha (or 5 %), (2) area of mature and overmature coniferous and deciduous forests decreased by 17.2×10^6 ha (25 %) and 1.7×10^6 ha (17 %), respectively, (3) total growing stock decreased by 3.2×10^9 m^3, and (4) total growing stock in forests available for harvest decreased by 3.7×10^9 m^3 (35 %) in coniferous forests and increased in deciduous forests by 1 %. Similar features of forest industrial developments have been reported for the Irkutsk Oblast (Vaschuk and Shvidenko 2006) and Far East (Sheingauz 2008). The process of qualitative degradation of most productive forests in regions with developed infrastructure was observed during the last 50 years.

Overall, man-made changes to forests in Siberia could be briefly summarized as follows:

- Decreasing quality of forests across the southern part of Siberia expressed by worsening species composition, reduction of areas of forests of high productivity, and deconcentration of forests available for industrial exploitation. Major reasons for this stem from the long-period practice of harvest of the most productive coniferous forests in the form of concentrated clear-cuts, nonecological technologies and machinery of logging, ineffective use of harvested wood, particularly of soft deciduous species (birch, aspen).
- Shifting forest harvest toward northern regions with undeveloped infrastructure, particularly roads, that causes a scattered distribution of logged areas. Harvest of basically coniferous species predestines substantial problems for transition to sustainable forest management in future.
- Siberian forests are not managed in a sustainable way. They suffer from large forest fires and outbreaks of dangerous insects (see Sect. 6.3) that mostly damages valuable coniferous forests. Forest fire protection is not sufficient, and each cubic meter of harvested wood is accompanied by losses of about 2.5–3 m^3 killed by disturbances.
- Periodical reforms of Russian forest management (of which those between 2000 and 2007 have been most destructive) substantially decreased governance of Siberian forests. Illegal harvest is widely distributed and reaches from 20 to 40 % of officially reported data, increasing in boundary regions (Vaschuk and Shvidenko 2006; Sheingauz 2001, 2008).

During the last 60 years, about 6×10^9 m^3 of commercial wood, basically represented by valuable coniferous wood, have been harvested in Siberian forests. Besides their resource function, forests provide different environmental, ecological, social, biospheric, cultural, etc., services (e.g., Lebedev et al. 1974). Water-protection services of Siberian forests such as provision of high-quality water, transformation of surface runoff into interflow, and regulation of catchment runoff are among the most important and widely recognized. However, some aspects of interactions of forests with hydrological regimes of landscapes (impacts of forests on total water content in landscapes, river discharge, and evapotranspiration) remain questionable (Voronkov 1988; Protopopov et al. 1991; Geographical… 2007; Onuchin et al. 2006; Onuchin 2009; Liu 2010).

One of the key problems of such debates was the question about increasing precipitation over forest areas caused by roughness of tree canopies that leads to ascending air flows under movements of air masses over forests. However, this theoretically attractive idea on the possible ability of a forest to increase the amount of precipitation has not been unambiguously supported by experimental data in boreal territories and cannot be assumed true over Northern Eurasia (Onuchin 2009; Liu 2010). Assessments of the impacts of forests on redistribution of the water balance between cumulative runoff and evapotranspiration is defined by vegetation, climatic, and geographical conditions (Fedorov 1977; Kabat et al. 2004; Hamilton 2008; Onuchin and Burenina 2008; Onuchin 2009; Liu 2010).

Typically, reduction in biomass and deforestation will increase net runoff, though the characteristics of the timing of such runoff will vary given the condition of soil water and infiltration potential which serves as a trigger mechanism for ground water recharge or surface water runoff (Kabat et al. 2004). At drainage basin scales, the change in the land cover mosaic and secondary vegetation regrowth creates a complex hydrological response as various age classes and successional species have a different effect on major water balance characteristics (Shiklomanov and Krestovsky 1988).

Forest management operations on catchments are recognized as an important factor transforming the major water balance characteristics. According to the type of anthropogenic impacts, geophysical conditions, and restoration dynamics, evapotranspiration and river runoff could increase or decrease (Onuchin et al. 2009). Large-scale logging and forest fires could become a crucial factor that defines conditions of runoff formation in small- and medium-size river basins.

While climate plays a leading role in forming yearly river runoff, non/climatic factors (amount and distribution of forest vegetation over landscapes, soils, size, and geological peculiarities of catchments) are also very important. Both groups of factors are interconnected leading to synergetic effects which could be used for regulation of the runoff by forest management operations taking into account climate and weather specifics (if they are properly understood). Currently, this understanding is insufficient and requires coupled biospheric-hydrological modeling (see Chap. 4, this volume).

Boreal forests with steady snow cover during cold periods play a specific hydrological role because of substantial differences of the balance of snow water between forests and open areas. Depending upon climatic, landscape, and vegetation conditions, forests usually have greater snow storage (cf., Bulygina et al. 2011) and less frozen ground providing more stable feeding of streams throughout the year. However, increased evapotranspiration rate in forests will lead to decrease in annual runoff (Shiklomanov and Krestovsky 1988). For regions where liquid precipitation dominates, the differences in water balance are mostly defined by productivity and morphological structure of ecosystems (but not by the structure of vegetation cover of the landscapes – forest versus treeless areas). More productive ecosystems, regardless of whether they are forests or agricultural lands, have higher evapotranspiration and lower river runoff.

6.2.2 *Major Carbon Pools and Productivity of Ecosystems*

The term *ecosystem productivity of forests* does not have a monosemantic definition. Usually two groups of indicators are used to quantify productivity which describe either the amount of accumulated organic matter (e.g., live biomass, dead biomass or detritus) or rates of production of organic matter (e.g., net primary production, NPP; net ecosystem production, NEP). Such indicators like growing stock volume, net and gross growth are used in forestry to quantify a resource service of forests.

6.2.2.1 Carbon Pools

Major organic carbon pools include live biomass, dead wood, and soil. Within this study, live biomass (LB) of forests was estimated based on modified forest inventory data and ecoregionally distributed multidimensional models that combine biometric characteristics of forests (species composition, age, site index, and relative stocking) and seven components of live biomass [stem wood, crown wood, bark, foliage, root, understory (shrubs and undergrowth) and green forest floors] (Shvidenko et al. 2007a). LB of agricultural land was assessed based on reported data of crops (FFSSR 2008) and regressions, which connect crop, byproducts, and residuals. LB of the rest of vegetation classes was calculated based on measurements in situ during 1960–2010 [the updated database by N. Bazilevich (1993) was used]. For all nonforest ecosystems, live biomass was assessed by three components – green parts, above ground wood, and below ground biomass.

The most recent (2009) total biomass estimate of terrestrial ecosystems in Siberia is 29.55 Pg C ($1\text{Pg}=1$ billion $t=10^{15}$ g), of which 86.5 % are in forests (Tables 6.3 and 6.4, Fig. 6.1). In general, all land classes have a clear zonal gradient of LB distribution with some deviations caused by the characteristics of land classes (e.g., age structure of forests). It corresponds to the fact that the carbon pool of LB of forest ecosystems along the climatic gradient of Central Siberia is positively correlated with mean annual temperature and duration of growing period (Pleshikov 2002).

The structure of live biomass depends on a number of factors – vegetation type, geographical location, level of productivity of ecosystems, and others. In forests, 55.9 % of LB is allocated in stem wood, 9.9 % in branches (both-over bark), 3.5 % in foliage, 23.0 % in roots, 2.2 % in understory, and 5.5 % in green forest floor. These average values vary greatly. For instance, the three- to fivefold increasing of LB of stems toward the south is accompanied by a decrease of the share of ground vegetation LB (such as moss, lichens, grass, and shrubs). In northern low productive ecosystems, the ground vegetation can contribute about half of the total LB storage in the ecosystem and roots – up to 30–35 % and more (Knorre 2003; Shvidenko et al. 2007a).

Other estimates of LB of the entire vegetation cover for the study's region in the above boundaries have never been reported. A number of the assessments that have been done for forest LB either for the Asian part of Russia or for individual administrative regions based on forest inventory of different years present rather consistent results (Alexeyev and Birdsey 1998; Zavarzin 2007; Usoltsev et al. 2011).

Dead wood is an important indicator of the condition and functioning of forest ecosystems. The amount of dead wood (snags, logs, stumps, dry branches of living trees) was estimated in all natural ecosystems based on an extended database. Of the

Table 6.3 Live biomass by major land classes and bioclimatic zones

	Live biomass, Tg C by land classes						
Zone	Forest	Agro	Burned	Wetland	Grassland	Open woodland	Total
Arctic					0.4		0.4
Tundra	404.2	0.2	1.9	308.4	850.5	50.6	1,615.8
FT, NT & SpT	2,841.7	0.3	5.4	179.1	291.9	187.8	3,506.2
Middle taiga	16,692.5	34.3	58.2	320.6	918.9	296.6	18,321.0
Southern taiga	4,870.7	40.9	2.4	152.9	35.6	11.2	5,113.7
Temperate forest	222.9	18.0	0.2	7.5	6.3	1.0	255.8
Steppe	467.9	126.5	0.4	33.6	22.7	1.8	652.9
D & SD	60.4	14.0	0.1	6.9	3.4	0.1	84.9
Total	25,560.3	234.2	68.5	1,008.9	2,129.7	549.1	29,550.7

Table 6.4 Average (by area unit) live biomass by land classes and bioclimatic zones

	Live biomass, kg C m^{-2}, by land classes						
Zone	Forest	Agro	Burned	Wetland	Grassland	Open woodland	Total
Arctic					0.13		0.13
Tundra	3.43	0.30	0.13	1.02	0.80	0.81	1.03
FT, NT & SpT	2.75	0.30	0.18	0.73	1.29	0.78	1.98
Middle taiga	4.38	0.33	0.38	0.88	1.24	0.84	3.31
Southern taiga	5.44	0.36	0.44	1.22	1.05	1.51	4.34
Temperate forest	4.02	0.38	0.45	1.25	1.02	1.48	2.20
Steppe	4.84	0.35	0.41	1.21	0.90	1.68	1.27
D & SD	5.47	0.34	0.41	1.10	0.59	1.85	1.31
Average	4.24	0.35	0.33	0.94	1.01	0.82	2.75

total amount of dead wood carbon in all natural ecosystems (Table 6.5) at 6.27 Pg C, about 92 % are in forests. The amount of dead wood in Siberian forests is extremely high (on average 8.33 tC ha^{-1}, in volume units 38.8 m^3 ha^{-1}, almost 40 % of average growing stock volume). The major reasons for that are: (1) an absolute majority of Siberian forests are unmanaged; (2) dominance of mature and overmature, often uneven-aged forests; (3) wide distribution of natural disturbances like fire and insects outbreaks which provide the substantial partial postdisturbance dieback; and (4) slow decomposition rate of dead wood over major part of Siberia.

We calculated carbon content of the above-ground organic layer (with content of carbon >15 %) and the top 1-m layer for mineral soils below; carbon content for organic (peat) soil was estimated for 1 m from the surface (Tables 6.6 and 6.7). Soil organic carbon generates the biggest carbon pools in Siberian ecosystems at 219.5 Pg C or 19.7 kg C m^{-2}. Of this amount, 5.0 % of the carbon lies in the on-ground organic layer.

Evidently, soil carbon content substantially varies by land classes ranging from 2.12 kg C m^{-2} for unproductive land to 44.13 kg C m^{-2} across wetlands. The zonal gradient is not clearly expressed because of availability of different soil types in the

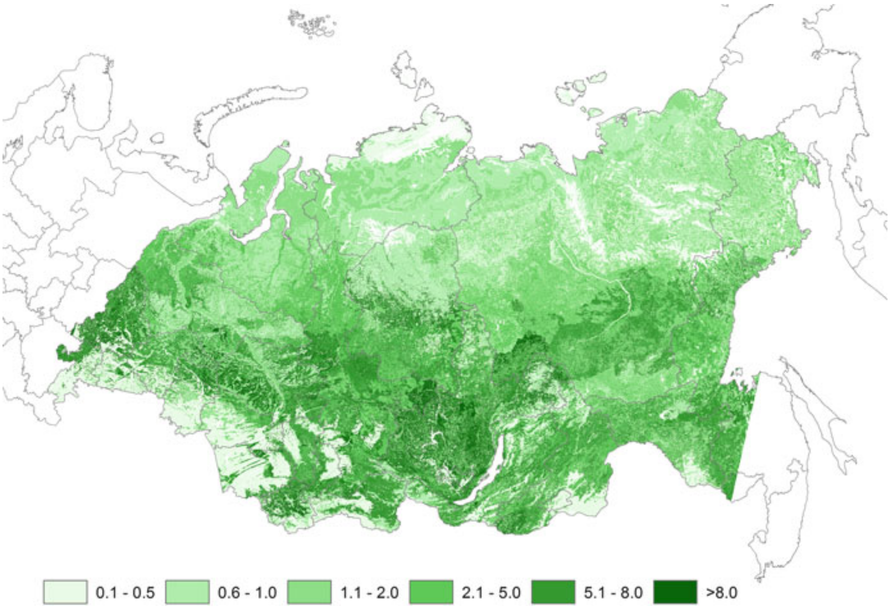

Fig. 6.1 Live biomass of Siberian ecosystems, kg C m^{-2}

Table 6.5 Dead wood by land classes and bioclimatic zones

	Dead wood by land classes							
	Stock, Tg C				Average, kg C m^{-2}			
Zone	Forest land	Wetland	Grass land	Total	Forest land	Wetland	Grassland	Total
Tundra	109.3	4.7	59.5	173.5	0.560	0.016	0.054	0.109
FT, NT & SpT	625.6	20.7	34.3	680.6	0.480	0.085	0.144	0.381
Middle taiga	4,018.1	46.7	293.0	4,357.9	0.926	0.129	0.382	0.797
Southern taiga	890.8	23.0	5.6	919.5	0.978	0.184	0.137	0.854
Temperate forest	46.2	1.0	2.5	49.7	0.713	0.152	0.227	0.605
Steppe	73.7	3.5	0.5	77.7	0.677	0.117	0.015	0.460
D & SD	10.6	0.6	0.2	11.3	0.871	0.082	0.031	0.447
Total	5,774.5	100.2	395.5	6,270.2	0.833	0.093	0.180	0.615

same bioclimatic zones. The average carbon ratio of soil to all types of vegetation (included LB and dead wood) is 6.12 and for forest −3.62.

Previous assessments of organic soil carbon and particularly of the on-ground organic layer vary substantially. For total organic soil carbon, they differ from our estimate in limits of ±10 % (Orlov et al. 1996; Rozhkov et al. 1996). Differences for individual land classes are higher. For example, estimates for forest soils are in the range from −40 (Alexeyev and Birdsey 1998) to +15 % (Rozhkov et al. 1996).

Table 6.6 Soil organic carbon pool (on-ground organic layer + 1 m deep of soil)

	Soil carbon, Pg C by land category									
Zone	UN	FOR	OW	BA	AR	HF & PS	FL & AA	WL	GL	Total
Arctic	0.01								0.03	0.04
Tundra	0.42	1.64	1.15	0.18	0.00	0.12	0.00	11.32	14.71	29.55
FT, NT & SpT	0.01	22.86	6.61	0.31	0.00	0.00	0.00	10.92	3.38	44.11
MT	0.13	61.32	5.27	2.35	0.05	0.93	0.44	16.40	11.00	97.90
ST	0.00	21.48	0.22	0.15	0.69	0.79	0.53	7.91	1.04	32.81
TF	0.00	1.13	0.03	0.01	0.38	0.32	0.37	0.24	0.20	2.68
Steppe	0.01	2.11	0.03	0.02	3.29	4.13	1.07	0.51	0.55	11.73
SD & D	0.00	0.11	0.00	0.00	0.01	0.39	0.03	0.09	0.05	0.68
Total	0.60	110.66	13.32	3.03	4.42	6.68	2.42	47.38	30.97	219.50

Land category: *UN* unproductive area, *For* forest, *OW* open woodland, *BA* burned area, *AR* arable land, *HF & PS* hayfield and pasture, *FL & AA* fallow and abandoned arable, *WL* wetland, *GL* grassland and shrubland. Zone: *SF & NT* sparse forest and northern taiga, *MT* middle taiga, *ST* southern taiga, *TF* temperate forest, *SD & D* semi desert and desert

Table 6.7 Average soil organic carbon density (on-ground organic layer+1 m deep of soil)

	Soil carbon, kg C m^{-2} by land category									
Zone	UN	FOR	OW	BA	AR	HF & PS	FL & AA	WL	GL	Average
Arctic	0.41								9.40	1.13
Tundra	2.16	13.76	18.56	12.10	0.00	12.16	7.06	37.51	13.30	16.32
FT, NT& SpT	5.27	22.13	27.34	10.70	10.00	6.44	10.35	44.69	14.16	24.63
MT	2.85	16.07	14.87	15.30	14.25	12.59	16.10	45.23	14.31	17.46
ST	4.97	24.02	29.62	27.78	18.61	16.74	18.65	63.16	25.55	27.66
TF	4.82	19.68	47.19	35.44	23.41	18.97	22.05	40.64	29.73	22.19
Steppe	5.35	21.85	27.83	23.57	25.11	21.30	25.50	18.41	20.49	22.44
SD & D	0.99	17.66	7.74	11.43	19.86	16.26	19.99	14.41	10.48	15.04
Average	2.12	18.38	19.94	14.82	23.45	18.24	21.00	44.13	14.10	19.74

A number of reasons contribute to this: use of different land cover in the assessments, incompleteness of information used, lack of planning of the experiment, etc. Soil carbon remains the most uncertain carbon pool of Siberian ecosystems.

6.2.2.2 Net Primary Production of Ecosystems

Historically, numerous empirical data on NPP of Russian forests were biased due to two reasons: (1) they are based on destructive in situ measurements with intervals of weeks and months that do not account for a substantial part of NPP (e.g., root exudates or volatile organic compounds, VOC) which could reach 15–20 % and more in boreal forests (Vogt et al. 1986) and (2) the typical incompleteness of NPP measurements of some components of ecosystems, like fine roots and below-ground parts of shrubs and the green forest floor (Schulze et al. 1999; Vasiliev et al. 2001). In order to eliminate bias, a new "semi-empirical" method for evaluation of NPP of Northern Eurasian forest ecosystems was developed (Shvidenko et al. 2007a, 2008). The method is based on simulation of biological production of forest ecosystems using aggregation of regional empirical regularities of growth of forest stands and dynamic models of live biomass of forest ecosystems. The method does not have any recognized biases in contrast to existing empirical methods of assessment of forest NPP on large areas. This method has been used for assessing forest NPP.

NPP for other classes of natural vegetation has been assessed based on empirical in situ measurements. In general, such measurements also have shortcomings similar to the above mentioned for forests (e.g., Vasiliev et al. 2001); however, we were not able to avoid these. NPP of agricultural land was defined similarly to live biomass of this land class.

The total annual NPP of Siberian ecosystems is estimated at 2.76 Pg C year^{-1}, or 257 g C m^{-2} year^{-1}. By land classes, agricultural lands have the highest NPP (402 g C m^{-2} year^{-1}) and open woodlands – the smallest (84 g C m^{-2} year^{-1}); 97.5 % of open woodlands are situated in northern zones of Siberia, mostly in the forest-tundra ecotone – this is the reason for such low productivity. NPP of forests is estimated at 283 g C m^{-2} year^{-1}. NPP of all land classes has clear zonal gradients (Table 6.9).

To our knowledge, there were no previous estimates of NPP for the entire region. The estimates for forests of individual regions reported by Usoltsev et al. (2011) are consistent with our results. Only one recent estimate of forest NPP for the Asian part of Russia has been reported – at 277 g C year^{-1} for 2003 (Shvidenko et al. 2008). Note that previous estimates of NPP for all terrestrial ecosystems over the entire country are very diverse – from 2.75 Pg C year^{-1} (Filipchuk and Moiseev 2003) for the ~2000s to annual averages of 4.35 Pg C year^{-1} for 1988–1992 (Nilsson et al. 2003) and 4.73 Pg C year^{-1} for 1996–2002 (Zavarzin 2007) and up to 5.1 ± 0.36 Pg C year^{-1} for 2003–2008 (Shvidenko et al. 2010b). The latter paper reports NPP for Asian Russian forests that is very close to the above estimate of forest NPP (Table 6.8) – at 1.68 Pg C year^{-1} against 1.70 Pg C year^{-1}.

An important question is how certain are the above NPP estimates of Siberian ecosystems. Relatively comprehensive analysis of uncertainties could be done for forests (the approach is considered in Shvidenko et al. 2010b) that resulted in ±6–8 % (CI 0.9). This conclusion is supported by comparisons with independent assessment by different methods. Yearly NPP defined by 17 DGVMs (Cramer et al. 1999), which included changing environment, on average differed from our assessment only by +6 %. The NPP product from Terra-MODIS gives the average result almost identical to data of Table 6.8, but shows a substantial bias of different sign for both low and high productive forests of the country.

Siberia faces a significant change of environment, which presumably substantially impacts productivity of ecosystems, i.e., climate change, increasing atmospheric concentration of CO_2, and nitrogen deposition, and along with this a substantial acceleration of anthropogenic impacts. While the two last decades have been the warmest for the entire period of records, still the observed temperature trends and precipitation are rather far from limits of sustainable functioning

Table 6.8 Net primary production of vegetation by land classes and bioclimatic zones

	Net primary production, Tg C year^{-1} by land classes						
Zone	Forest	Agro	Burned	Wetland	Grassland	Open woodland	Total
Arctic					0.2		0.2
Tundra	28.7	0.3	1.4	34.8	126.6	5.4	197.1
Sparse taiga	220.8	0.3	2.9	48.8	38.6	21.8	333.2
Middle taiga	1,065.1	39.5	22.4	94.7	180.9	27.3	1,429.8
Southern taiga	330.0	47.0	1.0	49.9	25.8	1.2	454.8
Temperate forest	19.5	20.7	0.1	3.7	5.4	0.1	49.5
Steppe	35.0	145.4	0.2	56.2	23.6	0.2	260.6
Semidesert and desert	3.8	16.1	0.0	8.4	3.2	0.0	31.6
Total	**1,702.9**	**269.3**	**28.1**	**296.4**	**404.2**	**55.9**	**2,756.8**

Table 6.9 Average net primary production by unit area by land classes and bioclimatic zones

	Net primary production, g C m^{-2} year^{-1} by land classes						
Zone	Forest	Agro	Burned	Wetland	Grassland	Open woodland	Total
Arctic					60		60
Tundra	244	350	95	115	119	86	126
Sparse taiga	214	346	100	200	171	90	188
Middle taiga	279	381	146	261	243	77	258
Southern taiga	369	419	185	399	758	156	386
Temperate forest	351	433	209	623	876	159	425
Steppe	363	400	195	2,021	936	166	506
Semidesert & desert	348	389	162	1,349	552	185	488
Overall average	**283**	**402**	**137**	**276**	**192**	**84**	**257**

of regional ecosystems, particularly forests. However, intensive regional weather anomalies become more frequent and sometimes disastrous.

The average global concentration of CO_2 in the atmosphere continues to grow: in 1995–2005 this indicator on average increased at 1.9 ppm year^{-1} (Forster and Ramaswamy 2007). The impact of increasing concentration of CO_2 on NPP are usually described by "Killing's formulae" $\mathrm{NPP}\ (C_0) = \mathrm{NPP}_0\ [1 + \beta \ln (C_a/C_{a=0})]$ where C_a – actual concentration of CO_2, β – growth factor; $C_{a=0}$ is a base concentration of CO_2, e.g., in the preindustrial period; $\mathrm{NPP}_0 = \mathrm{NPP}(C_{a=0})$ (Bacastov and Keeling 1973). As a whole, an invigorative impact of CO_2 on ecosystem productivity is supported by a number of research findings; however, there are different results and opinions about the base parameters of this process. Increasing CO_2 concentration supports earlier maturing of forest trees (under smaller size in age of maturity) and unproportional allocation of carbon in generative organs (de Graaff et al. 2006). Shortage of nitrogen decreases the fertilization effect of elevated concentrations of CO_2 on live biomass increment (Raich and Nadelhoffer 1989; Schneider et al. 2004). Net C accumulation in boreal and temperate forests correlates with regional levels of net deposition of nitrogen (e.g., Magnani et al. 2007). In comparative research of the fertilization impacts of elevated CO_2 concentration on forests of different biomes, Ciais et al. (2005) reported the significant impact of this factor on boreal forests.

There are a number of empirical and modeling studies in support of increasing productivity along the circumpolar boreal and polar belts. It points to increasing of biomass, density, and height of vegetation. For instance, in Canadian tundra the biomass of mosses has increased by 74 % and evergreen shrubs by 60 % during the last two decades (Hudson and Henry 2009). Some models predict the increase of productivity of spruce forests in European Russia (Oltchev et al. 2002; Olchev et al. 2008, 2009) in the future if projected increase of atmospheric CO_2 will be balanced by an increase of available soil nutrients (nitrogen, phosphorus, potassium). A rather consistent conclusion of a number of studies, climatic trends, and environmental change support an increase of productivity of ecosystems in Northern Eurasia. For forest ecosystems, annual average increase of net growth of Russian forests is estimated at 0.4–0.6 % per year between 1960 and 2000 (Alexeyev and Markov 2003; Shvidenko et al. 2007b), or about 20–25 % over this period. However, the possibility to distribute these data over Siberia should be used with caution due to the wide distribution of disturbances in the region. A decrease of growing stock in Alaska's forests during 1957–2007 was reported by Rautiainen et al. (2011).

Change of live biomass' stock and NPP integrates all natural processes in the biosphere as well as the human impacts. It is suspected to lead to a reorganization of many components of the production process: reallocation of carbon in above- and below-ground parts of ecosystems, changing rate of decomposition of dead vegetation matter, changing the ratio of major components of carbon cycling (e.g., for NPP and heterotrophic respiration), and others.

It is hypothesized that warming is one of the major drivers of increasing productivity of vegetation ecosystems of Northern Eurasia, particularly forests although the usual climatic norm of temperature of growth periods is lower than the temperature optimum for indigenous tree species of temperate (25–30 °C) and boreal (15–20 °C) latitudes. This, however, requires a corresponding increase in precipitation which was not observed over vast continental regions of Northern Eurasia during recent decades (Lapenis et al. 2005). There are examples from high latitudes when temperature increases lead to a decline of radial increment of trees due to a shortage of available water driven by elevated temperature (Barber et al. 2000). Increasing growth period could enter into the conflict with plant's photoperiodism, whereas insufficient chilling negatively impacts NPP. Besides short-term impacts of elevated temperatures on ecosystems, there are numerous ecosystem indirect responses and feedbacks caused by water regime change, change of succession, change of nutrient availability, species composition, and outbreaks of insects and pathogens (e.g. Lloyd and Bunn 2007).

Impact of climate also yields a change of allometric relationships in boreal forests. Based on more than 3,000 sample plots, Lapenis et al. (2005) showed a pronounced increase in the share of green parts (leaves and needles) and a decrease in the share of above-ground wood in Russian forests between 1960 and 2000. However, there is a large geographical variation of this process. The shift has been largest within European Russia, where both summer temperatures and precipitation have increased.

On the contrary, in the northern and middle taiga of Siberia, where the climate has become warmer but drier, the fraction of the green parts has decreased while the fractions of aboveground wood and roots have increased. These changes are consistent with experiments and mathematical models that predict a shift of carbon allocation to transpiring foliage with increasing temperature and lower allocation with increasing soil drought. This result might be considered as a possible demonstration of the acclimation of trees to ongoing warming and changes in the surface water balance which had a moderate trend during the considered period.

However, there are many unresolved questions in understanding the interaction of a changing environment with boreal vegetation. There is still no clear understanding how tree species and ecosystems function under dynamic conditions of multiple limitations for life resources. While there are no clear answers a number of important questions arise: (1) How stable is direct forcing of photosynthesis and NPP by the direct change of environment? (2) How much do limitations for resources (water, nutrients) restrict CO_2 fertilization effect and how long does the impact of such limitations remain substantial? (3) Could nitrogen depositions alleviate a shortage of nitrogen that is usual for high latitudes? (4) How will cryogenic destruction of permafrost impact landscapes of high latitudes? Future experimental and modeling efforts are needed to answer these questions of fundamental importance.

6.3 Disturbance and Succession Dynamics of Forests

6.3.1 Disturbance Regime and Succession Dynamics

Natural- and human-induced disturbance is an integral feature of the boreal world. Large-scale disturbance shapes the vegetation mosaics that define boreal landscapes and defines the structure of Siberian forest ecosystems by setting the beginning and end of successional dynamics (Heinselman 1978; Shugart et al. 1992; Antonovski et al. 1992). Disturbance is an inherent geographical, landscape, ecosystem, and site-specific phenomenon that interacts as relatively stable processes or combinations of specific or novel disturbance that defines the "disturbance regime" of that ecosystem or biogeocenosis (Chudnikov 1931; Tumel 1939; Shvidenko and Nilsson 2000b). Major types of disturbance (fire, insect/diseases outbreaks, harvest, snow- and windbreaks, pollution and industrial transformation) impact, on average, $10–25 \times 10^6$ ha of Siberian forest land annually.

Successional dynamics form the foundation for the beginning, development and destruction of forests, natural or planted (Sukachev 1972; Kolesnikov 1956; Sedykh 2009). Knowledge of successional regularities serves as the background for understanding the spatial and temporal dynamics of forest ecosystems. Specifics of forest forming successional processes are revealed in the number of stems, individual or species cohorts, spatial extent, health and duration of successional phases (i.e., time periods of a specific quantitative and qualitative morphological forest ecosystem state, which is characterized by homogenous structure and regularities of age dynamics) and stages (successional age development within the phases, e.g., a period with dark coniferous understory succeeding in secondary birch and aspen overstory).

Based on classical works of V. Sukachev and B. Kolesnikov, a comprehensive classification of successions in Siberian forests that has been developed and parametrized by the European Commission project *Siberia* (D. Efremov, A. Isaev, P. Khomentovsky, G. Korovin, V. Rozhkov, V. Sedykh, A. Sheingauz, A. Shvidenko) includes six classes – climatic-morphogenic, biogenic, cenogenic or age-related changes, pyrogenic or postfire, anthropogenic, and climax sparse forests growing in extreme conditions (e.g., on bogs or subalpine sites) which are divided into subclasses, genera, and kinds (Shvidenko et al. 2001; Farber 2000; Sedykh 2009). Of this classification, only two classes of succession – cenogenic (including three major subclasses – succession with change of species, without changes of species and point-dispersion) and climax sparse forests represent dynamics driven by endogenous factors of ecosystem development. The rest of the classes (>90 % of the forest land in Siberia) are driven be exogenous impacts, i.e., by disturbance. Expanding on this thought, the beginning and end of cenogenic phases are also set by disturbance, and disturbance on climax sparse forest lands could alter the system, potentially for centuries. If there is a landscape-scale balance of endogenous and exogenous factors, this maintains stability in landscapes at the regional scale. Thus, disturbance regimes define the specifics of the temporal and spatial dynamics of Siberian forests, and changes in disturbance regimes could alter the mosaic structure of regional-scale landscapes. According to estimates of the Project *Siberia* (Schmullius and Santoro 2005), phases of pyrogenic succession include from 40 to 96 % of the total forest land by individual ecological regions of Siberia.

6.3.2 Fire

Fire is a major natural disturbance in Siberian ecosystems, in particular, in forests, because of: (1) dominance of natural ecosystems in Siberia; (2) almost all Siberian forests are boreal forests, and 71 % of them are dominated by coniferous stands of high fire hazard; (3) a major part of the forested territory is practically unmanaged and unprotected – large fires (>200 ha) play an important role in this region; (4) natural ecosystems accumulate large amounts of dead organic matter due to slow decomposition of plant residuals; and (5) a substantial part of natural ecosystems (particularly in Central and Eastern Siberia) are situated in regions with limited amounts of precipitation during the fire season and/or frequent occurrences of long drought periods during the fire season that often generates fires of high severity. The double-faceted role of forest fires – destructive and creative – is well recognized in high latitudes. In the central and southern part of the boreal zone, forest fires are one of the most dangerous environmental phenomena, which cause significant economic losses and have a strong negative ecological impact on forest ecosystems and environment. In unmanaged and unused forests of northern and sparse taiga, specifically in permafrost regions, on-ground fire with a "normal" fire cycle (80–100 years) is a natural mechanism for preventing the decreased productivity of forests, paludification of forest lands and finally, hinders the distribution of desertification (Sedykh 1990). However, even in high latitudes, frequent human-induced recurrent non-stand replacing fires can significantly decrease the actual productivity and resilience of forests (up to 40–50 %).

Fire activity is basically driven by four major factors – weather/climate, amount and condition of fuel, ignition agents, and human activities. All these together form landscape specific fire (pyrological) regimes – stable combinations of individual types of vegetation (forest) fires and their characteristics, as well as specific interactions between ecosystem, fire, and other disturbance types. Fire regimes are quantified by a number of indicators, which are explicitly defined in space and time (extent of fire; frequency, e.g., in form of return fire interval; intensity of burning, measured, e.g., by radiative energy; indicators of postfire forest transformation, etc.).

On average, for basic forest upland types and geographical localities, the fire-return interval in Siberian taiga forests including all types of fire is 25–70 years. However, the variation of fire frequency is very large: upper limits are 250–300 years for wet sites and dark coniferous forests (and up to 500–700 years for wetlands), lower limits are 7–15 years, and even less, usually observed in dry pine and larch forests in densely populated areas. In a historical perspective, areas in which no fires occurred during a single life cycle of coniferous taiga forests (200–300 years) are negligibly small in drainage sites of the taiga zone (Furyaev 1996). For major forest types of the taiga zone, fire is physically possible if the amount of on-ground fuel exceeds 0.5 kg dm m^{-2}. Particularly severe fires occur in forests disturbed by insects, so-called *shelkoprjadniki*.

The majority of the fire events in Siberia are of human origin and about 20–30 % in some regions (measured by fire extent) can be attributed to natural factors alone (mostly lightning). The majority of fires (~75–85 %) are ground fires, either superficial or steady. Crown fires comprise about 20 %; however, in extremely severe fire years this share could be doubled (Shvidenko and Nilsson 2000a; Achard et al. 2008). Crown and peat fires are stand-replacing fires, while on-ground fires cause a partial dieback which is accounted for from 5–7 % (by initial growing stock) to 70–90 % after steady ground fires, particularly in usually wet sites and on permafrost. Indicators of fire regime depend on many factors: weather specifics during the vegetation period, fuel characteristics of forests and adjoining vegetation, type of forest formation, spatial structure of landscapes, their ecological regimes, inter-annual climate variability (recurrence of extreme droughts), density of population, accessibility of forests, level of forest fire protection, and others.

Severity and extent of fire define the level of transformation of indigenous vegetation that could be expressed by different indicators of disturbance rate (e.g., loss of productivity). Publications report that about 35 % of Siberian forests could be classified as disturbed forests. Irreversible change in forest ecosystems becomes particularly evident after so-called *mega*-or *catastrophic fires*. Catastrophic wildfires are fires covering an area of more than 10,000 ha, resulting in the total destruction of vegetation and organgenic horizons of soils, or the simultaneous occurrence of several fires of the same total area and intensity over a total area of 1,000 km^2

(Sheshukov 1967). Sukhinin (2009) defines catastrophic fires as those which envelop substantial part of a landscape (>20,000 ha) under conditions of a long-period anticyclone and the highest class of drought; they have an extremely high intensity of burning and postfire dieback >50 % of growing stock. During years of high fire danger, a "spring" fire regime is transformed into a "late-summer" one that reflects a substantial increase in fire severity and a following increase of carbon and nitrogen emissions.

Long-term consequences of catastrophic fires are the irreversible transformation of the forest environment, which is obvious beyond the restoration period of indigenous forest ecosystems, i.e., exceeds the lifetime of major forest forming species (that ranges from 150 to 400 years for major forest forming species of Siberia). They reveal the following aspects (Yefremov and Shvidenko 2004):

- 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
- Irreversible changes of the cryogenic regime of soils and rocks
- Change of long-term amplitude of hydrothermal indicators beyond natural fluctuation
- Changes of multi-year average hydrothermal and biochemical indicators of aquatic and sediment runoff, as well as of hydrological regimes and channel processes of water streams
- Accumulative impacts on atmospheric processes resulting in global climate change
- Acceleration of large-scale outbreaks of insects and disease
- Irreversible loss of biodiversity including rare and threatened flora and fauna species
- Transboundary water and air transfer of pyrogenic products
- Change of historical migration routes for migratory birds, ground and water animals

In particular, the correlation coefficient between the share of unforested areas in forest landscapes and the forest fire occurrence rate was estimated at 0.49 (CI 0.95) (Sheingauz 2001). At the level of forest enterprises, a 1 % increase in a forest fire occurrence rate on average causes an 8.4 % decrease in the percentage of forest cover.

By estimates, forest fires increased the total area of deforested lands in the Asian part of Russia by up to 20 million ha over the last 50 years (Yefremov and Shvidenko 2004). Generally, single or repeated catastrophic forest fires transform about 30 % of highly productive forest land (with a total stock of live biomass of up to 200–300 Mg dry matter per ha) to barren land areas for which forest regeneration is postponed for an indefinitely long period of time (process of "green desertification"). On average for the taiga zone, such lands comprise up to 70 % of bogs, 15 % of grass-small shrub and shrub lands, 10 % of open woodlands, and up to 5 % of stone fields and stone outcrops. These territories can only be rehabilitated through targeted and labor-consuming meliorations. The natural restoration of forests in these areas requires several hundred years.

Recent years reveal substantial impacts of catastrophic fires on regional weather. Observations of atmospheric patterns over burning and smoking forests in Eastern Siberia and the Far East in 1998 recognized the presence of anticyclones above huge areas of Northern Asia, from the Yenisei River to the Okhotsk Sea (Sokolova and Teteryatnikova 2002). These territories, where enormous amounts of forest fuels were accumulated and which had a large-scale smoke blanket of a size comparable to the extent of the baric systems (i.e., an area of more than 350–400,000 km^2), had a long period of high atmospheric pressure. It forces the cyclones to take a southern bypass. This caused intensified drought episodes over the fire-affected areas that extenuate the forest fire situation. The presence of anticyclones in temperate latitudes of Eastern Asia both in winter (that is common) and summer time (that is unusual) was due to the increased air density (through the cooling down of near-surface layers caused by the smoke aerosol), and summer anticyclones were duplicating the mechanism of winter ones. Alternatively, such a meteorological situation can generate long periods of rainfall and catastrophic floods as in the basin of Yangtze River in the summer of 1998.

Analysis of meteorological processes based on pressure charts identified an important specific feature. In all years, when in early summer the usual tropospheric ridges at a baric height of AT-500 arose in the smoke affected atmosphere, the anticyclones (associated with a drought) persisted in this area over the entire summer. This smoke-affected anticyclone remains over the entire warm period, and such a phenomenon was observed only in territories affected by the smoke. During the summer, the continental tropospheric ridge is being supported by powerful heat fluxes from fire and hot smoke. Only the decreased temperature in late summer eliminates the influence of smoke atmospheric aerosol that leads to the gradual destruction of the continental tropospheric ridge.

Meteorological conditions which initiated catastrophic forest fire occurred in 1954, 1968, 1976, 1988, and 1998 in the Amur River Region, in 1979, 1985, 1998, and 2003 – in Eastern Siberia (from Krasnoyarsk Kray to Burjatia and Chita regions), in 1996 – in Amur Oblast and in the Republic of Sakha, and in 2002 – in the Republic of Sakha (Sokolova and Teteryatnikova 2002). In spite of incomplete understanding of the mechanism of the above-mentioned regularities, one could assume that catastrophic forest fires have a substantial influence on the formation and alteration of the regional climates.

Substantial negative impacts of catastrophic fires in south taiga on biodiversity were reported (Kulikov 1998) and are particularly dangerous at ecotone boundaries of natural habitats of animal and plants. These fires decrease the amount of fodder, lead to fragmentation of habitats, and eventually substantially decrease populations of animals, reptiles, and birds. Also migrating birds and ungulates now use routes that differ from their traditional ones. However, forest fires of moderate intensity in high latitudes could protect and promote biodiversity at both ecosystem and species levels (Sedykh 2009).

Relatively reliable documented records of areas of vegetation fire in Siberia exist since 1998 when several remote sensing centers in Russia and abroad started systematic reporting of areas enveloped by fire and burned areas. Improving knowledge and availability of new satellite-based fire products substantially improved understanding of fire regimes and emission estimates from wildland fire. Three major remote sensing products that were used for detection of vegetation fire in Siberia – Spot Vegetation (VGT), Terra-MODIS, and Advanced Very High Resolution Radiometer on board of NOAA satellites (AVHRR) – have similar temporal and nadir spatial resolutions. Products from VGT and MODIS have better geometric fidelity, radiometric calibration, multi-spectral registration, multi-temporal registration, and absolute geolocation but are not based on thermal channels. The latter is important for fire detection due to dominance of ground fire in Siberia. Different sensors provide substantial diversity of seasonal variation of the number of fires and the area burned. However, detection of large fires (>200 ha), which comprise about 90 % of burned areas in Siberia are of the same magnitude. This results in relatively consistent estimates of burned areas by the above sensors (e.g., Bartalev et al. 2007; Van Der Werf et al. 2006) – the differences between the total annual areas that are enveloped by fire are in the range of ±20–25 %. However, some publications present a substantially higher variability. For instance, the average area of vegetation fire over the entire country (of which >90 % occurred in Siberia) is reported to be 19.6 million ha from 2003 to 2007 included 6.9 million ha in forest (Vivchar 2010), while the estimate of burned area in forest (Ershov et al. 2009) is 3.9 million ha for the same period. Both of these assessments are based on the same remote sensing products (Terra-MODIS). Reliability of these estimates remains questionable, particularly for large areas of grassland, croplands, woodland, and wooded grassland. Usually coarse resolution remote sensing, particularly those based on optical and infrared bands, underestimate the burned areas (Zhang et al. 2003). Official Russian fire statistics which represented fire in so-called "actively protected forests" of Siberia underestimated actual burned areas on forest land by an order of magnitude (Shvidenko and Goldammer 2001).

In this study we used data presented by the Institute of Forest (Krasnoyarsk) (available also at IIASA FOR website). Wildfire data were acquired based on AVHRR imagery (hot spots) with sampling control of burned area by LANDSAT (Sukhinin 2008). The approach and algorithm used are described in details in Soja et al. (2004). Taking into account that AVHRR (bands 2, 3, 4, and 5) overestimate burned areas, particularly for small fires, the estimates have been corrected by using regression with burned-area estimates from LANDSAT ETM+ (resolution 30 m) for a number of regions. Likely, the AVHRR/LANDSAT ETM+ method currently provides the most reliable estimates of areas of vegetation fires in Russia.

The average areas affected by fire between 1998 and 2010 in Siberia is estimated at 7.4×10^6 ha, of which 50–70 % are on forest land (Fig. 6.2) with the variation from 3.6 (2004) to 16.1×10^6 ha (2003). The change of burned areas for the last 13 years do not give any clear answer about the short-term dynamics of fire danger in Siberia.

However, there is evidence that occurrence of fire danger years have been increasing during recent decades. Specific weather during the two recent decades had a rapid and pronounced effect on fire activity and caused new tendencies of fire regimes. The latter include increase of the extent, frequency, and severity of fires;

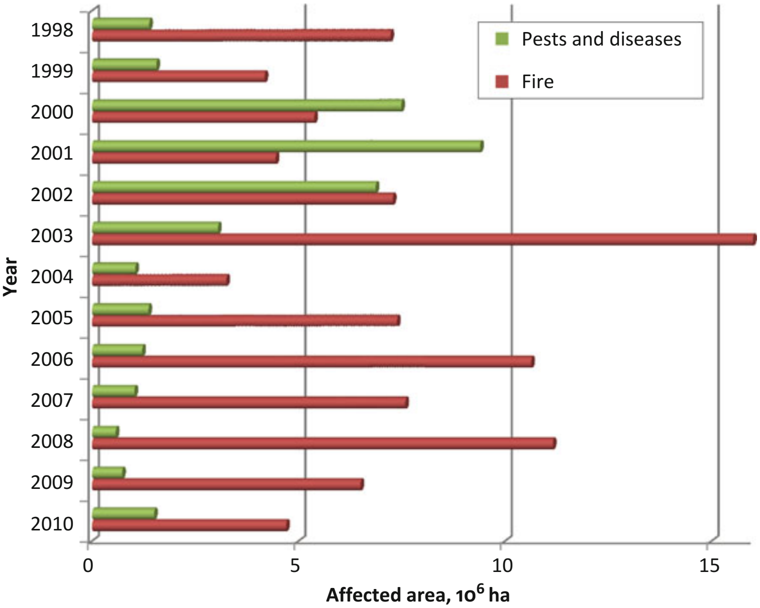

Fig. 6.2 Area affected by fire and pests in Siberia in 1998–2010. Average burned area 8.23×10^6 ha year^{-1} (From 4.2×10^6 ha in 1999 to 17.3×10^6 ha in 2003). Average area of pest and diseases breakout is 2.9×10^6 ha year^{-1} (From 0.6 to 9.4×10^6 ha)

the similar picture is observed during the last several decades across the entire circumpolar belt (Kasischke and Turetsky 2006; Yefremov and Shvidenko 2004; Ivanova 1996, 1998–1999). It has been shown that the observed increases of burned areas during recent decades are the result of climate change (e.g., Gillett et al. 2004). Large fires increased areas of usually nonburned land classes, particularly wetlands, which became more vulnerable to fire. It substantially increased the total amount of greenhouse gas emissions, as well as the amount of such gas components as CO, CH_4, CH_3Br, and CH_3Cl due to increasing smoldering consumption (Manö and Andreae 1994).

Vaganov et al. (1996) based on dendrochronological analysis for the last 380 years reconstructed fire frequency in pine forests of two regions in Krasnoyarsk Kray, and showed a statistically significant correlation between climatic indicators and occurrence of forest fire. The length of the mean fire return interval by the regions (of 35 and 18 years) was clearly impacted by anthropogenic impacts by end of the studied period.

For the zone of northern taiga (River NizhnyayaTunguska basin around Tura in East Siberia, about 65°N), the region of dominance of larch forests, Kharuk et al. (2008) showed that during the nineteenth century the fire return interval (FRI) decreased from 101 to 65 years in the twentieth century. For the more southern territories (~60°N) of the larch-mixed zone ecotone, the decrease was from 97 to 50 years.

Efremov and Shvidenko (2004) reported a trend of increasing annually burned area in Khabarovsk Kray during recent decades.

Evidently dynamics of fire frequency depend on many reasons, both climatic and anthropogenic. An important factor is industrial development of previously untouched territories. Ivanova (1996) reported the following sequence of extremely dangerous fire years for Evenkia: 2 in seventeenth century, 3 in eighteenth century, 9 in nineteenth century, and 29 in twentieth century.

Permafrost and wetlands interacts with fire activity, emissions of carbon, methane, and other greenhouse gases, and postfire mortality. Very likely higher temperatures and permafrost thaw will increase the fire activity and vulnerability of terrestrial ecosystems to burning due to (1) changing hydrological regimes over vast territories due to decreasing water table and increasing evapotranspiration, (2) wider distribution of deep burning, and (3) more intensive postfire dieback.

Interactions between fire regimes land use and climate may become increasingly important for carbon storage and fluxes in ecosystems. One could suppose that climate change and other pressures (such as industrial development and expanding populated areas) will provide a further profound effect on the boreal ecosystem. If current climatic predictions are realized, future fire regimes will be characterized by (1) increasing length of fire season; (2) accelerated fire activities – number of ignitions, large areas with extreme fire hazards, etc.; (3) increased area burned, severity of burning, and amount of consumed fuel; (4) increased occurrence of disastrous fires; and (5) increased postfire impacts on ecosystems and landscapes.

The ability of Siberian forest management to cope with these changes is very limited. Current forest fire protection operates within a narrow margin between success and failure, and disastrous fires of recent decades in Siberia clearly illustrated the scale of problems that arise. It requires substantial changes to forest management policies including setting of priorities, prevention programs, fire monitoring systems, initial attack capabilities, and modification of some legislative and institutional aspects of forest management like access restriction policies.

Research indicates the inability of current fire protection systems to successfully withstand the increased fire pressure even in countries with highly organized fire protection (like Canada and USA) and could lead to catastrophic consequences in countries with fire management in disarray (like Russia). The fire season-2010 in Russia, when large fires occurred in densely populated territories of European Russia, has brought economic losses of about USD ten billion.

Based on GCMs and different vegetation models, a substantial increase of fire hazard is predicted over the entire circumpolar belt mostly due to warming, particularly in southern and continental regions (see also le Goff et al. 2009; Balshi et al. 2009). There is a general tendency of increasing risk, extent, and severity of forest fire, as well as length of fire season. For Siberia, fire danger may increase by a factor of 3–4, with a peak in the middle of August. By end of the twenty-first century, the risk may be decreasing due to increase of precipitation according the contemporary GCM predictions (e.g., Mokhov et al. 2006, 2009, cf., Chapter 3). Intensification of fire activities will be accompanied by substantial shift of bioclimatic zones northward up to 600–1,000 km. New climate and accelerated fire regimes may halve areas of Siberian forests by 2080 (Tchebakova et al. 2009). For Canada, an average increase in the Seasonal Severity Rating and the resulting area burned is expected at

~50 % by mid-twenty-first century (2×CO_2 scenario, Flannigan and Van Wagner 1991). An earlier start of fire season and significant increases of area large fire in both Canada and Siberia has been predicted by Stocks et al. (1998). Many other studies predict increasing the area burned, particularly due to increasing lightning-caused fires. Altered fire regimes, succession dynamics, and permafrost behavior could result in a positive feedback intensifying rates of climate change (Kurz et al. 1995; Lyons et al. 1998; Soja et al. 2007).

National programs of adaptation to, and mitigation of negative consequences of climate change in the boreal zone, should include fire protection as a cornerstone of current and future sustainable forest management. Development of long-term strategies of adaptation by boreal landscapes to future climates is an urgent problem today. The inherent uncertainty of forecasts is a specific problem of such developments, and hence the need for use of win-win strategies which would be robust to a diversity of possible scenarios. International cooperation in further development of boreal fire protection is an issue of the highest priority.

6.3.3 Biotic and Other Disturbances

Among numerous biotic disturbances, insect and disease outbreaks are most important. Official data on biotic factor impacts remain only a source of information because remote sensing is still not able to identify the partial damage which is usually caused by pests and pathogens. Very likely, official statistics underestimate the real impacts of biotic disturbances, although this underestimation is probably less than for fire because major areas of insect and disease infestations are located in southern regions, where forest pathological monitoring is provided. According to rather consistent opinions of Russian experts, the damage caused by insect and diseases is of the same magnitude of that generated by fire (Isaev 1997; Baranchikov et al. 2001; Isaev et al. 2001). In areas of insect and disease outbreaks, the trees are killed completely or partially, productivity and vitality of forests are substantially decreased, and large amounts of dead wood are accumulated. The latter increases flammability of damaged forests and frequency and severity of fires that slows down the natural regeneration.

Phyllophagous are the most harmful group of insects, particularly, in territories of concurrent interactions between different types of vegetation (e.g., the ecotone forest-steppe, or taiga-subtaiga forests). In zonal taiga vegetation types, insect outbreaks are initiated by special weather and landscape conditions and have a clear cycling character (e.g., Baranchikov 2011). As a rule, warmer and drier weather provokes large-scale outbreaks. For instance, the most dangerous Northern Eurasia forest insect – Siberian silk moth (*Dendrolimus superans sibiricus* Btl.) has favorable conditions for outbreaks in dark coniferous and pine forest, if the sum of active temperature exceeds 1,600 °C and radiation dryness index (RDI) by Budyko is >1.5; for larch forests the weather should be drier (RDI >2.0). Outbreaks of other dangerous insects (*Bupalus piniarius*, *Dendrolimus pini*, *Lymantria dispar*, *L. monacha*) are usual when the amount of heat >1,800–2,000 °C and RDI is 1.5–2.0 (Rozhkov 1965; Pleshanov 1982; Yurchenko et al. 2003). Under such conditions, outbreaks take on an eruptive (pulsating) character of the dynamics of insect populations, occupy significant areas and cause significant economic damage, lead to deep ecological transformation, and result in changes of composition and structure of forest cover (Epova and Pleshanov 1995).

The history of insect outbreaks in Asian Russia is impressive. In the southern taiga of Tomsk Oblast and Krasnoyarsky Kray, seven outbreaks of Siberian silk moth occurred during the period from 1878 to 1970, and the areas of dark coniferous forest that perished totaled more than 8×10^6 ha (Isaev 1997). The area of forests killed in Siberia and the Far East by this dangerous insect between 1880 and 1969 is estimated to be 13×10^6 ha with destroyed growing stock of two billion m^3. Six outbreaks were observed in territories of Irkutsk Oblast from 1870 to 1963, and *Pinus sibirica* forests were killed over an area of 1.06×10^6 ha with losses of 160×10^6 m^3 of wood (Rozhkov 1965). The outbreak of Siberian silk moss in East Siberia (1993–1997) impacted about one million ha and resulted in timber loss of $\sim 50 \times 10^6$ m^3 in highly productive dark coniferous forests (Isaev 1997). Much warmer than usual weather conditions during the last 3 years of the twentieth century provoked an outbreak of Siberian silk moth over a total area of almost ten million ha (2001), mostly in larch forests in the far north, where this pest was not typically observed.

Official data for the last decades shows an increase of the areas affected by biogenic factors. According to official statistics, the total area of outbreaks of insect and diseases (defined as forested area in which pathological die-back exceeds the natural mortality more than two times) in Russian forest under state forest management during the period from 1973 to 1987 ranged between 1.5×10^6 ha and 3.8×10^6 ha, with an average 2.73×10^6 ha (Isaev 1991, 1997). During the decade 1988–1997, the average annual area reported was at 1.55×10^6 ha with the seasonal variability of individual years from 1.43 to 2.28×10^6 ha. The average for 1998–2010 was 5.48×10^6 ha with the peak of 10.4×10^6 ha in 2001 (FAFMRF 2010). The yearly average area for Siberia is estimated at 2.9×10^6, with substantial variation – from 0.6×10^6 to 10.4×10^6 (Fig. 6.2).

Pine forests are damaged by pine silk moth (*Dendrolimus pini*), usually in southern regions of West and Central Siberia, and up to Mongolia, where it produces severe defoliation of pine stands in dry sites with poor sandy soils. Outbreaks occur after several drought years, and could last up to 7–8 years. Curtain dieback of trees begins after 2–3 years of damage, and complete dieback after a longer period. The biggest harm is observed in young planted pine forests. *Bupalus piniaris* significantly damages pine forests in critical site conditions (e.g., in forest steppe of Upper Priobie). Unpaired silkworm (*Lymantria dispar*) damages practically all deciduous and larch forests; often its outbreaks co-occur with other dangerous insects (e.g., *Denrolimus superans, Lymantria monacha*) (Kondakov 1987). Although under one-two defoliations, deciduous and larch forests restored their assimilation organs, decrease of current increment can reach 50 %. *Lymantria monacha* is a very heat-loving species, and its outbreaks happen only under the heat availability of GDD at about 2,200 °C, usually in the forest steppe of West Siberia, where single severe defoliations are usually observed.

Large-scale outbreaks of dangerous insects during recent decades were also reported for the north of the American continent (e.g., Kurz et al. 2008b; Volney and Fleming 2007). As a rule, similar to Siberia, the massive outbreaks were facilitated by the impacts of extremely warm and dry summers of several years in a row and milder than usual winters that together supported shortening the life cycle and fertility of insects. It is expected that projected climate change in the boreal zone will cause the increase of frequency and intensity of outbreaks in both direct (through direct impact of climate) and indirect (through decreasing resilience of ecosystems and disruption of community interactions between different components of biogeocenosis) ways (e.g., Stireman et al. 2005).

Other large-scale disturbance processes, like drying of large areas of forests, caused by a complicated combination of biotic and abiotic factors, are reported for different regions of the country. This is a rather typical process in Far Eastern spruce-fir forests. During recent decades, several waves of increasing dieback of trees were observed here. During the large wave of the second half of the 1960s, the areas of drying forests were estimated to be 5.5×10^6 ha in territories of the two administrative regions of the Russian Far East – Khabarovsk and Primorsk Krays (44 % of the total spruce-fir forests there) with the storage of dead wood of more than 360×10^6 m^3 (24 % of the total living and dead growing stock by the moment), with average storage of dead wood at about 100 m^3 ha^{-1} (Ageenko 1969). The next wave occurred between 1970 and 1980 in Sikhote-Alin where only in seven forest enterprises, 165,000 ha of forest died with a growing stock of 14 million m^3 (data of forest pathological survey of 1987–1988). The last wave of dryness was observed during the period from 1989 to 1993. Many hypotheses have been expressed attempting to explain this phenomenon, but there is no generally accepted answer (Manko and Gladkova 2001).

Air pollution, industrial destruction of sites and unfavorable weather conditions, wind and snowbreak also damage forests over large territories. As a rule, these data are not reported in any regular way. A special survey on impacts of air pollution (1991) indicated 321×10^3 ha of dead forests with 465×10^3 ha strongly disturbed due to this impact. The survey was substantially incomplete. Surveys in the area around Norilsk (the northern part of Krasnoyarsk Kray) in 1992 estimated 2×10^6 ha of dead forest-tundra landscapes, of which 650×10^3 ha of forests has been killed; another 1.0×10^6 ha forests were found with evident serious negative impact (Isaev 1991, 1997). Kharuk et al. (2006) estimated areas of forests declined in Siberia by pollution at $3–3.5\times10^6$ ha, – three to four times more than the officially reported data for all the country.

6.4 Carbon Budget of Siberian Ecosystems

There is a substantial set of publications considering different aspects of the carbon budget of ecosystems of Northern Eurasia for individual regions, different vegetation types and countries as a whole (e.g., for Russia). These publications used diverse methods, had different information background, and reported a wide range of estimates. In this section, we present the carbon budget for the territory delineated for this study (for the first time), as well as important results obtained by major methods of carbon accounting for parts of the region and sometimes – for comparison – for the entire country.

Current philosophy of ecosystem carbon accounting is based on two prerequisites: (1) a need to follow the major requirements of applied systems analysis, and (2) that a proper understanding of the role which terrestrial ecosystems play in the global carbon cycling requires a *verified terrestrial ecosystems full carbon account* (FCA). The FCA means (1) assessing all fluxes of major carbon-containing greenhouse gases, aerosols, and lateral carbon fluxes in the hydrosphere and lithosphere should include all ecosystems and processes in a spatially and temporally explicit way; (2) uncertainties are assessed comprehensively and transparently at all stages and for all modules of the account; and (3) the methodology used presents information how to optimally manage the uncertainties (Shvidenko et al. 2010b).

The FCA is considered a complicated, stochastic dynamic underspecified (fuzzy) system that cannot be directly verified due to obvious cost and resource limitations. Fuzziness of the FCA defines that any approach of carbon accounting, individually implemented, is unable to recognize structural uncertainties, and the usually reported uncertainties in essence represent only a part (i.e., “within model”) of the real uncertainties. Thus, the FCA requires a systematic combination of the relevant methods (landscape-ecosystem method which covers bottom-up semi-empirical assessments of C pools and fluxes, direct measurements of C exchange with the atmosphere by eddy covariance, dynamic vegetation models (DVMs), and top-down inverse modeling) and harmonization and multiple constraints of independent results.

6.4.1 Carbon Account by Landscape-Ecosystem Approach

The landscape-ecosystem approach (LEA) is an attempt to implement major systems requirements to the FCA based on as comprehensive as possible description of land and ecosystems and the use of all related empirical data and models. This allows for consideration of the LEA as a basis for designing carbon accounting schemes and as a background for comparative analysis. The LEA includes a relevant combination of pool-based and flux-based approaches. The pool-based method estimates the change of ecosystems’ carbon pools for a definite period of time. The flux-based approach is used as a chain calculation:

$$\mathrm{NECB} = \mathrm{NPP} - \mathrm{HR} - \mathrm{D} - \mathrm{L}$$

where NECB denotes net ecosystem carbon balance (or net biome production, NBP), NPP – net primary production, HR – ecosystem heterotrophic respiration, D – flux due to disturbances (including consumption of plant products), L – lateral fluxes to the hydrosphere and lithosphere. HR includes heterotrophic soil respiration and the flux due to decomposition of dead wood. Sign of NECB in this study is used according to the micrometeorological convention: "minus" means carbon sink (uptake from the atmosphere) and "plus" means carbon source (emission to the atmosphere).

The pool-based method has substantial practical limitations due to high uncertainties of the size and dynamics of some pools, particularly soils. An Integrated Land Information System that includes (1) a hybrid land cover (HLC) and (2) numerous attributive datasets of available measurements serves as an information background of the LEA. The HLC for the Russian territory was developed based on the system integration and harmonization of multi-sensor remote sensing products (GLC-2000, MODIS VCF, AVHRR, LANDSAT TM, ENVISAT ASAR, others), available on-ground data (e.g., State Land Account, State Forest Account), and other appropriate information. The downscaling and parameterization of the HLC have been done for each 1-km pixel using a special optimization algorithm. Details of the approach are considered in Schepaschenko et al. (2010).

Sets of different empirical models were used to assess major components of the FCA (NPP, HR, D, and L) by land classes of the HLC. Taking into account that some initial data, both official statistics (e.g., areas of forest fire, illegal harvests) and results of measurements (e.g., NPP for forests) are biased or obsolete, corresponding corrections have been done based on independent sources of information. NPP for forests has been assessed based on a new, presumably unbiased approach (see Sect. 6.2).

In order to asses HR, a special model has been developed (Schepaschenko et al. 2011). Based on measurements of HR in situ, the model provides corrections by zonal specifics of soil types, land uses, and vegetation classes. While the fluxes due to disturbances were defined by a fairly common approach (as a product of the disturbed area and amount of consumed [transformed] carbon), the calculation schemes accounted for the specifics of each individual type of disturbance (e.g., Kajii et al. 2002). The consumption of plant products (agriculture, forest) was calculated based on official statistical data including imports and exports.

The total HR is estimated at 2.09 Pg C year^{-1}, or ~76 % of NPP (Tables 6.8–6.11). HR of two land classes (disturbed forests and open woodlands) exceeds NPP. Consequently, all these ecosystems are unlikely to be in equilibrium. Litter in these semi-natural ecosystems decomposes slowly, e.g., Mukhortova and Evgrafova (2005), so that fire and other disturbances are a major regulator of the amount of dead organic material and substantially affects soil respiration. Additional imbalance is caused by removal of harvested products in forests and agriculture. Independent estimates in the northern taiga of Central Siberia by Klimchenko (2007) estimated heterotrophic soil respiration consistent to data reported by Quegan et al. (2011) – between 73 and 59 % of NPP. Similarly, Wirth et al. (2002) estimated 48 % for postfire chronosequences in pine forests of Siberian middle taiga, although reported values for NEP (or NEE) for taiga forests of Central Siberia vary greatly – from 50–60 to 250–270 gC m^{-2} year^{-1} (e.g., Röser et al. 2002; Shibistova et al. 2002; Schulze 2002). Substantial differences between NPP and soil respiration can occur, particularly for crops, since a major part of the NPP is removed as yield, e.g., the sink of agro-ecosystems of the taiga zone of the region was estimated to be

Table 6.10 Heterotrophic soil respiration by bioclimatic zone and land classes

	Heterotrophic respiration, Tg C year^{-1} by land classes						
Zone	Forest	Agro	Burned	Wetland	Grassland	Open woodland	Total
Arctic					0.2		0.2
Tundra	14.2	0.1	1.4	28.3	108.9	5.7	158.6
FT, N & SpT	133.0	0.2	3.1	41.5	36.9	27.6	242.4
Middle taiga	700.2	31.9	26.7	93.5	202.4	43.3	1,097.9
Southern taiga	227.1	42.3	2.2	49.6	19.6	2.1	342.9
Temperate forest	18.1	16.2	0.1	2.6	2.7	0.2	39.9
Steppe	24.9	126.2	0.4	17.6	10.6	0.3	180.0
Semidesert and Desert	2.5	8.2	0.0	2.3	10.7	0.0	23.8
Total	1,120.0	225.2	33.9	235.4	391.9	79.2	2,085.6

Table 6.11 Average heterotrophic soil respiration by bioclimatic zone and land classes by area unit

	Heterotrophic respiration, g C m^{-2} year^{-1} by land classes						
Zone	Forest	Agro	Burned	Wetland	Grassland	Open woodland	All land classes
Arctic					59		59
Tundra	121	166	91	94	99	91	99
Sparse taiga	129	215	107	170	155	114	136
Middle taiga	184	308	174	258	263	122	198
Southern taiga	254	377	399	396	483	275	289
Temperate forest	326	339	325	440	394	307	341
Steppe	257	347	375	634	397	271	348
Semidesert & Desert	229	198	249	373	259	223	238
All zones	186	336	166	219	176	119	192

111 gC m^{-2} year^{-1}, or 42 % of NPP (Vedrova 2002). Such effects usually are not represented in DGVMs.

Temperature and precipitation are considered as the best predictors of the annual and seasonal dynamics of the soil respiration rate (Raich et al. 2002). The high positive correlation between CO_2 emission and soil temperatures was found in natural and agricultural ecosystems of the Russian taiga zone (Kudeyarov and Kurganova 1998). Soil temperature and soil moisture are considered the crucial environmental factors controlling soil surface carbon dioxide exchange rate. These factors interact to affect the productivity of terrestrial ecosystems and the decomposition rate of soil organic matter (Feiziene et al. 2010).

On the global scale, Raich and Schlesinger (1992) have found that soil respiration rates are positively correlated with mean annual air temperatures and mean annual precipitation. A close correlation exists between mean annual net primary productivity (NPP) of different vegetation biomes and their mean annual soil respiration rates.

Evidently, extrapolation of decomposition rates into a future warmer world based on observations of current apparent temperature or moisture sensitivities may not be adequate. Rather, it is necessary to understand how substrate availability will change and how a changing set of environmental constraints to decomposition in a future climate will determine the future apparent temperature and climate sensitivity of decomposition (Davidson and Janssens 2006).

Hence, it seems likely that soil organic C will decrease with increasing temperature due to climate change (e.g., Shaver et al. 1992). This knowledge has been incorporated by many authors (Schimel et al. 1990; Jenkinson et al. 1991; Thornley et al. 1991; Kirschbaum 1993) who used soil organic matter models to show how a future temperature increase could lead to the release of large quantities of C from the world's soils. Gifford (1994) on the other hand, conducted a similar analysis, but concluded that there should be no loss of C with increasing temperature. However, the most critical factor in all these analyses is the relativity between the climate response functions of net primary productivity and soil organic matter decomposition. There is a general expectation that increasing temperature leads to increases in both net primary productivity which provides the input to soil organic C, and the rate of soil organic matter decomposition which determines the loss of soil organic C. The critical question is whether NPP or organic matter decomposition rate is stimulated more by increasing temperature (Kirschbaum 1995).

Fire carbon emissions (for 2009) have been defined based on data of V.N. Sukachev Institute of Forest (see Sect. 6.3) by the methods described in Kajii et al. (2002) and Shvidenko et al. (2011), using also an emissions ratio by biomes and type of vegetation collected by Andrea (2010, personal communication) (Table 6.12). By the area, this year was relatively favorable by fire danger. Of the total 6.57×10^6 ha, about 50 % of burned area was in forest. The clear "spring – early summer" fire regime of this year defined the relatively small fire C emissions – 91.2 Tg C, of which 55 % were in forest and 22 % on wetlands. Almost 80 % of the total C emissions were in the form of CO_2. Interannual variation of fire carbon emissions is large – from ~40 to 220 Tg C year^{-1} (Shvidenko et al. 2011).

Table 6.13 contains a net ecosystem carbon balance of Siberian ecosystems. Overall, Siberian terrestrial ecosystems serve as a carbon sink of 349 Tg C year^{-1}, or 32.5 g C m^{-2} year^{-1}. If consumption of plant products is included, the sink decreases to 245 Tg C year^{-1}. Practically all of the sink is provided by forests. Disturbed forests are a clear source. On average, grasslands are neutral. However, tundra grasslands become a small source. Figure 6.3 presents spatial distribution of NECB across the region.

NECB(NBP):NPP ratio for all vegetation classes is ~0.11. The overall C sink is basically provided by forests (−71 ± 25 g C m^{-2} year^{-1}) which is very close to the long-term carbon sink of EU-25 forests – 75 ± 20 g C m^{-2} year^{-1} (Luyssaert et al. 2010), although major drivers of that are different. Within agricultural land, cultivated arable land served as a C source (about +40 g C m^{-2} year^{-1}). This flux is almost completely compensated by increasing carbon sequestration on abandoned agricultural land. Large areas on permafrost were also estimated as a weak source, generally considered as neutral. Uncertainties ("within an approach"

Table 6.12 Carbon emissions 2009 in Siberia by products of burning

Vegetation	Area, 10^3 ha	Emission, 10^3 t C	Including the main emission species, 10^3 t C							
			CO_2	CO	CH_4	NMHC	OC	BC	$PM_{2.5}$	TPM
Forest	3,390.7	50,961.9	42,770.6	4,278.7	519.1	367.8	514.7	51.0	553.1	805.7
Arable	235.0	337.0	292.3	25.5	3.6	3.2	1.7	0.3	2.7	4.4
Hayfield	322.9	1,050.1	903.9	83.7	12.5	10.4	5.3	1.1	8.7	13.9
Pasture	517.4	1,583.4	1,379.0	116.5	16.4	14.3	7.9	1.6	12.2	20.1
Fallow	92.7	273.1	239.0	19.4	2.6	2.4	1.4	0.3	2.1	3.4
Abandoned arable	232.4	801.5	699.5	58.0	8.0	7.2	4.0	0.8	6.1	10.1
Wetland	666.8	20,193.5	17,567.0	1,456.9	260.3	117.2	119.2	20.2	137.4	218.2
Open woodland	245.7	5,683.8	4,698.4	530.9	71.1	39.4	56.4	5.7	66.0	94.4
Disturbed forest	99.9	1,395.2	1,180.2	108.2	12.1	10.6	14.8	1.4	14.7	21.7
Grassland	769.8	8,914.7	7,862.0	568.7	96.6	48.9	51.2	8.9	57.9	93.5
Total	6,573.2	91,194.1	77,592.0	7,246.5	1,002.4	621.4	776.6	91.2	860.7	1,285.4

Table 6.13 Net ecosystem carbon balance of Siberia in 2009

Indicators	Total, Tg C year^{-1}	Fluxes by land classes, Tg C year^{-1}					
		For	Agro	Burned	Wetland	Grassland	Open woodland
NPP	2,756.9	1,702.9	269.3	28.1	296.4	404.2	55.9
HR	2,085.6	1,119.9	225.2	33.9	235.4	391.9	79.2
Fire	91.2	51.0	4.0	1.4	20.2	8.9	5.7
Other disturbances	53.9	53.9					
Decomposition	133.9	106.0		12.4	2.3	11.4	1.8
Lateral flux	43.2	24.2	2.7	0.8	4.3	8.5	2.7
Subtotal	−349.1	−347.9	−37.4	+20.4	−34.2	+16.5	+33.5
Consumption	104.6	12.0	85.1		4.0	3.5	
Grand total	−244.5	−335.9	+47.7	±20.4	−30.2	+20.0	+33.5

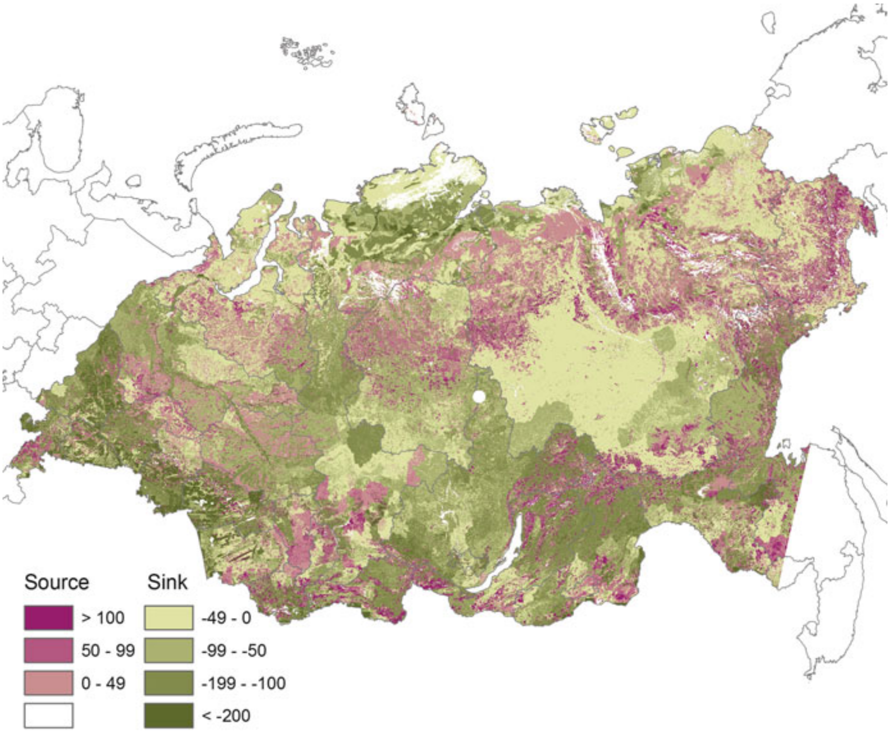

Fig. 6.3 Net ecosystem carbon balance for 2009, g C m^{-2} year^{-1}

estimate, the confidential interval, CI, is 0.9) of major fluxes, such as NPP and HR, are estimated at ±7–12 %.

Recently, Pan et al. (2011) within the global estimate reported change of carbon stock in forests of Asian Russia based on the pool-based approach. They estimated forests of Asian Russia as the net carbon sink at 260 Tg C year^{-1} on average for 1990–2007. This estimate is consistent with data of Table 6.13 (−244.5 Tg C year^{-1}).

Overall a similar character of the NECB has been reported for Central Siberia (Quegan et al. 2011). This study presented five independent estimates of the full carbon account of a large region of Central Siberia (about 307 million ha in boundaries of Krasnoyarsk Kray and Irkutsk Oblast) using three different methodologies: a landscape-ecosystem approach, two DVMs – Sheffield DGVM (Woodward and Lomas 2004) and LPJ (Sitch et al. 2003; Gerten et al. 2004), along with two atmospheric inversions. Apart from one of the DVMs, all methods produce estimates of the NECB that are consistent both among themselves and with a range of other estimates. They indicate the region to be a carbon sink with a NECB of 27.1 ± 7.4 gC m^{-2} year^{-1}, which is equivalent to 347 ± 95 TgC year^{-1} if considered representative for boreal Asia. This is comparable with fossil fuel emissions for the Russian Federation, currently estimated as 427 TgC year^{-1}, but implies that boreal Asia does not play the major role in the northern hemisphere land sink, typically estimated to be of magnitude 1.5–2.9 Pg C year^{-1}. LEA and DVM produce substantially different partitioning of NBP into its component fluxes. The DVMs find NPP to be nearly balanced by soil respiration, disturbance being a relatively small term pushing the system closer to equilibrium. Due to the LEA, soil respiration is significantly less than NPP, and disturbance plays a much larger role in the overall carbon balance. This study concluded that the use in the LEA of observationally based estimates of soil respiration and a more complete description of disturbance fluxes suggests that the partitioning derived by the LEA is more credible, and that improved process descriptions and constraints by data are needed in the DVMs.

6.4.2 Analysis of Carbon Balance of Boreal Asia Based on Terrestrial Ecosystem Model

Based on the process-based Terrestrial Ecosystem Model (TEM, Hayes et al. 2011), McGuire et al. (2010a, b) analyzed the C balance of boreal Asia for 1997–2006. The boreal Asia region is defined in boundaries settled by the TransCom 3 model experiments (Gurney et al. 2002). The TEM considers the effects of a number of factors on its simulations of C dynamics including changes in atmospheric CO_2 concentration, tropospheric ozone pollution, nitrogen deposition, climate variability and change, and disturbance/land use including fire, forest harvest, and agricultural establishment and abandonment. TEM also calculates pyrogenic emissions of CO_2, CH_4, and CO from the combustion of vegetation and soil carbon in wildfires. The dissolved organic carbon (DOC) leaching dynamics of TEM are a function of soil C decomposition rate, soil DOC concentration, and water flux through the soil. The methane dynamics module (MDM-TEM) was used to estimate the exchange of CH_4 with atmosphere of both wetlands, which generally emit CH_4 to the atmosphere, and uplands, which generally consume CH_4 from the atmosphere. The MDM-TEM assesses the effects of a number of factors on its simulations of CH_4 dynamics including the area of wetlands, fluctuations in the water table of wetlands, temperature, and labile carbon inputs into the soil solution derived from the NPP estimates of TEM.

The results of these simulations were compared with estimates of CO_2 and CH_4 exchange from atmospheric inversion models and with observations of terrestrial C export from Arctic watersheds. The simulated transfer of land-based C to the Arctic Ocean was compared against estimates based on a sampling of DOC export from major Arctic rivers (McClelland et al. 2008). The land-atmosphere CO_2 exchange estimate was compared with results from the TransCom 3 atmospheric inversion model intercomparison project (Gurney et al. 2008), and CH_4 to results from atmospheric inversion-estimated surface emissions (Chen and Prinn 2006). To compare the "bottom-up" results from our model simulations with the "top-down" estimates from these inversion studies, we summarize our estimates of surface-atmosphere CO_2 and CH_4 exchange for the land area matching the boreal Asia region defined in the TransCom 3 model experiments (Gurney et al. 2002).

The TEM estimates a net uptake of 42.7 Tg C year^{-1} as CO_2 from the atmosphere to the land area of boreal Asia (limited by basins of large Siberian rivers) over the 1997–2006 time period (Fig. 6.4). This terrestrial sink is the result of a positive uptake of 302 Tg C year^{-1} by the terrestrial component as net ecosystem production (NEP), the balance between NPP (3,260 Tg C year^{-1}) in vegetation and the decomposition of soil organic matter through heterotrophic respiration (HR 2,958 Tg C year^{-1}). However, NEP during this time period was substantially offset by the release of C as CO_2 from fires across the region (255 Tg C year^{-1}) and the decomposition of agricultural and forestry products (4.3 Tg C year^{-1}). Nearly 70 % of the pyrogenic CO_2 emissions is attributed to the combustion of soil C (178 Tg C year^{-1}), which when added to the 75 Tg C year^{-1} gain to the soil from the difference between litter inputs from vegetation and HR and to other losses from net biogenic CH_4 emissions and DOC export, results in a net loss of 202 Tg C year^{-1} from the Arctic Basin soil C pool between 1997 and 2006. The loss of soil C is estimated to be greater than the net gain in vegetation C simulated in this study (118 Tg C year^{-1}), resulting in an estimated overall loss of 84 Tg C year^{-1} in ecosystem C stores in the land area of boreal Asia over this time period.

The estimates of land-atmosphere CO_2 exchange in this study are generally consistent with the range of uncertainty in estimates from the atmospheric perspective, although the TEM estimates differ overall in the direction of flux compared to the model means of the TransCom 3 results. For boreal Asia, TransCom model means suggest a net sink ranging from 30 to 470 Tg C year^{-1} (±33 to 48 Tg C year^{-1}), while TEM estimates of Net Ecosystem Exchange (NEE) range from −90 to 0 Tg C year^{-1}, depending on the time period. Monthly NEE estimates from TEM match the seasonal patterns in the TransCom estimates and are within the range of uncertainty for most months during the 1997–2006 time period. The exceptions occur primarily during the peak drawdown of the summer months, where forward process-based models typically predict less uptake relative to inverse models (Pacala et al. 2009). The differences in peak uptake between the two estimates are greatest in large fire years when TEM estimates large fire emissions, e.g., 2002–2003 in boreal Asia,

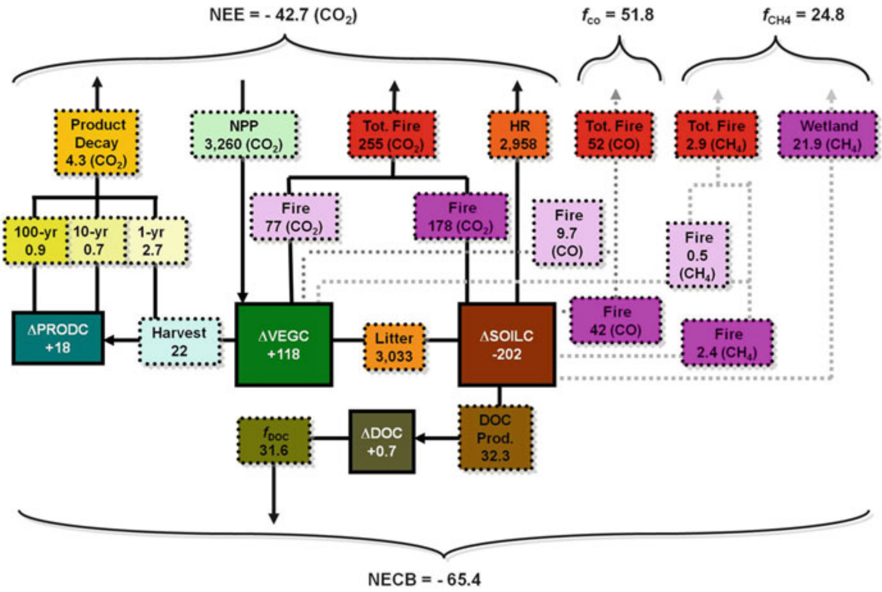

Fig. 6.4 Simulated carbon stock changes and fluxes (Tg C year^{-1}) of the terrestrial ecosystems of boreal Asia, 1997–2006 (Source: McGuire et al. 2010a, b)

although the TransCom estimates do show some negative effect on land uptake during those years.

Although the area of this simulation by TEM is somewhat different from that used in the LEA assessment of major components of carbon cycle above (Tables 6.8 and 6.10), comparison of these two results points out some specific features of applications of DGVMs to polar and boreal domains. On average, estimates of NPP by TEM, like other DGVMs, seem unbiased and relatively closed to empirical data while modeled HR for these regions is higher. The reason for that is likely a balance between NPP and HR which in one way or another is hypothesized in major DGVMs, but such a balance does not exist in northern ecosystems with a slow decomposition rate and regulating role of fire.

The combination of the biogenic MDM-TEM and the pyrogenic estimates of CH_4 fluxes indicate that the terrestrial areas of boreal Asia annually released approximately 41.5 Tg CH_4 to the atmosphere between 1997 and 2006, with most of the emissions (38.0 Tg CH_4 year^{-1}) from biogenic sources. There was substantial interannual variation of emissions with the peak emissions in 1998 and lowest emissions in 1997. TEM simulations indicate that emissions in boreal Asia increased ($R=0.66$; slope = 0.6 Tg CH_4 year^{-1}; $n=11$; $p=0.03$) during the analysis period. Over the decade of analysis, there were very weak trends for increases in air temperature (0.6 °C; $R=0.33$; $p=0.3$) and simulated soil temperature (0.14 °C; $R=0.33$; $p=0.3$) in boreal Asia that could have stimulated methanogenesis. While interannual variability in emissions in boreal Asia was not significantly correlated with changes in soil temperature ($R = 0.25$; $n = 11$; $P = 0.45$), it was marginally correlated with precipitation variability ($R = 0.52$; $n = 11$; $p = 0.09$). Although precipitation seems to control interannual variability in CH_4 emission on boreal Asia, the increase in simulated water table depth ($R = 0.14$; slope = 0.10 mm year^{-1}; $p = 0.67$) is weaker than the increases in soil temperature.

The monthly emissions for 1996–2001 estimated by Chen and Prinn (2006) using a 3D model inverse method for the North American and Eurasian Arctic sectors with the MDM-TEM estimates were compared (McGuire et al. 2010a, b). The inversions show well-defined seasonal cycles peaking in July–August. Significant inter-annual variations in these peaks typically ±4 Tg C year^{-1} in boreal Asia occur. The annual average emissions and timing and average amplitudes of the seasonal cycles were in reasonable agreement with the process-based estimates of CH_4 exchange. The monthly emissions agreed well between inversion and process-based modeling estimates in boreal Asia ($R = 0.90$; slope = 0.65; $n = 60$; $p < 0.001$).

The TEM estimated the DOC delivery to the ocean from boreal Asia to be 31.6 Tg C year^{-1} between 1997 and 2006, which is consistent with empirically based estimates of DOC delivery to the ocean. About a third of the total DOC exported to the Arctic Ocean each year is contributed by rivers emptying into the Kara Sea. Boreal needleleaf deciduous forests and forested wetlands had the largest loss rate of DOC, averaging about 6 g C m^{-2} year^{-1}, and the analysis suggested that these biomes in the Kara Sea and Laptev Sea watersheds are responsible for over 61 % of the terrestrial DOC (22.2 Tg C year^{-1}) delivered to the Arctic Ocean each year. Between 1997 and 2006, this analysis did not indicate any trend in DOC export.

This analysis indicated that from 1997 to 2006, the terrestrial areas of boreal Asia annually gained 42.7 Tg C as CO_2 from the atmosphere, lost 31.6 Tg C as DOC to the ocean, lost 24.8 Tg C as CH_4, and lost 51.8 Tg C as CO to the atmosphere for a total negative carbon balance of 65.4 Tg C year^{-1} (Fig. 6.4). While boreal Asia is estimated to be a sink for C, it can generally be considered as a source for greenhouse gas forcing based on the conversion of net CH_4 emissions to CO_2 equivalents. Between 1997 and 2006, these simulations estimated that the region was a net source of 33.1 Tg CH_4 year^{-1}, a magnitude that is comparable with the atmospheric inversion of CH_4 that was presented in this study and within the uncertainty of other CH_4 inversions (McGuire et al. 2009). This magnitude of CH_4 emissions is equivalent to 761.3 Tg CO_2 year^{-1} calculated on a 100-year time horizon for which 1 g of CH_4 is equivalent to 23 g of CO_2 in terms of global warming potential (IPCC 2001). This is over 600 Tg CO_2 greater than the net CO_2 sink of 156.6 Tg CO_2 year^{-1} (42.7 Tg C–CO_2 year^{-1}) estimated by our simulations. A key issue is whether the global warming potential of the Arctic Basin is evolving to be a greater sink or source of greenhouse gases.

The net uptake of atmospheric CO_2 simulated for the terrestrial ecosystems of the boreal Asia between 1997 and 2006 is a result of the net uptake in vegetation C through NPP being greater than the release of vegetation C to the atmosphere through fire and harvest and the release of soil C through decomposition and pyrogenic CO_2 emissions (Fig. 6.4). The net increase in vegetation C is primarily associated with the positive effects of CO_2 fertilization, N deposition, and climate (e.g., effects of longer and warmer growing seasons on NPP). The net release of soil C to the atmosphere is a function of warming on decomposition and the combustion of C in more frequent fires. Although not part of NEE, any effect of climate variability that increases biogenic emissions of CH_4 and the leaching of DOC can also contribute to a decrease in the soil C pool. To understand how the effects of these various controlling factors interact to produce the contemporary (1997–2006) dynamics of land-atmosphere CO_2 exchange, it is necessary to compare the importance of the various factors influencing terrestrial CO_2 exchange between the analysis period of this study to previous decades when various studies have suggested that high-latitude terrestrial ecosystems acted as a stronger CO_2 sink (McGuire et al. 2009).

The historical simulations of the C balance of boreal Asia using TEM indicate a strengthening atmospheric CO_2 sink in tundra ecosystems (Fig. 6.5a), and a strengthening source from boreal forest ecosystems (Fig. 6.5b). The results suggest that CO_2 fertilization effects on NPP are playing the primary role in the C uptake component for both tundra and boreal forest ecosystems, and that these effects are increasing along with the rise in atmospheric $[CO_2]$ over the past several decades. However, the effect of CO_2 fertilization on NEE has been dampened in tundra ecosystems with a weakening sink/increasing source effect from changes in climate since the 1970s. The source effect of climate variability in tundra ecosystems suggests that increases decomposition have been outpacing any warming-driven increases in NPP. The increases in decomposition in the simulations are a function of greater microbial activity in response to warmer temperatures, as well as a result of more soil C available for decomposition from increasing active layer depths due to permafrost degradation. Other studies suggest that the microbial decomposition of previously frozen organic matter can overcome uptake from increased vegetation productivity to alter the C balance in tundra ecosystems over decadal time-scales (Schuur et al. 2009). The simulations show an increasing net C sink in the boreal forest ecosystems of boreal Asia prior to the 1970s that has been trending toward a weakening sink/increasing source since the 1970s as a result of climate and disturbance effects. In the last decade of analysis, it is the large impact on NEE (the increased source) from fire that is driving the net C source from boreal forests.

Similar to previous findings that the regional net CH_4 emissions have increased during the twentieth century (Zhuang et al. 2004), this simulation indicates that emissions continued to increase between 1996 and 2006. While precipitation seems to control interannual variability in CH_4 emission on boreal Asia, the increase in simulated water table depth is weaker than the increases in soil temperature over the decade. Estimates of CH_4 emissions by the MDM-TEM are very sensitive to increases in soil temperature, which increase methanogenesis, and changes in water table position, which affect the amount of soil carbon subject to methanogenesis – an anaerobic process (Zhuang et al. 2007). Thus, the slight regional increase of CH_4 emissions appears mainly due to the increasing soil temperature.

A previous analysis with MDM-TEM suggests that climate change has the potential to substantially increase biogenic CH_4 emissions throughout northern high latitudes during the twenty-first century (Zhuang et al. 2006). Another analysis focused

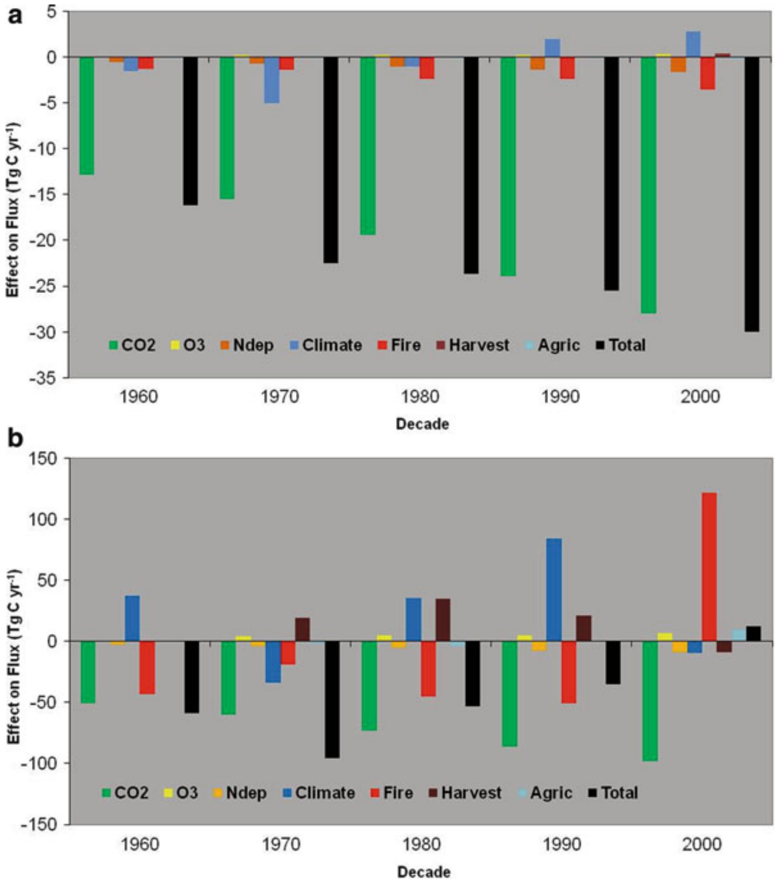

Fig. 6.5 Total and individual average annual effects (Tg C year^{-1}) of temporal variability in atmospheric [CO_2], tropospheric O_3 levels, N deposition rates, climate, fire, forest harvest and agricultural establishment and abandonment on NEE for each decade since the 1960s across (**a**) tundra and (**b**) boreal forest ecosystems in boreal Asia (Source: McGuire et al. 2010a, b)

on Alaska indicates that methane emissions can potentially double by year 2100, and that the temperature sensitivity of methanogenesis dominates over the water table sensitivity (Zhuang et al. 2007). It is also expected pyrogenic CH_4 emissions to increase with climate change if fire becomes more frequent in northern high latitudes as projected by several studies (Flannigan et al. 2009; Balshi et al. 2009).

Although no trends in DOC export occur during the 1997–2006 study period, the simulations indicate that DOC delivery to the ocean has been increasing by 0.047 Tg C year^{-1} over the twentieth century throughout northern high latitudes. Based on a factorial simulation experiment, most of this increase (0.039 Tg C year^{-1}) has been the result of climate variability and change. The response of DOC export to climate variability and change is primarily a result of changes in decomposition rates over this time period whereas the response to land-use change and fire is primarily caused by changes in the availability of the soil organic carbon substrate. As described earlier, warming increases decomposition to enhance the production of DOC from soil organic matter and the amount of DOC available for leaching to the neighboring river networks. Warmer temperatures also increase the active layer depth due to permafrost degradation to influence DOC export. This exposes more soil organic matter to decomposition and hence produces more DOC. Thus, permafrost degradation accentuates the effects of warming on the DOC concentration of runoff in our simulations. These results suggest that the delivery of DOC to the Arctic Ocean will likely increase as the climate warms.

The study indicates that between 1997 and 2006, the terrestrial ecosystems of boreal Asia were a source of carbon to the atmosphere and to the Arctic Ocean (McGuire et al. 2009, 2010a, b). Because of CH_4 emissions of wetlands, boreal Asia continues to act as source of greenhouse gas forcing to the warming of the Earth. These analyses suppose that CH_4 emissions are increasing, and other studies have indicated that CH_4 emissions are expected to generally increase with continued warming of the Arctic (Zhu et al. 2011). It appears that the sink for atmospheric CO_2 in boreal Asia is diminishing because of more fire disturbance in this decade compared to previous decades. Continued warming of the Arctic is expected to substantially increase fire activity. The results of this study emphasize the importance of analyzing the dynamics of the C balance of boreal Asia as a linked system of CO_2 and CH_4 exchange with the atmosphere and delivery of DOC to the ocean. Earth system models that consider carbon-climate feedbacks should treat the carbon processes of boreal Asia as a linked system.

6.4.3 Eddy Covariance

Systematic long-term annual eddy covariance measurements and accompanying climatology in Siberia became possible in the framework of the EuroSiberian Carbon Flux (1998–2000) and TCOS-Siberia (2000–2002) projects initiated by the Max-Planck Institute of Biogeochemistry, Jena, Germany.

The first results of net ecosystem exchange of CO_2, water, and heat in various ecosystems in Siberia for the 1998 growing season were summarized by Schulze et al. (1999) and later, for 1998–2000 and 2002–2004, were overviewed by Tchebakova et al. (2011). Seasonal and annual dynamics of the carbon exchange in a 200-year pine forest, a *Sphagnum* bog, a true grass steppe and a tussock tundra, and possible feedbacks of the CO_2 exchange to the atmosphere in a changing climate were evaluated.

Net ecosystem exchange of CO_2 (NEE) in various ecosystems is related to sensible heat and thus, the Bowen ratio (β), the ratio between sensible and latent heat (Karelin and Zamolodchikov 2008; Schulze et al. 1999). Maximal fluxes of CO_2 of 10–12 μmol m^{-2} s^{-1} were usually found in the afternoon and in midsummer with the

Table 6.14 Annual carbon balance components of major ecosystems in central Siberia

	Forest[a] (1998–2000)	Bog[b] (1998–2000)	Steppe[c] (2002–2004)	Tundra[d] (2004)
Max. CO_2-flux, μmol m^{-2} s^{-1}, July	10	6	12	8
Net ecosystem exchange of CO_2, gC m^{-2} $year^{-1}$	−156	−52/−30[e] (200 days)	−122	−38 −6[e]
Ecosystem respiration, gC m^{-2} $year^{-1}$	372	170 (200 days)	375	201[e]
Ecosystem assimilation, gC m^{-2} $year^{-1}$	−534	−222 (200 days)	−497	−207[e]

[a] Tchebakova et al. (2002)
[b] Arneth et al. (2002)
[c] Belelli-Marchesini (2007)
[d] Corradi et al. (2005)
[e] Karelin and Zamolodchikov (2008)

maximum Bowen ratios in the forest and steppe where $\beta > 1$ and 6–8 μmol m^{-2} s^{-1} in the bog and tundra with the less intensive energy exchange above water surfaces $\beta < 1$.

Daily NEE depends on meteorological parameters like PAR (photosynthetically active radiation), temperature of both the air and soil, and the air humidity. In winter, early spring, and late fall, NEE is slightly positive. During the growing season, the NEE course is distinct: it is increasing from spring and reaches its maximum in the midsummer and then is decreasing by fall. In mid-summer, NEE increases after sunrise, changes its sign from the positive to negative at 6 a.m., and reaches its maximum around noon, and then decreases and changes its sign from negative to positive about 9 p.m.

Table 6.14 summarizes the main components of the carbon balance of the four ecosystems studied. Net ecosystem exchange (NEE) is close to the net ecosystem production (NEP) in annual and seasonal terms (Schmid et al. 2000). The tussock tundra in East Siberia was a carbon sink of−38 gC $m^{-2}year^{-1}$ while the southern tundra in Taimyr were a minor carbon sink of −10 gC $m^{-2}year^{-1}$ (Karelin and Zamolodchikov 2008; Zamolodchikov et al. 2003). The pine forest in middle taiga was a sink of −156 gC $m^{-2}year^{-1}$ while the Sphagmun bog was a sink of only −29 gC $m^{-2}year^{-1}$ (Arneth et al. 2002). The true steppe in Khakassia was a significant sink at −122 gC $m^{-2}year^{-1}$. In the annual course, tundra started working as a carbon sink in June, the forest and the bog from late May or early June, and the steppe from the end of April. In the fall, these ecosystems become a source: tundra from the beginning of September, the pine forest and the bog from the beginning of October, steppe from the end of October.

Averaged for 1999–2000, the annual NEP of CO_2 was equal to 156 gC m^{-2} (13 mol m^{-2}), and the annual ecosystem respiration (summed from respiration in the growing season as 312 gC m^{-2} modeled from the air temperature and respiration of 66 gC m^{-2} in winter measured by the eddy covariance method) resulted in a total photosynthetic production of 534 gC m^{-2} (Tchebakova et al. 2002). Lloyd et al. (2002) estimated annual NEP for this pine forest to be 174 gC m^{-2} (14.5 mol m^{-2}) and ecosystem respiration to be 384 gC m^{-2} totaling 558 gC m^{-2} of photosynthetic production.

The annual NEP of the pine forest was 156 gC m^{-2} which fell within 90–210 gC m^{-2} of the NEP of boreal conifer forests in North America and western Europe measured by the eddy covariance method (Goulden et al. 1996; Valentini et al. 2000). Schulze et al. (1999) and Wirth et al. (1999) evaluated the NPP of this particular pine forest from inventory measurements correspondingly 123 and 144 gC m^{-2}. Bazilevich (1993) and Monserud et al. (1996) found the NPP of pine forests in the middle taiga of West Siberia to be 206 gC m^{-2} and to be 161 gC m^{-2} in Central Siberia. Comparative results were received by eddy covariance measurements on two forested sites in European southern taiga (Kurbatova et al. 2002).

As a result of low respiration, gross primary production (GPP) is 1.5–2 times lower than that of conifer forests in Western Europe (Valentini et al. 2000). From 25 various forest ecosystems in western Europe cited in this study, only 3–4 forests from the harsh climates of Iceland and highlands of the Alps in Italy produce about the same NEP as the pine forest in the Siberian middle taiga at the latitude of 60°N. Interestingly, despite the different weather conditions of 1998 and 2000, NEE varied insignificantly – only 4 % of the annual value. Anthoni et al. (1999), for instance, noted that the difference in NEP in years with El Niño and without may reach 90 %.

As the climate warms and gets drier in the future, studied ecosystems may turn from a sink to a significant source. Zamolodchikov et al. (2003) pointed the temperature 14 °C as a limit above which photosynthesis in tundra is inhibited and respiration simultaneously increases, together promoting additional carbon emissions into the atmosphere enhancing climate warming. In a warmed and dried climate, carbon emission from bogs increases: as carbon dioxide from drying bogs (Morishita et al. 2003) or as methane from watered bogs. In current climate methane emissions from the cryolithozone accounts some 6 % (Karelin and Zamolodchikov 2008).

In the pine forest, NEE increases in the course of the growing season. The carbon uptake in the 1999 growing season that was 2 weeks longer than the 1998–2000 average was 18 % greater than C-uptake in other years. Thus, one may suggest that in a longer growing season in a warming climate, the forest production would first increase in Siberia. However, because climate is predicted to be not only warmer but also drier, the forests would die out due to lack of water. Thus, because of the decomposition of dead wood (Knohl et al. 2002; Vygodskaya et al. 2002) and the potential for unprecedented fires (Furyaev et al. 2001), in a warmed climate the forest may become a carbon source for many years.

Boreal bog ecosystems are usually a carbon sink of 30–100 gC m^{-2} during the growing season or year (Arneth et al. 2002; Corradi et al. 2005) and a GPP of some 200 gC m^{-2} for the growing season (Table 6.14). However, during dry summers, the upper bog may turn from a carbon sink into a carbon source of 50 gC m^{-2} (Arneth et al. 2002) suggesting that some bogs may dry out in a warming climate and become a significant carbon source in the atmosphere. Comparing different studies, Corradi et al. (2005) expect, though, that global warming would increase the CO_2–C sink in wetlands and tundras.

Subboreal true steppes may be both a significant carbon sink under different disturbance regimes (fire, pasture), or a slight sink if they work at a “stationary” regime (Titlianova and Tisarzhova 1991) when microbes consume NPP during several years depending on weather conditions. In our study, in an “nonstationary” regime, the true steppe was a sink of 115 gC m^{-2} $year^{-1}$ for three seasons recovering after multiyear pasturing and that of 130 gC m^{-2} $season^{-1}$ recovering after fire (Belelli-Marchesini 2007; Belelli-Marchesini et al. 2007). The true steppe produces as much GPP as the pine forest; GPP of both the steppe and pine forest is 2–2.5 times larger than that of the bog and the tussock tundra (Table 6.14).

Thus, along with increased carbon emissions due to increased fire events and area burned in a warming climate, carbon uptake by plants also increases, smoothing the negative effects of large fires.

6.4.4 Synthesis

Each of the major methods of carbon accounting has its own strengths and weaknesses. Under proper systems designing, the LEA allows to achieve the most reliable assessment for recent past and current, in a spatially and temporarily explicit way. However, this method does not consider mechanisms of the processes and lacks any substantial predictive capacity. DVMs (and, particularly DGVMs) describe processes and explain drivers. However, they are a somewhat rough tool for regional and national consideration due to the impossibility of properly including regional peculiarities in the models and sufficiently represent the transformation (disturbances) of vegetation cover. There is no solid methodology yet for estimating the uncertainty of DGVMs. However, they are practically a single tool for prediction. They also supply estimates of important components of carbon cycling for cross-checking uncertainties. Applications of DGVMs to northern ecosystems show that on average DGVMs estimates NPP rather reliably while overestimate HR. This results in underestimating the NECB (NBP) of terrestrial ecosystems in Siberia by DGVMs.

Eddy covariance methodology supplies important direct estimates of exchange of atmospheric carbon between ecosystems and the atmosphere. These estimates are extremely important for understanding the productivity processes of individual ecosystems and parameterization of models. However, these data have substantial uncertainties and – what is important – there are substantial problems with upscaling of the results of local measurements.

Inverse modeling presents a unique possibility for top-down verification of the above bottom-up estimates. Recent results for Russian natural land received from four different inversion approaches for 2000–2004 gave a mean of carbon sink -0.65 ± 0.12 Pg C $year^{-1}$ (inter-model variability) and the median -0.61 Pg C $year^{-1}$ (P. Ciais, 2010, personal communication). In earlier work, Gurney et al. (2003) calculated the average C flux using 17 different inverse models at -0.58 Pg C $year^{-1}$ for boreal Asia (45 ± 44 gC m^{-2} $year^{-1}$). A smaller sink for this region has been reported by Baker et al. (2006) – 29 ± 19 gC m^{-2} $year^{-1}$ and Patra et al. (2006) – 26 ± 61 gC m^{-2} $year^{-1}$.

Taking into account that European Russia provides about one-third of the entire country's sink and the level of reported uncertainties, all the above results are fairly consistent.

Still, the uncertainty of inverse modeling is high (up to 50–80 %) due to imperfect transport models and rare stations for measuring atmospheric concentration in Russian territories. However, the inverse estimates of the last decade are consistent and all together provide valuable information in understanding the carbon cycle of Russian terrestrial ecosystems. Eddy covariance measurements are important for the parameterization of the models and a perception of how terrestrial ecosystems function but lack proper gradients for upscaling over large territories.

In spite of substantial uncertainties, different methods give rather consistent estimates for Northern Eurasia (Table 6.15).

The above estimates basically refer to the C–CO_2 part of carbon cycling. Atmospheric methane provides the second-largest radiative forcing after CO_2. Globally, the contribution of CH_4 to the radiative forcing from preindustrial to present time is estimated at about 20 % of all greenhouse gases (Le Mer and Roger 2001). To our knowledge, there were no estimates for the region considered in this study. Rather detailed studies of methane emissions were provided in West Siberia based on detailed in situ measurement (Glagolev et al. 2010, 2011) and inverse modeling (Kim et al. 2011). These estimates are rather consistent varying in limits from 2.9 to 3.2 Tg CH_4 year^{-1}. In a recent inventory, Shvidenko et al. (2010a) estimated the total biosphere methane flux for entire Russia at 16.2 Tg C–CH_4 year^{-1} including 10.5 Tg C–CH_4 year^{-1} from wetlands and other wet soils, 1.5 Tg C–CH_4 year^{-1} from agriculture, 1.1 Tg C–CH_4 year^{-1} from fire, and 3.1 Tg C–CH_4 year^{-1} from water reservoirs. This study estimated methane fluxes from West Siberian wetlands at 3.4 TgC–CH_4 year^{-1} that is consistent with the above studies. Taken into account that wetlands of Siberia comprise about 75 % of Russian territories in this land cover class (107.4 million ha of the total of 144.6 million ha), one could suppose that a major part of the country's methane emissions is provided by the study's region. Modeling results that were obtained by TEM are substantially higher – about 38 Tg CH_4 year^{-1} from biogenic sources (McGuire et al. 2010a, b). These estimates show that by the global warming potential, C–CO_2 sink in Siberia is almost compensated by the methane emissions, although uncertainties of methane's assessment for Russia are high.

Given the large stores of carbon in northern high latitude regions, the response of the carbon cycle of boreal Asia to changes in climate is a major issue of global concern (McGuire et al. 2006). Analyses to date indicate that the sensitivity of the carbon cycle of Siberia during the twenty-first century is also highly uncertain.

Table 6.15 A comparison between values of NBP (gC m^{-2} $year^{-1}$) from different studies

Method	Model	NBP (gC m^{-2} $year^{-1}$)	Description	Period	Study Area (Mha)	Citation
LEA	FCA	−32.5 ± 21	All land types	2009	Siberia, 1019.0	This study
	FCA	−33 ± 8	All land types	2003	Central Siberia 297	Quegan et al. (2011)
	FCA	−21 ± 10	All land types	1988–1992	Russia 1709	Nilsson et al. (2003)
	FCA	−30 ± 8	All land types	1998–2002	Russia 1709	Nilsson et al. (2003)
	FCA	−23 ± 10	Forest land (vegetation only)	1961–1998	Russia 882	Shvidenko and Nilsson (2002)
	FCA	−36 ± 23	Forest land	1961–1998	Russia 886	Shvidenko and Nilsson (2003)
Inventory	PCA	−34–57	Forest land	1987–1990	Russia 884	Dixon et al. (1994)
	PCA (TBFRA- 2000)	−48	Forest & other wooded land	1993	Russia 886	Liski et al. (2000)
DVM	LPJ	+6 ± 6	All land types	1995–2003	Central Siberia 297	Quegan et al. (2011)
	SDGVM	−19 ± 14	All land types	1995–2003	Central Siberia 297	Quegan et al. (2011)
	LPJ	−17	Forest land	1981–1999	Russia 774	Beer et al. (2006)
Atmospheric inversion	MPI	−23 ± 13	All land types	1995–2003	Central Siberia 297	Quegan et al. (2011)
	LSCE	−24 ± 34	All land types	1995–2003	Central Siberia 297	Quegan et al. (2011)

(continued)

Table 6.15 (continued)

Method	Model	NBP (gC m^{-2} $year^{-1}$)	Description	Period	Study Area (Mha)	Citation
	IM	−49 ± 28	All land types	1992–1996	Boreal Asia 1280	Maksyutov et al. (2003)
	IM	−45 ± 44	All land types	1992–1996	Boreal Asia 1280	Gurney et al. (2003)
	IM	−29 ± 19	All land types	1998–2003	Boreal Asia 1280	Baker et al. (2006)
	IM	−26 ± 61	All land types	1999–2001	Boreal Asia 1280	Patra et al. (2006)
	IM	−38 ± 7	All land	2000–2004	Russia 1709	Ciais et al. (2010)

Modified from Quegan et al. (2011)

Note: The definition of boreal Asia in each of the atmospheric inversion studies varies; we have used a value of 1280 Mha throughout (Kaplun et al. 1994). In the Table, FCA and PCA refer to Full Carbon Account and Partial Carbon Account, respectively and TBFRA-2000 is the Temperate and Boreal Forest Resources Assessment 2000. IM – Inverse models. Sign “minus” denote the carbon sink

6.5 Changes Within Climate-Driven Ecotones in Siberia

The response of trees to climate change is expected to be significant at the climate-driven ecotones, e.g., in the alpine and northern forest-tundra ecotones. There are a number of observations of tree response to warming, including species invasion into the tundra, stand densification, and growth increment increase along the northern and alpine tree-lines during recent decades (e.g., Kullman 2007). These phenomena are also considered for different regions of Asian Russia (e.g., Shiyatov 2003; Shiyatov et al. 2007; Soja et al. 2007; Devi et al. 2008; Kharuk et al. 2004, 2010a, 2010b). These studies were located within the Ural and Altai – Sayan Mountains, the northern tree line around the Yenisei meridian, and the "larch-mixed taiga" ecotone in Central Siberia. The results obtained showed that Siberian pine and larch growing in the alpine forest-tundra ecotone are strongly responding to warming by an increasing increment, stand densification and regeneration density, upward tree line shift, and transformation of *krummholz* to arboreal forms. Similar phenomena were observed for the northern forest-tundra ecotone.

6.5.1 Northern Tree Line

The Northern tree line on the Polar Ural Mountains (the western border of the study's region) and westward from the Yenisei meridian is formed by a combination of elevation and northward temperature gradients. Along the northern edge of boreal forests in the Polar Ural Mountains, Shiyatov et al. (2007) reported a 35-m upward shift of closed larch dominated stands between the years 1910 and 2000. Along with the current shift of tree-lines, dendrochronology analysis describes former tree-line dynamics in the forest-tundra ecotone (Shiyatov 2003). Observations within the most northward forest stand (Ary-Mas, 72°+N) dominated by larch showed regeneration advance into tundra and stand densification (Kharuk et al. 2004, 2006). For the period 1970–2000, stand density was increased (at ~1.6 times); the advance of regeneration was approximately 3 m year^{-1}.

6.5.2 Tree-Line Evolution in South Siberian Mountains

Historically, climate-induced waves of upslope and downslope tree migration were reported for the alpine forest-tundra ecotone (Fig. 6.6). Tree mortality was observed during the Little Ice Age and followed the cooling with a lag. Living tree mortality dates showed that the tree-line advance began at the end of the nineteenth century and lagged behind temperature changes. Larch and Siberian pine regeneration now survives at elevations up to 160 m higher in comparison with the maximum observed tree-line recession during the Little Ice Age and surpasses its historical maximum

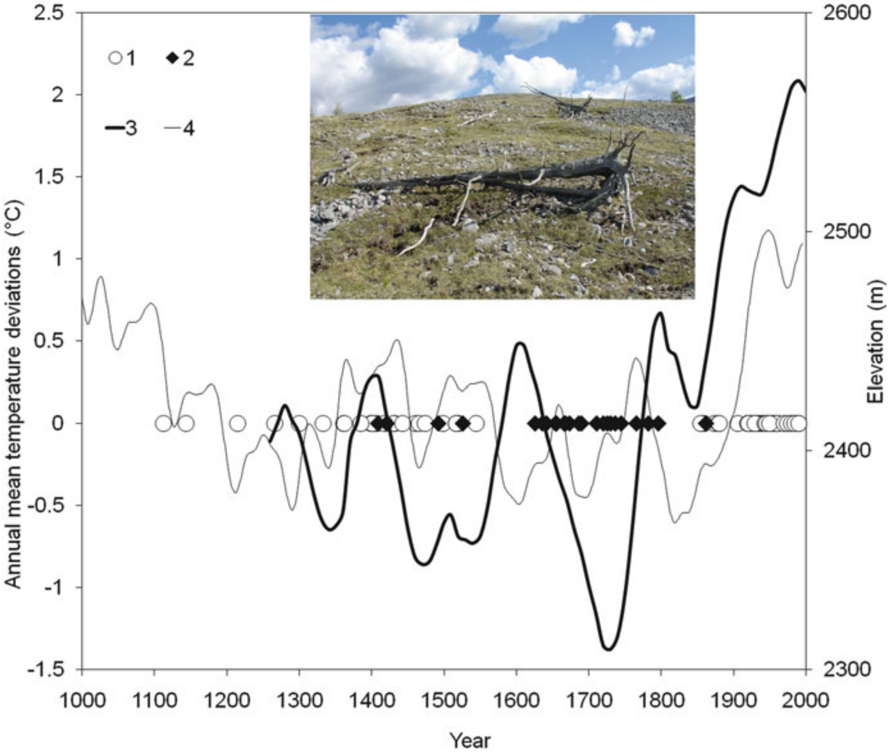

Fig. 6.6 The history of tree establishment and mortality at the Sengilen site and reconstructed air temperatures for northern Siberia and the Northern Hemisphere. 1, 2 are the dates of tree origin and mortality, respectively. 3 and 4 are the reconstructed air temperature deviations for southern Siberia (March–November temperature; Schwikowski et al 2009) and the Northern Hemisphere (annual temperature), respectively. Bars show elevation of treelines: *A* – "historical," *B* – "refugee," *C* – "postcooling" treelines; *D* – regeneration line. Insert: a view on the "refugee tree line"

during the last millennium by up to 90 m. Temperature change of 1 °C promoted an upward shift in the tree-line of about 80 m. The tree-line advance rate was estimated at 0.90 ± 0.22 m year^{-1} (Kharuk et al. 2010b). Similar values were found for the Polar Ural Mountains (0.4 m year^{-1}; Shiyatov et al. 2007). The mean rate of regeneration advance during the last century was 1.2 ± 0.24 m year^{-1}, increasing to 2.35 ± 1.26 m year^{-1} during the last three decades. The observed warmer winter temperatures were important for regeneration recruitment because of reduced desiccation and snow abrasion, which are the main causes of tree/regeneration damage and mortality (Shiyatov 2003; Kharuk et al. 2006, 2009). Meanwhile at high elevations, seedlings are still in the vulnerable stage and can be killed by cold winters (in synergy with winds), resulting in recession of the tree-line.

6.5.3 *Forest Densification and Area Change*

Studies within the Altai-Sayan Mountain System sites showed a 150 % increase of dense forest stand area within upper forest belt during the last four decades due to growth of preestablished trees (Kharuk et al. 2010a, 2010c). An increase of growth increment in trees was observed starting in the mid 1980s, which was strongly correlated with mean summer temperatures.

Stand densification was also observed along rivers and streams due to earlier snowmelt, which increases the growing period. At the southern edge of the boreal forests in Siberia an upward shift of the closed forest border was observed to be about 63 ± 37 m between 1960 and 2000. Studies within the Polar Ural Mountains also showed a considerable stand densification over the last four decades (Shiyatov 2003; Devi et al. 2008). Forest densification itself improves the microclimate for tree survival under harsh environmental conditions by reducing desiccation and snow abrasion. Greater stand density also leads to increased snow accumulation, which facilitates the local regeneration potential in a positive feedback loop (Kharuk et al. 2007). During recent decades, in the Polar Ural Mountains, a doubling of winter precipitation was correlated with an upward shift of the tree-line (Devi et al. 2008). Substantial densification in tree-line populations seems to be a common phenomenon in northern and high-elevation environments and occurs more frequently than actual elevational tree-line advance (Kullman 2007; Kharuk et al. 2008).

6.5.4 *Forest Response to Climate Variables and Relief Features*

Forest response to climate variables at high elevations is nonuniform because tree establishment and survival depend on the availability of sheltered (wind protected) areas. In mountains, the forest spatial distribution is dependent on azimuth, elevation, and slope steepness (Vygodskaya 1981; Polykarpov et al. 1986), and this pattern changed over recent decades. With respect to aspect, the forest area distribution is asymmetric and elevation-dependant. At lower elevations, forest patterns were oriented approximately northward with minimal forest cover observed on the southern slopes where trees experience water stress. As the elevation increased, the forest area distribution orientation changed in a clockwise direction, becoming oriented eastward at the highest elevation. The observed changes can be attributed to wind impact, which increases as elevation increases. The typical upper boundary is a mosaic as tree and regeneration survival depends on the availability of sheltered relief which is provided by rocks or local depressions. It was found that at any given elevation, the majority of forests occupied slopes with greater than mean slope values, and at higher elevations forests shifted to steeper slopes (Kharuk et al. 2010c).

Thus, forest response to warming was dependant on topographic relief features and this response significantly modified the spatial patterns of high elevation forests in southern Siberia during the last four decades.

6.5.5 Transformation of Krummholz into Vertical Forms

Milder climate also promotes changes in tree morphology, i.e., transformation of mat and prostrate *krummholz* into the vertical form (Kharuk et al. 2006, 2010b; Shiyatov et al. 2007; Devi et al. 2008). Recent decades of warming caused a widespread transformation of larch and Siberian pine mat and *krummholz* to a vertical form, which began mainly in the late 1980s. This date coincides approximately with the period when winter temperatures surpassed the mean value during the twentieth century. Larch was much less likely than Siberian pine to be found in *krummholz* forms. Larch surpasses Siberian pine in frost and wind resistance and grew in arboreal forms where Siberian pine was still prostrate. Shiyatov et al. (2007) and Devi et al. (2008) reported similar transformation of larch *krummholz* into vertical forms. Meanwhile, periodic shoot and needle desiccation, caused by synergy of low temperatures during cold winters and wind impact, decrease vertical growth.

6.5.6 Ecotone "Zone of Larch Dominance – Mixed Taiga"

For Central Siberia it was shown (Kharuk et al. 2007) that dark coniferous species (Siberian pine, spruce and fir) are expanding into habitat of larch. The invasion of dark coniferous species into historical larch habitat was quantified as an increase of the proportion of those species both in the overstory and regeneration. Siberian pine and spruce have high K_i [propagation coefficient: $K_i = (n_i - N_i)/(n_i + N_i)$, where N_i and n_i – the proportion of a given species in the overstory and regeneration, respectively] values both along the margin and in the center of zones of absolute larch dominance, where their presence in the overstory is <1 %. The age structure of the regeneration (with mortality control) showed that it was formed mainly during the last two to three decades. The results obtained indicate climate-driven migration of Siberian pine, spruce, and fir into traditional larch habitat. Very likely, this process is substantially driven by changes in permafrost regimes. On the western and southern margins of the larch-dominance zone, regeneration of dark coniferous species formed a second layer in the forest canopies, which could eventually replace larch in the overstory. With stand densification, Siberian pine received an additional advantage since larch is a shade intolerant species (Kharuk et al. 2007).

In a warming climate, Siberian pine should enjoy a competitive advantage due to its higher temperature response and shade tolerance. Thus, current climate change should lead to the shift of Siberian pine into larch forests. Substitution of deciduous larch by evergreen conifers, decreases albedo and provides a positive feedback for even greater warming. The other expected consequence is an increase of biodiversity since Siberian pine-dominated communities provide a better food base for animals and birds. Larch will continue to maintain its advantage in drier areas and in zones of temperature extremes, particularly on permafrost.

6.6 Future Trajectories of Forest Ecosystems in Siberia

6.6.1 Individual-Based Models of Forest Dynamics

Climate change has been identified as a driver of structural compositional change in the Russian forest. Purves and Pacala (2008) reviewed predictive models of forest dynamics and structure and suggested that the world's relatively low-diversity boreal forests are prime areas for the examination of ecological models because enough inventory data has been collected to make the species parameter estimations needed by the models. We concur with the spirit of their assertion. The model discussed here is the product of two decades of an ongoing synthesis of the silvics of boreal forest trees for species parameter estimations for boreal forests (Shugart et al. 1992). In the past 20 years, individual-based models (IBMs) have expanded to provide increasingly accurate predictions and simulations of forest change over time (Mladenoff 2004). These models have been applied to investigate forest disturbance and succession, to manage forest stands, and to predict how forests will respond to alterations in environmental scenarios.

The examples considered here use one of a class of forest individual-based models called "gap models" (Shugart and West 1980) to project responses of the Russian boreal forests to changes in climate. Individual-based gap models simulate individual trees, their growth, mortality, and decomposition into litter in a relatively small area, typically the size of a forest gap (Urban and Shugart 1992). These models simulate the vertical dimension but often are incorrectly classified as nonspatial models in that they do not interact in the horizontal. This limitation ended with subgrid-based and horizontally explicit versions (Urban et al. 1991; Weishampel et al. 1992). The models often include ecosystem processes such as nutrient cycling and interactions with the local abiotic environment (Scheller and Mladenoff 2007).

One of the primary results of the importance of the dynamics of structure is illustrated in Fig. 6.7. Successional carbon dynamics is shown as predicted by the FAREAST model (Yan and Shugart 2005) simulating the forest dynamics of Changbai Mountain (intrazonal boreal forests on the North Korean and Chinese border). In this succession, deciduous conifer forest (with *Larix* as the dominant species) converts over time to a mixed Spruce-Fir (*Picea* and *Abies*) forest. The deciduous stands begin to break up after about 100 years of stand development. The forest acts as a strong carbon sink for the first 100 years of forest dynamics after stand initiation on bare ground (in case of regeneration after disturbance the decomposition of legacy material would exceed C accumulation in live biomass for the first 10–20 years, possibly longer). After about 100 years, the mortality and decomposition of the initial early successional forest biomass causes the forest to be a relatively strong carbon source for almost 200 years. Then the carbon standing crop of the forest settles into a quasi-equilibrium where the forest is neutral in its carbon source-sink relation to the atmosphere. The leaf area of the forest is relatively constant from about 50 years onward. The dynamic response of this forest to disturbance from a leaf-canopy model (based solely on leaf gross-primary-production kinetics) would

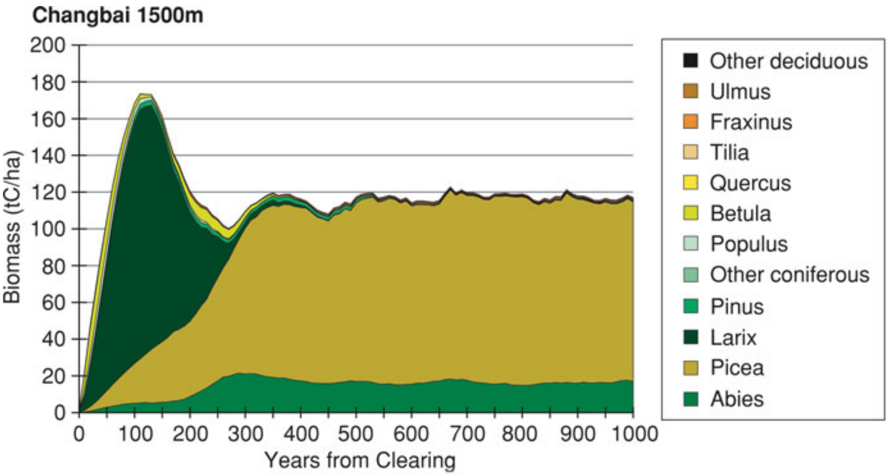

Fig. 6.7 The simulated forest species composition dynamics expressed as cumulative biomass (t C ha^{-1}) for succession from bare ground Changbai Mountain (People's Republic of China/ Democratic People's Republic of Korea) at 1,500 m in elevation (From Yan and Shugart 2005)

not capture these significant shifts in the source-sink status of the forest because it ignores several essential factors that control the retention of C accumulated through production processes such as tree size, longevity, and species succession. Furthermore, these factors are critical for simulating tree mortality which are a major pathway in C cycling of forest ecosystems. Yet this process is difficult to capture in most current biophysical models, because of their mathematical structure (ordinary differential equations applied over relatively large areas with an assumption of spatial homogeneity). An important additional consideration is the need to include a woody debris pool which also plays a significant role in C storage and cycling.

These are specific examples of an important general problem. Many of the models that are currently being applied to determine regional and global productivity use mathematical functions that are derived from the physiological and biophysical performance of leaves – even though the models themselves are typically formulated and calibrated for landscapes. The actual heterogeneity of leafy canopies found in both the horizontal and the vertical dimensions of vegetation can create significant problems in such upscaling (Shugart 2000). For example, a leaf area of 4 held by a single large tree is *not* metabolically equivalent to a leaf area of 4 held by a collection of small trees – the plant respiration rates in the two cases could be very different. Essentially, vegetation of different structures could be similar for one ecosystem property (e.g., productivity, biomass, height, etc.) but not for any of the others.

This might be thought of as an interesting theoretical problem, were it not for the fact that highly aggregated leaf-based models (in some cases augmented by remotely sensed variables such as photosynthetically active radiation or PAR absorbed by the vegetation) are the backbone of our prediction of global productivity, carbon uptake and loss, and vegetation cover. These models can characterize the productivity and biophysical properties of large regions and are used for assessing carbon fluxes associated with these regions. Thus, the issue of properly including the effects of vertical and horizontal variability in our understanding of regional ecosystem dynamics has arisen as an important problem to improve our predictive capability.

Forest gap models are well suited to evaluate the effect of climatic fluctuations on forest structure and composition. Following the addition of species range data, the forest gap model, FAREAST, was tested across the broad geographic and climatic variation of Russia using independent forest inventory biomass data (Shuman et al. 2011).

The version of the FAREAST model (Yan and Shugart 2005) applied here simulates the composition of the Russian boreal forest in response to current and changing climate conditions and is suitable for exploring the feedback between climate and forest composition at both the continental and regional scale. Species silvics for the more temperate-forest species of the southern border with China and Russia are already in the FAREAST model; parameters for species in Northern Eurasia were added for a total of 52 tree species. Species range maps for these 52 species are used to include appropriate diversity on a site-specific basis. The model was used to simulate the impact of changes in temperature and precipitation on both total and genera-specific tree biomass across Siberia and the Russian Far East.

For the model runs with temperature or precipitation change, a linear increase in temperature or precipitation or both takes place from years 0 to 200 of the simulation. This is followed by an additional 150 years of simulation during which the climate stabilizes around the conditions attained in year 200. A nonparametric factorial ANOVA was used to assess differences in the biomass (t C ha^{-1}) of *Larix* spp., dark conifers, and the total forest biomass among model runs that employed different climate treatments at 10-year intervals.

Under the influences of a warming climate, the FAREAST model simulates cases in which the patterns of succession change qualitatively. Two examples are shown in Fig. 6.8. In the top panels of Fig. 6.8, the simulated forest dynamics (200 simulated plots averaged annually over 350 years) shows succession of the *Larix*-dominated forest for conditions appropriate to Irkutsk region in southern Siberia. The successional pattern is for an increase in *Larix* biomass during initial stand development that reaches a maximum biomass in simulated year 200. As the initial even-aged stands of *Larix* break up and transition to a mixed-aged mosaic, the biomass over the landscape drops (Fig. 6.8) over the next 150 years (from years 200 to 350). Under climate warming, *Larix* persists as a dominant until the even-aged stands break-up and then there is a transition to a *Betula –Pinus* mosaic landscape. The composition shift is much like a successional response with a species shift as forests mature. This compositional shift is part of the simulated "normal" successional development seen in forests of the Russian Far East (Fig. 6.8) in which an initial pioneering successional stage dominated by *Larix* transitions to *Pinus-Picea* forest. One also can see this classic successional replacement pattern in the simulations of the northern Chinese forests (Yan and Shugart 2005, Fig. 6.7). Under climate change, the forests of the Russian Far East retain the replacement successional

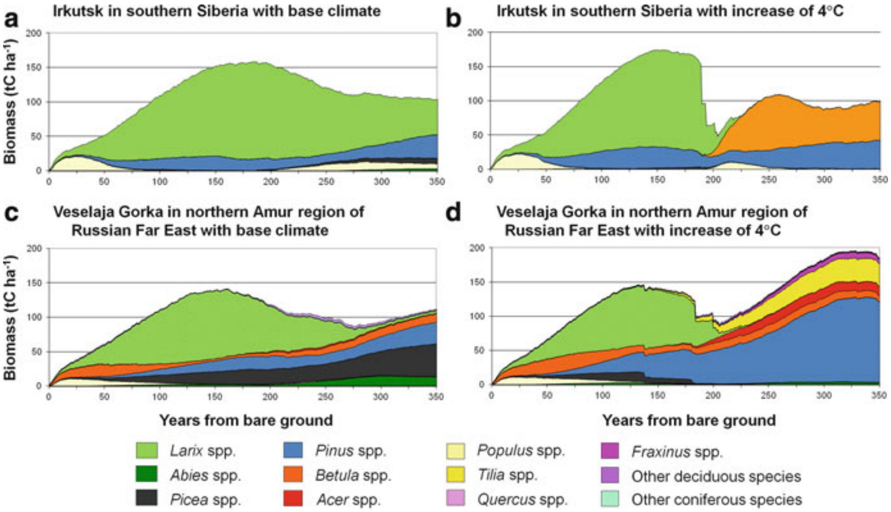

Fig. 6.8 Cumulative biomass (t C ha^{-1}) of species from model simulations for two locations in Russia. Each graph displays composition by the dominant genera. The base cases in each of the pairs of graphs represent the successional dynamics from a bare ground condition in year 0 for 350 years of ecological succession. Also, in each pair of simulations is a climate-change case with a temperature increase ramping up over the first 200 years of succession to an increase in average temperature of 4 °C; this level of change in then continued until year 350. (**a**) and (**b**) Simulated mixed species biomass dynamics (t C ha^{-1}) for Irkutsk in southern Siberia. The effect of temperature increase of 4 °C across 200 years of forest succession causes transition from *Larix* spp. dominance to mixed species forest (**b**) when compared to base scenario (**a**). Legend for (**a** and **b**) shown to the *right* side of (**b**). (**c**) and (**d**) Simulated mixed species biomass dynamics (t C ha^{-1}) for Veselaja Gorka in the Russian Far East. The effect of temperature increase of 4 °C across 200 years causes transition to a mixed-species forest dominated by *Pinus* spp. (**d**) when compared to base scenario (**c**). for (**c** and **d**) shown to the *right* side of (**d**)

pattern (Fig. 6.8) but the composition of the mature-phase forest is different (a mixed *Pinus* with broad-leaved deciduous-tree-species forests). In the Irkutsk forest, landscape climate change induces a new successional pattern of stand replacement; in the Far East forest the same pattern of climate change has the same broad type of successional replacement but with different dominant species.

Distributed gap-models can project forest response to climate change (Fig. 6.9) including forest structural properties over the Siberian boreal forest. These model responses can be compared to those of other more aggregated models (Vygodskaya et al. 2007; Tchebakova et al. 2009) to determine the sensitivity of the predicted responses to forest structure. Using the FAREAST model distributed on points across Siberia, one can inspect the response of the forest to different climate-change scenarios. The case shown in Fig. 6.9 is for a simple sensitivity analysis with an increase of 4 °C across 372 sites. What emerges is an expected pattern of biomass distribution for Siberia and the Russian Far East (Fig. 6.9, left) with high levels of biomass (t C ha^{-1}) in the Russian Far East and in the southern part of Siberia.

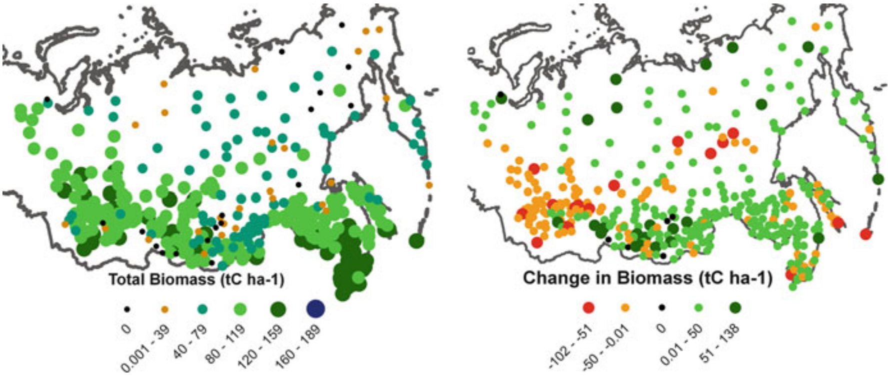

Fig. 6.9 230-year-old forest landscapes at 372 sites across Siberia and Russian Far East simulated by the FAREAST model for Each point is the average of 200 one-twelfth *ha* plots simulated through succession from bare ground and then averaged at Each point. *Left*: Simulated total mixed-species biomass for historical climate data. *Right*: Difference in total biomass (t C ha^{-1}) between a +4 °C climate warming and the historical baseline. Decrease in biomass is in *red* and *orange*; increase in shades of *green*

Under a warming, there is a substantial decrease in biomass through middle Siberian sites, particularly in the forests of the region surrounding Novosibirsk and Tomsk in southwestern Siberia. The diverse high-biomass forests of the Russian Far East maintain their biomass levels and even increase due to a warming, but there is a potential change in composition (Fig. 6.8). The change is complex across all of Siberia and the indication is that wide forest monitoring is necessary to obtain a complete picture of the nature of the change. Please note that the responses do not include the possibilities of increased rates of disturbance (notably fire and insect pests), which could be expected to increase in their effects with warming.

6.6.2 Potential Land Cover Change in Siberia Predicted by Siberian Bioclimatic Model

The changing climate rearranges land cover and impacts biophysical and biochemical processes directly and indirectly through land cover change. To understand these climate-induced vegetation changes, bioclimatic models of either a static (time-independent), dynamic (time-dependent), or mixed nature are used. To simulate zonal vegetation across Siberia (within the window: 60–140°E and 48–72°N, about 12 million km^2) during the twenty-first century, a Siberian bioclimatic model, SiBCliM was designed (Tchebakova et al. 2003), a static, envelope-type large-scale bioclimatic model based on the Siberian vegetation classification of Shumilova (1962). SiBCliM uses three bioclimatic indices to characterize a climatic envelope of each vegetation class: (1) growing degree-days above 5 °C, characterizing plant requirements for warmth;

(2) negative degree-days below 0 °C, characterizing plant tolerance to cold; and (3) an annual moisture index (ratio of growing degree days above 5 °C to annual precipitation), characterizing plant resistance to water stress. SiBCliM was updated to include permafrost (the active layer depth), a critical ecosystem determinant in the extremely cold continental climates of Siberia (Tchebakova et al. 2009, 2010). SiBCliM includes 14 vegetation classes, 10 boreal (tundra, forest-tundra, northern, middle, southern dark-coniferous and light-coniferous taiga, forest-steppe, and steppe), and four temperate (conifer-broadleaved, forest-steppe, steppe, and semidesert) vegetation classes that do not exist in the current Siberian climate but are included in SiBCliM because of their potential importance in future climates. The SiBCliM performance was evaluated by comparing modeled and actual vegetation maps using the kappa statistics (Monserud and Leemans 1992). The overall agreement between these two maps was a "fair" match (kappa 0.53).

To simulate vegetation cover and hot spots of vegetation change in Siberia in a changing climate by the end of the twenty-first century, we used two IPCC climate change scenarios that reflect opposite ends of the spectrum, the Hadley Centre HadCM3 A2, the largest temperature increase, and B1, the smallest temperature increase (IPCC 2007a, b). We evaluated then possible feedbacks of vegetation change to the climatic system (albedo and thus net radiation change) that may mitigate/accelerate vegetation shifts at the end of the twenty-first century in response to the harsh HadCM3 A2 scenario (Fig. 6.10 1C). According to this scenario, northern vegetation types (tundra, forest-tundra, and taiga) would decrease from 81.5 to 30 %, with southern (forest-steppe, steppe, and semidesert) vegetation prevailing on 67 % of Siberia (Table 6.16). A moderate change in vegetation is predicted from the B1 scenario (Fig. 6.10 1B). According to this scenario, habitats for northern vegetation classes would decrease from 81.5 to 50 % enabling southern habitats to expand from 18.5 to 50 %.

Fire and the thawing of permafrost are considered to be the principal mechanisms that will promote zonal vegetation shifts across Siberia in a rapidly changing climate.

In a future warm and dry climate in Siberia, zonobiomes could shift northward as far as 600 km (Tchebakova et al. 2009). Trees at the northern tree-line would move by means of migration. Migration rates of boreal tree species as estimated from paleoecology may reach 300–500 m year^{-1} or even less (Udra 1988; King and Herstrom 1997), thus taking a millennium for a vegetation zone of hundreds of kilometers in width to be completely replaced by vegetation of a neighboring zone under warming. Species with broad climatic niches and high migration rates could adjust to a rapidly warming climate while species with a restricted range of suitable habitats and limited dispersal are likely to disappear first (Solomon and Leemans 1990). While extirpation and immigration are the main processes at the margins of the forest distribution, within the forest zone, natural selection and gene flow are the primary processes favoring tree adaptation to climate change (Davis and Shaw 2001; Rehfeldt et al. 2004). Evolutionary processes of adjusting to predicted climate change would take a time at least one order of magnitude greater than the time it takes for the climate itself to change. Estimates for *Pinus sylvestris* in Siberia

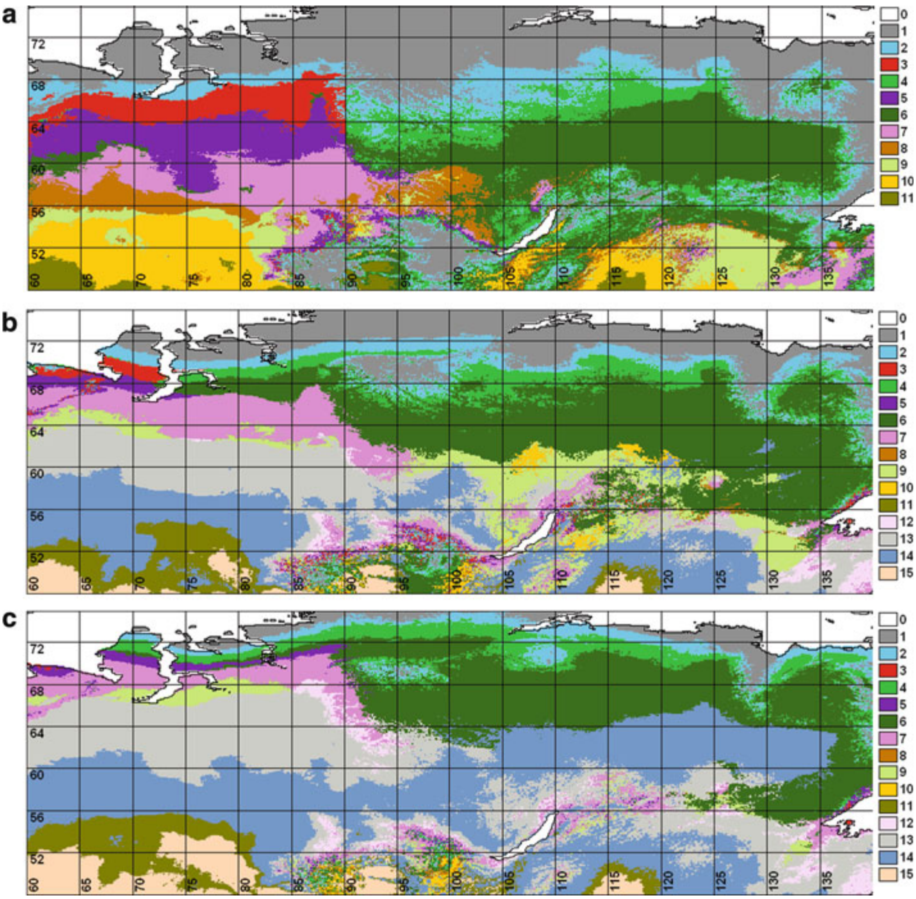

Fig. 6.10 Vegetation distribution in 2080 predicted from current climate (**a**) and the moderate HadCM3 B1 (**b**) and the harsh A2 (**c**) climate change projections. Vegetation class key: 0 - Water; Boreal: 1 - Tundra; 2 - Forest-Tundra; Northern Taiga: 3 - dark, 4 - light; Middle taiga: 5 - dark, 6 - light; Southern Taiga: 7 - dark, 8 - light; 9 - Subtaiga, Forest-Steppe; 10 - Steppe; 11 - Semidesert; Temperate: 12 - Broadleaf; 13 - Forest-Steppe; 14 - Steppe, 15 - Desert

Table 6.16 Potential vegetation change (%) in Siberia by 2080 predicted from two climate change scenarios

Vegetation	Current climate, %	Had CM3 A2, %	Δ, %	Had CM3 B1, %	Δ, %
Tundra	18.3	2.0	−16.3	7.5	−10.8
Forest-tundra	8.5	2.4	−6.1	4.0	−4.5
Taiga					
Light-conifer	36.1	19.9	−16.2	25.7	−10.4
Dark-conifer	18.5	9.0	−9.5	12.1	−6.4
Forest-steppe	6.1	23.8	17.7	22.5	16.4
Steppe	10.0	30.1	20.1	19.1	9.1
Semidesert	2.5	12.9	10.4	9.0	6.5

suggest that 5–10 generations (above 150 years) are required for the evolutionary process to follow a predicted warming. Genotypes would be reorganized within tree distributions, and tree boundaries would follow a changing climate. The forest adjustment to climate change would occur, but it would require a long time due to the large amount of change predicted by the end of the current century (Rehfeldt et al. 2004).

At the southern tree-line, forest fire would promote a replacement of forest vegetation by grasslands. A drier climate would result in increased tree mortality in the southern taiga, thus increasing fire fuel accumulation. When paired, both factors, increased fuel load and fire weather, show that risks of large fires would significantly escalate in dry southern Siberia and in central Yakutia advancing new habitats for steppe and forest-steppe rather than forests. In a warmer and drier climate, postfire forest regeneration may not be possible due to decreased precipitation and increased evapotranspiration. Grasses would replace forest, as suggested in several model scenarios (Rizzo and Wiken 1992; Smith and Shugart 1993), because they are adapted to less precipitation and droughts, and they are able to recover after frequent fires due to a short life cycle.

Future climate is often regarded as analogous to the mid-Holocene climate (Borzenkova and Zubakov 1984). In Siberia, the mid-Holocene climate as reconstructed from mid-Holocene vegetation (Chap. 3) was warmer and wetter than the present (Monserud et al. 1996). The climate of the twenty-first century as predicted from GCMs is warmer and drier. The mid-Holocene and future climates are likely to be dissimilar and impact terrestrial ecosystems differently, so they may not be regarded as analogous.

Altered land cover would generate additional regional forcing and feedback to the climate system resulting in a potential nonlinear response to changes in climate. Predicted significant changes in land cover across Siberia by the end of the century would initiate change in surface albedo and thus energy fluxes between the biosphere and the atmosphere. To evaluate possible effects of feedbacks of vegetation-induced albedo change to net radiation change to accelerating/mitigating vegetation shifts over Siberia, we first evaluate albedo change by 2080. Albedo of both current and the 2080 vegetation was calculated for each pixel as a sum of winter albedo (vegetation covered by snow), summer albedo (snow-free vegetation), and albedo of the winter-to-summer and summer-to-winter transition periods. Albedo values were ascribed to each pixel for each year period from Budyko (1974). The snow period was calculated from the regression relating it to July and January temperatures ($R^2 = 0.72$, $p < 0.0000$); the winter-to-summer and summer-to-winter transition period was calculated from the regression relating this period to the snow period ($R^2 = 0.51$, $p < 0.0000$). Average annual albedo change by 2080 was calculated as the difference between 2080 and current albedo. According to the harsh A2 scenario, albedo would increase over 44 % of the area in the southern and middle latitudes in Siberia due to the forest retreat. Albedo would decrease in 56 % of the territory mainly in the northern latitudes and highlands, where tundra would be replaced by forest with smaller albedo and in southern grasslands where the snow-free period would extend. With consideration of changes in snow cover, tundra characterized by a high seasonal variation in albedo showed increased feedbacks (greater atmospheric heating) compared to forests characterized by less seasonal variation in albedo that showed lesser feedbacks (less atmospheric heating) (Chapin III et al. 2000). Thus, resulting warming due to effects of albedo and snow cover change would be greater at high latitudes and lesser warming or some cooling would occur at middle and low latitudes.

Change in albedo would change energy fluxes: shortwave radiation (Rs) and thus net radiation (R). Net radiation evaluated as $R = (0.6{*}\mathrm{Rs} + \alpha)$ with $R^2 = 0.93$, $p < 0.0000$, and shortwave radiation evaluated as $\mathrm{Rs} = Q{*}(1 - \alpha)$, where Q is total radiation and α – albedo, results then in $\Delta R \sim 0.6{*}\ Q{*}\ (\Delta\alpha)$, assuming Q and $R = (0.6{*}\mathrm{Rs} + \mathrm{a})$ are constant in the future climate.

The simulations show that under a greater warming (scenario A2), net radiation balance would increase by $2{,}200 \times 10^{13}$ MJ year^{-1} in half of the area in the north and would decrease by 700×10^{13} MJ year^{-1} in the other half of the area in the south totaling $1{,}500 \times 10^{13}$ MJ year^{-1} over the entire Siberian window, about 1.2×10^{13} m$^{2.}$ Compared to the net radiation 1,000–2,000 MJ m^{-2} year^{-1} in current climate, this change is about 10 % in the A2 climate and 6 % in the B1 climate.

To estimate albedo-induced net radiation feedbacks to vegetation, net radiation was transformed to growing degree-days, GDD, the climatic constraint we use in our SiBCliM, with $R^2 = 0.82$, $p < 0.0000$. Corrections for growing degree-days were calculated coupling this regression with the net radiation maps in the A2 and B1 climates at 2080 (Figs. 6.11 and 6.12). SiBCliM was run again for the A2 and B1 climates to understand how vegetation would shift with regard to the predicted albedo-induced feedbacks. Potential albedo feedbacks due to land cover change predicted from IPCC scenarios may result in additional warming in the north promoting the further forest advance into tundra, and some cooling in the forest-steppe ecotone promoting the forest return in the south (cf., Vygodskaya et al. 2007). Due to albedo feedback effects, the forest may gain some more area of tundra and may lose less area in grasslands gaining an additional 6–8.5 % (Fig. 6.13, green).

Thus, global and regional circulation models need to account for feedbacks from terrestrial ecosystems to get more reliable projections.

6.6.3 *Prediction at Landscape Level*

Reliable prediction of future states of the boreal forest under global change requires understanding the complex interactions among forest regenerative processes (succession), natural disturbances (e.g., fire, wind, and insects), and anthropogenic disturbances (e.g., timber harvest). At a landscape level, long-period predictions have been simulated based on the process-based, spatially explicit dynamic model of forest succession and disturbance LANDIS-II (LANDscape DIsturbance and Succession) (Mladenoff 2004; Scheller et al. 2007). The model independently simulates multiple ecological and anthropogenic processes so that interactions of these processes are an emergent property of the simulations. LANDIS-II consists of a

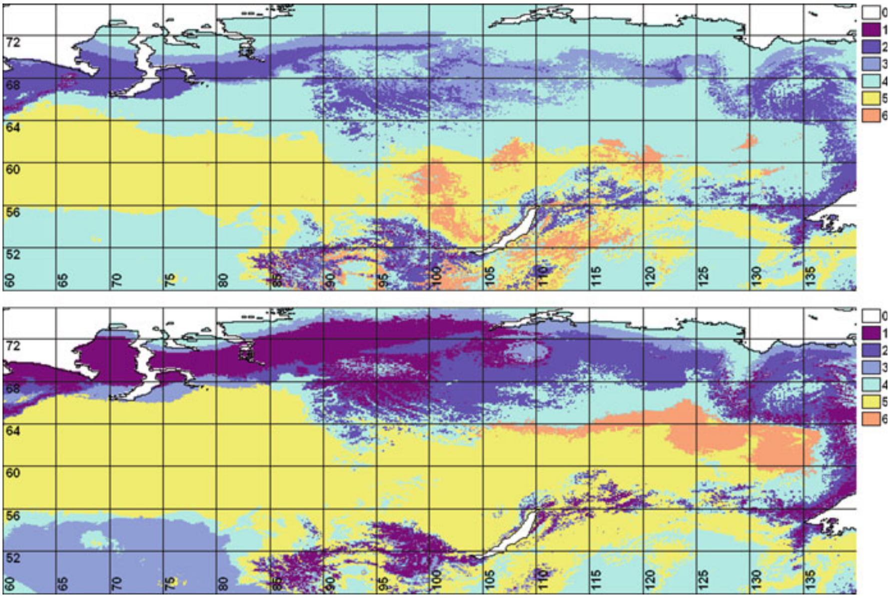

Fig. 6.11 Vegetation-induced albedo change in 2080 predicted from the moderate HadCM3 B1 (*upper*) and the harsh A2 (*lower*) climate change projections projections. Albedo class key: 0. Water; 1. - <-0.3, 2. -0.3-(-0.2), 3.-0.2 -(-0.1), 4.-0.1-0, 5. 0-0.1, 6.>0.1

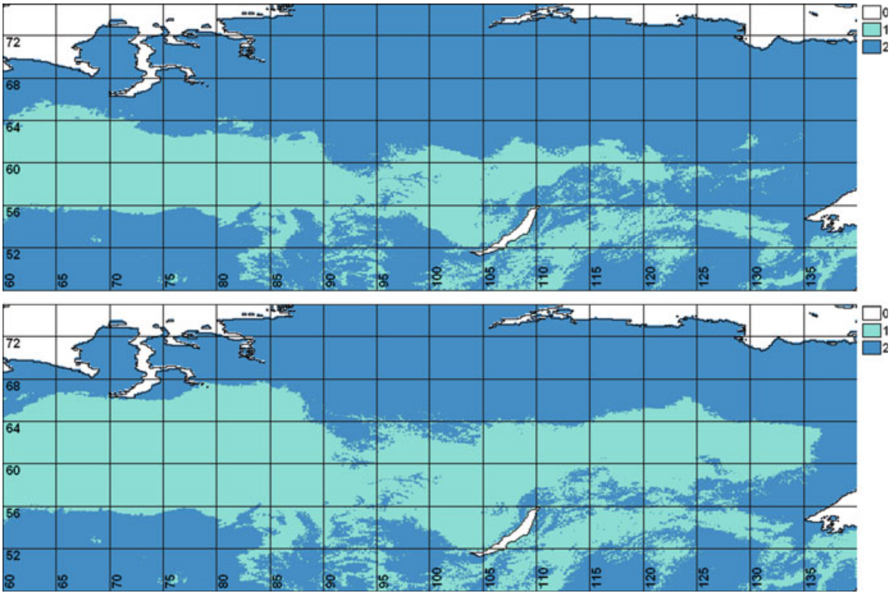

Fig. 6.12 Albedo-induced net radiation change in 2080 predicted from the moderate HadCM3 B1 (*upper*) and the harsh A2 (*lower*) climate change projections. Dark-blue marks net radiation increase (warming), light-blue marks net radiation decrease (cooling)

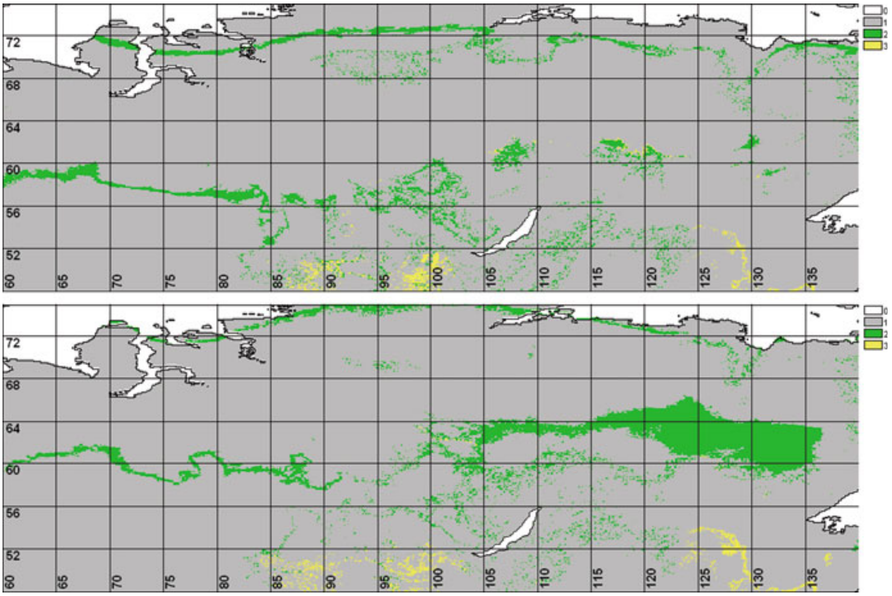

Fig. 6.13 Potential albedo feedback effects on the forest area: *green* – forest area increased due to additional warming (albedo decrease) in the north and some cooling (albedo increase) in the south promoting the forest return; *yellow* – forest area decreased

core collection of libraries and optional extensions that represent the ecological processes of interest (e.g., succession, wind disturbance, biotic disturbance, fire, biomass harvest, etc.). The model can be linked to the outputs of global circulation models (GCMs) to allow climate change to interact with landscape processes in the simulation environment and to process-based physiological models.

LANDIS-II represents the landscape as a grid of interacting cells at an appropriate resolution (e.g., 100 m), and each cell may contain multiple species and each species can be represented by one or many age cohorts. Each cohort will establish and respond to disturbance as a function of its life history attributes. Various disturbance extensions can be turned on or off, and the timber harvest extension allows the examination of alternative management regimes. The primary model outputs are maps of forest conditions, including species, age classes, aboveground biomass (living and dead), disturbance types, and their respective severities.

The model has been used to study the relative effects of climate change, timber harvesting, fire and insect outbreaks on forest composition, biomass (carbon), and landscape pattern in south-central Siberia (Gustafson et al. 2010, 2011a, b). The study area was represented by an almost intact forest region near Ust'-Ilmsk, at the boundary of southern and middle taiga, with a total area of about 315,000 ha. Permafrost is rare in the study area. Future climate parameters were based on the Hadley GCM (HadCM3) A2 scenario (Gordon et al. 2000) for the years 2080–2099. Mean monthly temperatures in the study area were predicted to rise by about 5 °C during the twenty-first century, and annual precipitation was predicted to increase by about 20 %. For the study area, the Hadley GCM projections were intermediate among those of the major GCMs, and precipitation and temperature trends were linear through the twenty-first century and variability was stable. LANDIS-II was coupled with a forest carbon and water balance model PnET-II, version 4.1–1.2c (Aber et al. 1995). This model matched well empirical observations in the region under current climate (e.g., for aboveground NPP within 4 %, Gustafson et al. 2010).

The most interesting result of the study was that major response variables (e.g., forest composition, Fig. 6.14) were more strongly influenced by timber harvest and insect outbreaks than the direct effects of climate change. The effect of the expected future climate was significant, but its effect was minor compared to harvest and insects, except the abundance of Scots pine. Climate did have a modest effect on the fire regime. The total area burned per decade and mean severity of fires was projected to be slightly increased, with higher variability under future climate. However, both the area burned and fire severity were lower by end of the simulation period under the future climate scenario because of changes in the species composition of the forest. The amount of live aboveground biomass and the level of forest fragmentation were related to the amount of disturbance associated with each scenario. Biomass increased during the last 100 years of the simulations under the insect scenario because insects favor tree species with higher growth rate.

The direct effects of climate change in the study area are not as significant as the exploitation of virgin forest by timber harvest and the potential immigration of the Siberian silk moth. Direct climate effects generally increased tree productivity and modified probability of establishment, but the indirect effects on the fire regime often seemed to counteract the direct effects. Harvest and insects significantly produced changes in forest composition, reduced living biomass, and increased forest fragmentation. It is expected that a warming climate will allow a major tree-killing insect, the Siberian silk moth (*Dendrolimus sibiricus superanse*), which currently does not occur in the study area, to exploit resources north of its current distribution by reducing the frequency of extreme cold events that kill overwintering individuals.

Simulation of the historical climate and disturbance regimes (historical regime of natural variability – HRNV) showed variation within the empirical range of proportions for most species and age classes, but the range of variability for some species (and ages) is currently near the extreme. Several reasons may contribute to this. The initial conditions map was partially impacted by human intervention during the recent decade that has generated more perturbation compared to the HRNV. This may shift the regularities of successions which have a “wavy” character and do not reach equilibrium during relatively short (e.g., 200 years) periods. Finally, while the model reproduces the empirical (current) fire regime quite closely, gradation of disturbance parameters (e.g., fire tolerance) may be too coarse to describe subtle differences of the fire tolerance of some species (e.g., spruce and fir).

Of the multiple global changes studied, climate had the least direct effect on species and seral stage composition. However, the arrival of the Siberian silk moth would be an indirect effect of climate warming, and the consequences may be quite

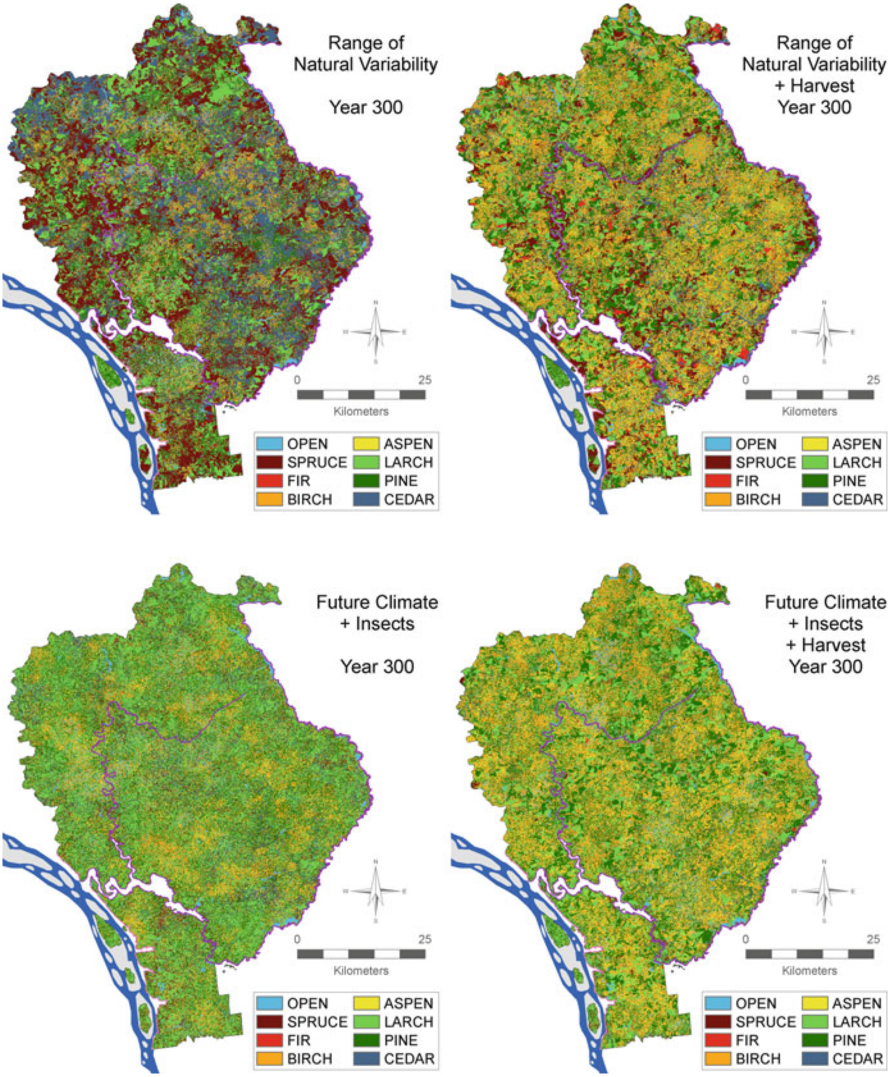

Fig. 6.14 Maps of change of forest composition under four different scenarios. Prediction for intact forests at ecotone of southern and middle taiga (the area at 315×10^3 ha, Ust'-Ilimsk region of Irkutsk Oblast) by LANDIS-II model

devastating. More direct climate effects on composition have a lag time and they induce long-lasting ecological changes that interact with other disturbance processes to fundamentally alter the ecosystem dynamics of these forests. Timber harvest activity produces a sudden and significant change in composition, particularly age class distribution. Climate also did not have a significant effect on biomass, likely because the positive effects of warmer temperatures on net primary production and establishment probability were canceled out by increased losses to fire. This is consistent with projections for boreal forests in Canada (Kang et al. 2006; Kurz et al. 2008a; Girardin and Mudelsee 2008). However, this study did not incorporate CO_2 fertilization effects on net primary production that may significantly interact with other global change effects (Alo and Wang 2008; Peng and Apps 1999).

Another application of LANDIS-II to the same region examined the ability of broad silvicultural strategies to reduce losses to disturbance, maintain the abundance of preferred species, mitigate fragmentation and loss of age class diversity, and sequester carbon under future climate conditions (Gustafson et al. 2011b). A factorial experiment was conducted manipulating three factors representing timber cutting strategies (cutting method, cutting rate and cutblock size). Simultaneously, the model simulated natural disturbances (fire, wind, insect outbreaks) and forest succession under projected future climate conditions as predicted by an ensemble of four global circulation models (CCCma, DFDL-CM2, HadCM3, and MPI-echam5).

As a result, the cutting method and cutting rate treatments had a large effect on species and age class composition, residual living biomass and susceptibility to disturbance. Clear-cutting reduces productivity in the short term, but increases it over the long term (>200 years), an effect that is likely related to changes in species composition. However, some of the more productive species may not be those of greatest commercial value. Cutblock size (within ecologically accepted limits) seems to have little effect except on fragmentation, so it can be used to achieve fragmentation objectives without fear of compromising other objectives. Based on the results, a “recommended” strategy was simulated and compared to the current forest management practice (“business as usual”) (Gustafson et al. 2011b). The recommended strategy resulted in higher forest productivity, increased abundance of favored species, and reduced fragmentation, but it did not significantly reduce losses to disturbance. No single strategy appears able to achieve all possible forest management objectives. Forest management has limited power to reduce total losses to disturbance because the species most likely to reduce disturbance rates are not currently economically valuable. Silviculture can have an effect on losses by a single disturbance type, but not all types simultaneously.

Although these results do not point to a clear, universal management solution to sustaining healthy forests in south-central Siberia, they do provide insight into the direction and magnitude of the effects of very general strategies in the face of climate change and interacting disturbances.

The application of LANDIS-II to forests of central Siberian landscapes lead to conclusions that global change is likely to significantly change forest composition of central Siberian landscapes, reduce the ability of Siberian forests to sequester carbon, and may significantly alter ecosystem dynamics and wildlife populations by increasing forest fragmentation. However, the model does not predict irreversible decline and death of forests in the region, as some other models considered above do.

6.7 Brief Summary

In order to understand how Siberian terrestrial ecosystems might respond to ongoing and anticipated climate and environmental change, at least four different important processes should be considered – expected ecosystem change in vitality and productivity, acceleration of natural disturbance, migration and alteration of the land cover (including changes in patterns of species cohorts), and character and intensity of anthropogenic pressure. Global change in both of its major interacting drivers – climate and humans – generates diverse but mostly dangerous challenges for Siberian ecosystem, particularly forests.

Vulnerability of Siberian ecosystems, particularly in a long run, is high. Overall, global change could provide both positive and negative impacts on ecosystems, their spatial distribution, structure, and functioning. Major drivers of increasing ecosystems productivity are: (1) elevated atmospheric CO_2 concentration, (2) increased nitrogen deposition, and (3) longer and warmer growing seasons. However, the combined impacts of these processes on productivity of northern ecosystems (and particularly, forests) and the long-term C balance are not completely clear (see also De Vries et al. 2006; Euskirchen et al. 2006; Juday et al. 2005), particularly the interaction between processes (i.e., dynamics of NPP and HR in the changing environment, intensification of disturbance regimes, and changes in ecosystems). There is much empirical and modeling evidence of changes in ecosystems in boreal Asia, including productivity, both increasing and decreasing, particularly at northern and southern tree-lines and altitudinal transition zones. Overall, terrestrial ecosystems of Siberia still serve a net carbon sink of about 0.3–0.4 Pg C annually. This sink is provided by forests and – to a much smaller extent – by wetlands. Other major land classes serve, on average, as a relatively small carbon source.

Some empirical and modeling results show that future climate and environmental change, together with increasing natural disturbance could have a clearly negative impact on vegetation and change some ecosystems from C sinks to C sources, particularly in disturbed forests and ecosystems on permafrost. These changes also serve as prerequisites to feedbacks to weather and climate, which could accelerate future disturbance regimes in Siberia. The future trajectories of Siberian ecosystems, particularly forests, will strongly depend upon a number of large-scale social and economic decisions which inter alia include transition to integrated land management on the landscape basis, implementation of an ecologically friendly paradigm of industrial development of Siberian territories, increase overall governance of renewable natural resources, and transition to adaptive forest management. These problems are still far from any practical solution in the region.

Risks to terrestrial ecosystems, which include steppe, forest, tundra, and agricultural lands, that are initiated by climate change and anthropogenic pressure are summarized:

- Negative impacts of processes that degrade or destroy permafrost structure including physical destruction of sites, thermokarst, and solifluction
- Dramatic changes of the heat balance of landscapes

- Irreversible changes in hydrological regimes on large territories
- If IPCC climatic predictions were realized, the region would become a large source of carbon, mostly in form of methane
- Loss of soil fertility due to water erosion, soil compaction, desertification, lack of nutrients, salinization, change of water table and other changes in water regimes, and soil contamination
- Decrease of resilience and the decline of biological productivity of boreal forests, particularly at southern edge of the forest domain and in permafrost territories
- Critical increase of mortality of trees in boreal forests
- Lack of water resources in arid areas of the region
- Damage of agriculture lands in river valleys due to an increase in inundation
- An increased or expanded spatial distribution of traditional and new insects and more frequent occurrence of pan-Siberian outbreaks
- Dangerous alteration of forest fire regimes
- Loss of biodiversity due to disturbances and loss of species which are not able to cope with the changing environment
- Impacts of air pollution, soil and water contamination in regions of intensive industrial development

In spite of numerous studies on global change in Siberia, many ecological processes and tendencies are poorly understood. There are a number of fundamental problems that require urgent investigation: setting thresholds of acceptable (nondestructive) impacts on ecosystems taking into account nonlinear and multivariant responses of ecosystems to a long-term accumulation of stress; system (holistic) analysis of a complicated dynamic system to include assessment of ecosystem impacts, responses, and feedbacks in ecosystems that are biophysically unique (i.e., ecologically, socially, economically, and distinctly evolved); theory and practice of decision making in a changing world under a variety of uncertainties; and the development of integrated observing systems. Uncertainty of climatic, social, and economic predictions is high. These uncertainties create special difficulties to the development of future strategies of coevolution of human and nature in high latitudes.

This region requires the urgent development of an anticipatory strategy of adaptation to, and mitigation of, the negative impacts of global change, because this is a large enough region to feedback to regional and global climate systems and this is a region that is predicted to experience temperature changes up to two- to threefold greater than the global mean.

References

Aber JD, Ollinger SV, Federer CA, Reich PB, Goulden ML, Kicklighter DW, Melillo JM, Lathrop RG (1995) Predicting the effects of climate change on water yield and forest production in the northeastern United States. Clim Res 5:207–222

Achard F, Eva HD, Mollicone D, Beuchle R (2008) The effect of climate anomalies and human ignition factor on wildfires in Russian boreal forests. Philos Trans R Soc B Biol Sci 363:2331–2339

Ageenko AS (ed) (1969) Forests of the Russian Far East. Far Eastern Forestry Research Institute, Khabarovsk, 390 pp (in Russian)

Alexeyev VA, Birdsey RA (1998) Carbon storage in forests and peatlands of Russia. General technical report NE-244. USDA, Forest Service, Northeast Research Station, Radnor, PA, 137 pp

Alexeyev VA, Markov MV (2003) Statistical data about forest fund and change of productivity of forests of Russia during the second half of the 20th century. Saint Petersburg Forestry Research Institute, Saint Petersburg, 271 pp (in Russian)

Alo CA, Wang G (2008) Potential future changes of the terrestrial ecosystem based on climate projections by eight general circulation models. J Geophys Res G Biogeosci 113(1):G01004, 16 pp

Anthoni PM, Law BE, Unsworth MH (1999) Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem. Agric Forest Meteorol 95:151–168

Antonovski MY, Ter-Mikaelian MT, Furyaev VV (1992) A spatial model of long-tem forest fire dynamics and its applications to forests in western Siberia. In: Shugart HH, Leemans R, Bonan GB (eds) A systems analysis of the global boreal forest. Cambridge University Press, New York, pp 373–403

Arneth A, Kurbatova J, Kolle O, Shibistova OB, Lloyd J, Vygodskaya NN, Schulze ED (2002) Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian bog II. Interseasonal and interannual variability of CO_2 fluxes. Tellus B Chem Phys Meteorol 54:514–530

Bacastov R, Keeling CD (1973) Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle: II. Changes from A.D. 1700–2070 as deducted from a geochemical model. In: Woodwell GM, Pekan EV (eds) Carbon and the biosphere. U.S. Atomic Energy Commission Series 30, Springfield, pp 86–135

Baker DF, Law RM, Gurney KR, Rayner P, Peylin P, Denning AS, Bousquet P, Bruhwiler L, Chen YH, Ciais P, Fung IY, Heimann M, John J, Maki T, Maksyutov S, Masarie K, Prather M, Pak B, Taguchi S, Zhu Z (2006) TransCom 3 inversion intercomparison: impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988–2003. Glob Biogeochem Cycles 20 (art no. GB1002). doi:10.1029/2004GB002439 17 pp

Balshi MS, McGuire AD, Duffy P, Flannigan M, Walsh J, Melillo J (2009) Assessing the response of area burned to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach. Glob Chang Biol 15:578–600

Baranchikov YuN (2011) Siberian moth – a relentless modifier of taiga forest ecosystems in Northern Asia. In: Boreal forests in a changing world: challenges and needs for actions. IBFRA, Krasnoyarsk, pp 105–107

Baranchikov YN, Kondakov YP, Petrenko ES (2001) Catastrophic outbreaks of Siberian silk moth in forests of Krasnoyarsk Kray. In: Lepeshev AA (ed) Safety of Russia. Regional problems of safety. Krasnoyarsk Kray. Znanie Publ, Moscow, pp 146–147

Barber VA, Juday GP, Finney BP (2000) Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405:668–673

Bartalev SA, Egorov VA, Loupian EA, Uvarov IA (2007) Multi-year circumpolar assessment of the area burnt on boreal ecosystems using SPOT-VEGETATION. Int J Remote Sens 28:1397–1404

Bazilevich NI (1993) Biological productivity of ecosystems of Northern Eurasia. Nauka, Moscow, 293 pp

Beer C, Lucht W, Schmullius C, Shvidenko A (2006) Small net carbon dioxide uptake by Russian forests during 1981–1999. Geophys Res Lett 33(15):L15403, 4pp

Belelli-Marchesini L (2007) Analysis of the carbon cycle of steppe and old field ecosystems of Central Asia. PhD thesis, Italy University of Tuscia, Viterbo, 227 pp

Belelli-Marchesini L, Papale D, Reichstein M, Vuichard N, Tchebakova N, Valentini R (2007) Carbon balance assessment of a natural steppe of southern Siberia by multiple constraint approach. Biogeosciences 4:581–595

Bonan GB, Shugart HH (1989) Environmental factors and ecological processes in boreal forests. Ann Rev Ecol Syst 20:1–28

Bonan GB, Shugart HH, Urban DL (1990) The sensitivity of some high latitude boreal forests to climatic parameters. Clim Chang 16:9–31

Borzenkova II, Zubakov VA (1984) The climate optimum of the Holocene as a model of the beginning of the 21st century. Russ Meteorol Hydrol 8:69–77

Budyko MI (1974) Climate change. Nauka, Leninggrad, 285 pp (in Russian)

Bulygina ON, Groisman PYa, Razuvaev VN, Korshunova NN (2011) Changes in snow cover characteristics over Northern Eurasia since 1966. Environ Res Lett 6:045204. doi:10.1088/1748-9326/6/4/045204, 10 pp

Chapin Iii FS, McGuire AD, Randerson J, Pielke R Sr, Baldocchi D, Hobbie SE, Roulet N, Eugster W, Kasischke E, Rastetter EB, Zimov SA, Running SW (2000) Arctic and boreal ecosystems of western North America as components of the climate system. Glob Chang Biol 6:211–223

Chen YH, Prinn RG (2006) Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model. J Geophy Res D Atmos 111(10):D10307, 25 pp

Chudnikov PI (1931) Impact of fire on regeneration of Urals Forests. Selkhozgiz (Agricultural State Publishing House), Moscow, 160 pp (in Russian)

Ciais P, Janssens I, Shvidenko A, Wirth C, Malhi Y, Grace J, Schulze ED, Heimann M, Phillips O, Dolman AJ (2005) The potential for rising CO_2 to account for the observed uptake of carbon by tropical, temperate, and boreal forest biomes. SEB Exp Biol Series 109–149

Ciais P, Canadell JG, Luyssart S et al (2010) Can we reconcile atmospheric estimates of the Northern terrestrial carbon sink with land-based accounting? Curr Options Environ Sustain 2:1–6

Corradi C, Kolle O, Walter K, Zimov SA, Schulze ED (2005) Carbon dioxide and methane exchange of a north-east Siberian tussock tundra. Glob Chang Biol 11:1910–1925

Cramer W, Kicklighter DW, Bondeau A, Moore Iii B, Churkina G, Nemry B, Ruimy A, Schloss AL (1999) Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Glob Chang Biol 5:1–15

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173

Davis MB, Shaw RG (2001) Range shifts and adaptive responses to quaternary climate change. Science 292:673–679

de Graaff MA, van Groenigen KJ, Six J, Hungate B, van Kessel C (2006) Interactions between plant growth and soil nutrient cycling under elevated CO_2: a meta-analysis. Glob Chang Biol 12:2077–2091

De Vries W, Reinds GJ, Gundersen P, Sterba H (2006) The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Glob Chang Biol 12:1151–1173

Devi N, Hagedorn F, Moiseev P, Bugmann H, Shiyatov S, Mazepa V, Rigling A (2008) Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. Glob Chang Biol 14:1581–1591

Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J (1994) Carbon pools and flux of global forest ecosystems. Science 263:185–190

Efremov D, Shvidenko A (2004) Long-period consequences of catastrophic fires in forests of the Russian Far East and their impacts on global processes. In Furyaev VV (ed) Forest fire management at ecoregional level. World Bank, Moscow, pp 66–73 (in Russian)

Epova VI, Pleshanov AS (1995) Zones of injuriousness of insects-phyllophagous of Asian Russia. Nauka, Novosibirsk, p 46

Ershov DV, Kovganenko KA, Sochilova EN (2009) GIS-tecnology for estimation of fire carbon emissions based on Terra-MODIS data and state forest account. Curr Probl Earth Obs Space 6(II):365–372 (in Russian)

Euskirchen ES, McGuire AD, Kicklighter DW, Zhuang Q, Clein JS, Dargaville RJ, Dye DG, Kimball JS, McDonald KC, Melillo JM, Romanovsky VE, Smith NV (2006) Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. Glob Chang Biol 12:731–750

Fedorov SV (1977) Studying of water balance elements in forest zone of the European area of the USSR. Hydrometeoizdat, Leningrad, 264 pp (in Russian)

FAFMRF (2010) Report on forest pathological monitoring in forests of Russia in 2009. Federal Agency of Forest Management of Russian Federation, Moscow, 86 p

FAO (2006) World reference base for soil resources 2006, 2nd edn. World Soil Resources Reports. IUSS Working Group WRB. FAO, Rome, 145 pp. ISBN: 92–5–105511–4. ftp://ftp.fao.org/agl/agll/docs/wsrr103e.pdf

Farber SK (2000) Formation of stands of East Siberia. Nauka, Novosibirsk, 433 pp (in Russian)

Feiziene D, Feiza V, Vaideliene A, Povilaitis V, Antanaitis S (2010) Soil surface carbon dioxide exchange rate as affected by soil texture, different long-term tillage application and weather. Zemdirbyste 97:25–42

FFSR (1962) Forest fund of RSFSR (state by January 1, 1961). Main Forest Management Department of Council of Ministers of RSFSR. Moscow, 628 p (in Russian)

FFSSR (2008) Regions of Russia. Social and economic indicators. Official edition. Federal Service of State Statistics, Moscow, 1000 pp (in Russian)

Filipchuk AN, Moiseev BN (2003) Assessment of atmospheric carbon uptake by vegetation cover in Russia. World climate conference, Moscow, 29 Sept–3 Oct, 503 p

Flannigan MD, Van Wagner CE (1991) Climate change and wildfire in Canada. Can J For Res 21:66–72

Flannigan M, Stocks B, Turetsky M, Wotton M (2009) Impacts of climate change on fire activity and fire management in the circumboreal forest. Glob Chang Biol 15:549–560

Forster P, Ramaswamy V (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S.e.a (ed) Climate change 2007: the physical science basis. Contribution of WG I to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge

Fridland VM (1989) Soil map of the USSR. Committee on Cartography and Geodesy, Moscow, (in Russian)

Furyaev VV (1996) Rope of fire in process of forest development. Nauka, Novosibirsk, 252 pp

Furyaev VV, Vaganov EA, Tchebakova NM (2001) Effects of fire and climate on successions and structural changes in the Siberian boreal forest. Eurasian J For Res 2:1–15

Geographical… (2007) Geographical studies in Siberia. In: Landscape hydrology: fundamental and practical research. Geo Publishing, Novosibirsk, 262 p

Gerten D, Schaphoff S, Haberlandt U, Lucht W, Sitch S (2004) Terrestrial vegetation and water balance – hydrological evaluation of a dynamic global vegetation model. J Hydrol 286:249–270

Gifford RM (1994) The global carbon cycle: a viewpoint on the missing sink. Aust J Plant Physiol 21:1–15

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. Geophys Res Lett 31:L18211 1–4

Girardin MP, Mudelsee M (2008) Past and future changes in Canadian boreal wildfire activity. Ecol Appl 18:391–406

Glagolev MV, Sirin AA, Lapshina ED, Filippov IV (2010) Carbonaceous greenhouse gases flux from West Siberian wetland ecosystems. Herald Tomsk State Polytech Univ 3(93):120–127

Glagolev M, Kleptsova I, Filippov I, Maksyutov S, Machida T (2011) Regional methane emission from West Siberia mire landscapes. Environ Res Lett 6:045214

Gordon C, Cooper C, Senior CA, Banks H, Gregory JM, Johns TC, Mitchell JFB, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim Dyn 16:147–168

Goulden ML, Munger JW, Fan SM, Daube BC, Wofsy SC (1996) Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Glob Chang Biol 2:169–182

Gurney KR, Law RM, Denning AS, Rayner PJ, Baker D, Bousquet P, Bruhwiler L, Chen YH, Clals P, Fan S, Fung IY, Gloor M, Heimann M, Higuchi K, John J, Maki T, Maksyutov S, Masarie K, Peylin P, Prather M, Pak BC, Randerson J, Sarmiento J, Taguchi S, Takahashi T, Yuen CW (2002) Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models. Nature 415:626–630

Gurney KR, Law RM, Denning AS, Rayner PJ, Baker D, Bousquet P, Bruhwiler L, Chen YH, Ciais P, Fan S, Fung IY, Gloor M, Heimann M, Higuchi K, John J, Kowalczyk E, Maki T, Maksyutov S, Peylin P, Prather M, Pak BC, Sarmiento J, Taguchi S, Takahashi T, Yuen CW (2003) TransCom 3 CO_2 inversion intercomparison: 1. Annual mean control results and sensitivity to transport and prior flux information. Tellus B Chem Phys Meteorol 55:555–579

Gurney KR, Baker D, Rayner P, Denning S (2008) Interannual variations in continental-scale net carbon exchange and sensitivity to observing networks estimated from atmospheric CO_2 inversions for the period 1980 to 2005. Global Biogeochem Cycles 22:GB3025

Gustafson EJ, Shvidenko AZ, Sturtevant BR, Scheller RM (2010) Predicting global change effects on forest biomass and composition in south-central Siberia. Ecol Appl 20:700–715

Gustafson EJ, Sturtevant BR, Shvidenko AZ, Scheller RM (2011a) Using landscape disturbance and succession models to support forest management. Chapter 5. In: Li C, Lafortezza R, Chen J (eds) Landscape ecology in forest management and conservation. Challenges and solutions for global change. Higher Education Press and Springer, Beijing/New York, pp 99–118

Gustafson EJ, Shvidenko AZ, Sheller RM (2011b) Effectiveness of forest management strategy to mitigate effects of global change in south-central Siberia. Can J For Res 41:1405–1421

Hamilton LS (2008) Forest and water. Food and Agriculture Organization of the United Nations, Rome, p 78

Hayes DJ, McGuire AD, Kicklighter DW, Gurney KR, Burnside TJ, Melillo JM (2011) Is the northern high latitude land-based CO_2 sink weakening? Global Biogeochem Cycles 25(3):GB3018. doi:10.1029/2010gb003813

Heinselman (1978) Fire intensity and frequency as factors in the disturbance and structure of northern ecosystems. In: Mooney HA, Bonnicksen TM, Christensen NL, et al (eds) Fire regimes and ecosystem properties. General technical report WO-26. USDA, Honolulu, pp 7–57

Hudson JMG, Henry GHR (2009) Increased plant biomass in a high arctic heath community from 1981 to 2008. Ecology 90:2657–2663

IPCC (2001) Climate change 2001: mitigation. Contribution of working group III to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press/IPCC, Cambridge, 881 p

IPCC (2007a) In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge/New York

IPCC (2007b) Climate change 2007: impact, adaptation and vulnerability. Chapter 4: Ecosystems, their properties, goods and services. Contribution of working group II to the fourth assessment report. Cambridge University Press, Cambridge, pp 211–272

Isaev AS (1991) Forecast of use and reproduction of forest resources by economic regions of the USSR by 2010. State Committee of USSR on Forest, Moscow, p 508

Isaev AS (ed) (1997) Program of the extraordinary activities on biological struggle with pests in forests of Krasnoyarsk Krai. Federal Forest Service of Russia, Moscow, 157 pp (in Russian)

Isaev AS, Khebopros RG, Nedorezov LV, Kondakov YP, Kiselev VV, Sukhovolsky VG (2001) Population dynamics of forest pests. Nauka, Moscow, 374 pp

Ivanova GA (1996) Extreme fire seasons in Evenkia forests. Siberian Ecol J 1:29–34

Ivanova GA (1998–1999) The history of forest fire in Russia. Dendrochronologia 16–17, 147–161

Jenkinson DS, Adams DE, Wild A (1991) Model estimates of CO_2 emissions from soil in response to global warming. Nature 351:304–306

Juday GP, Barber V, Duffy P, Linderholm H, Rupp S, Sparrow S, Vaganov Eu, Yarie J (2005) Forests, land management, and agriculture. Chapter 14. In: ACIA, Arctic climate impact assessment 2005, Cambridge University Press, pp 782–862

Kabat P, Claussen M, Dirmeyer PA, Gash JHC, Bravo de Guenni L, Meybeck M, Pielke RA Sr, Vörösmarty CJ, Hutjes RWA, Lütkemeier S (eds) (2004) Vegetation, water, humans and the climate: a new perspective on an interactive system. Springer, Berlin, 566 pp

Kajii Y, Kato S, Streets DG, Tsai NY, Shvidenko A, Nilsson S, McCallum I, Minko NP, Abushenko N, Altyntsev D, Khodzer TV (2002) Boreal forest fires in Siberia in 1998: estimation of area burned and emissions of pollutants by advanced very high resolution radiometer satellite data. J Geophys Res D Atmos 107(24):ACH 4-1–ACH 4-8 art. no. 4745

Kang S, Kimball JS, Running SW (2006) Simulating effects of fire disturbance and climate change on boreal forest productivity and evapotranspiration. Sci Total Environ 362:85–102

Kaplun F, Brumarova N, Vidyapin V (eds) (1994) New Russia. Information and statistical book. International Academy of Informatization, Moscow, 740 pp (in Russian)

Karelin DV, Zamolodchikov DG (2008) Carbon exchange in cryogenic ecosystems. Nauka, Moscow, 343 pp

Kasischke ES, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. Geophys Res Lett 33:1–5

Kharuk VI, Im ST, Ranson KJ, Naurzbaev MM (2004) Temporal dynamics of larch in the forest-tundra ecotone. Dokl Earth Sci 398:1020–1023

Kharuk VI, Ranson KJ, Im ST, Naurzbaev MM (2006) Forest-tundra larch forests and climatic tends. Russ J Ecol 37:291–298

Kharuk V, Ranson K, Dvinskaya M (2007) Evidence of evergreen conifer invasion into larch dominated forests during recent decades in central Siberia. Eurasian J For Res 10:163–171

Kharuk VI, Dvinskaya ML, Im ST, Ranson KJ (2008) Tree vegetation of the forest-tundra ecotone in the western Sayan mountains and climatic trends. Russ J Ecol 39:8–13

Kharuk VI, Ranson KJ, Im ST (2009) Climate-induced mountain tree line ecotone dynamics in southern Siberia. International conference on computational information technologies for environmental sciences CITES-2009, Krasnoyarsk, 5–15 July, p 83

Kharuk VI, Im ST, Dvinskaya ML (2010a) Forest-tundra ecotone response to climate change in the western Sayan mountains, Siberia. Scand J For Res 25:224–233

Kharuk VI, Im ST, Dvinskaya ML, Ranson KJ (2010b) Climate-induced mountain tree-line evolution in southern Siberia. Scand J For Res 25:446–454

Kharuk VI, Ranson KJ, Im ST, Vdovin AS (2010c) Spatial distribution and temporal dynamics of high-elevation forest stands in southern Siberia. Glob Ecol Biogeogr 19:822–830

Khotinsky NA (1984) Holocene vegetation history. In: Velichko AA, Wright HE, Barnosky CW (eds) Late quaternary environments of the Soviet Union. University of Minnesota Press, Minneapolis, pp 179–200

Kim H-S, Maksyutov S, Glagolev MV, Machida T, Patra PK, Sudo K, Inoue G (2011) Evaluation of methane emissions from West Siberian wetlands based on inverse modeling. Environ Res Lett 6:035201, 8pp

King GA, Herstrom AA (1997) Holocene tree migration rates objectively determined from fossil pollen data. In: Huntley B et al (eds) Past and future rapid environmental changes: the spatial and evolutionary responses of terrestrial biota. Springer, New York, pp 91–101

Kirschbaum MUF (1993) A modelling study of the effects of changes in atmospheric CO_2 concentration, temperature and atmospheric nitrogen input on soil organic carbon storage. Tellus Ser B 45 B:321–334

Kirschbaum MU (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol Biochem 27:753–760

Klimchenko AV (2007) Parameters of carbon cycle in restoration-age-specific row of larch forests with small shrubs and green mosses of northern taiga of Middle Siberia. PhD thesis, Institute of Forest of Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 21 pp (in Russian)

Knohl A, Kolle O, Minayeva TY, Milyukova IM, Vygodskaya NN, Foken T, Schulze ED (2002) Carbon dioxide exchange of a Russian boreal forest after disturbance by wind throw. Glob Chang Biol 8:231–246

Knorre AA (2003) Using of registering structures to estimate annual production of phytocoenoses components in forest and swamp ecosystems of Yenisey Siberia. V.N. Sukachev Institute of Forest, Abstracts of PhD thesis, Krasnoyarsk, 24 pp (in Russian)

Kolesnikov BP (1956) Cedar forests of the Far East. Transactions of the Far Eastern branch of the Academy of Sciences of the USSR. Ser Bot 2(4), 264 pp (in Russian)

Kondakov YP (1987) Phytocenotic specifics of outbreaks of needle- and leaf-eating insects in forests of Siberia. In: Vladyshevsky DV, Petrenko ES (eds) Ecological assessment of habitats of forest animals. Nauka, Novosibirsk, pp 29–40

Kudeyarov VN, Kurganova IN (1998) Carbon dioxide emissions and net primary production of Russian terrestrial ecosystems. Biol Fertil Soils 27:246–250

Kulikov AN (ed) (1998) Forest fires in Russian Far East. Project's report WWE RU1029, Khabarovsk

Kullman L (2007) Tree line population monitoring of *Pinus sylvestris* in the Swedish Scandes, 1973–2005: Implications for tree line theory and climate change ecology. J Ecol 95:41–52

Kurbatova J, Arneth A, Vygodskaya NN, Kolle O, Varlargin AV, Milyukova IM, Tchebakova NM, Schulze ED, Lloyd J (2002) Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian bog I. Interseasonal and interannual variability of energy and latent heat fluxes during the snowfree period. Tellus B Chem Phys Meteorol 54:497–513

Kurz WA, Apps MJ, Stocks BJ (1995) Global climate change: disturbance regimes and biospheric feedbacks of temperate and boreal forests. In: Woodwell G (ed) Biotic feedbacks in the global climate system: will the warming speed the warming? Oxford University Press, Oxford, pp 119–1333

Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson ET (2008a) Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. Proc Natl Acad Sci U S A 105:1551–1555

Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Caroll AL, Ebata T, Safranyik L (2008b) Mountain pine beetle and forest carbon feedback to climate change. Nature 452:987–990

Lapenis A, Shvidenko A, Shepaschenko D, Nilsson S, Aiyyer A (2005) Acclimation of Russian forests to recent changes in climate. Glob Chang Biol 11:2090–2102

Lavrenko EM, Sochava VB (eds) (1956) Vegetation cover of the USSR. Academy of Sciences of the USSR, Moscow/Leningrad, 460 pp (in Russian)

le Goff H, Flannigan MD, Bergeron Y (2009) Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. Can J For Res 39:2369–2380

Le Mer J, Roger P (2001) Production, oxidation, emission, and consumption of methane by soils: a review. Eur J Soil Biol 37:25–50

Lebedev AV, Gorbatenko VM, Krasnoschekov UN, Reshetkova NB, Protopopov VV (1974) Environmental role of forests of the lake Baikal basin. Nauka, Novosibirsk, 215 pp (In Russian)

Lenton TM, Held H, Kriegler JW, Lucht W, Rahmstorf S, Schellnhuber HJ (2008) Tipping elements in the earth climate system. PNAS 105(6):1786–1793

Liski J, Karjalainen T, Pussinen A, Nabuurs GJ, Kauppi P (2000) Trees as carbon sinks and sources in the European Union. Environ Sci Policy 3:91–97

Liu J (2010) Investigation in forest and water relations with an emphasis on China. IUFRO world congress 2010, Seoul

Lloyd AH, Bunn AG (2007) Responses of the circumpolar boreal forest to 20th century climate variability. Environ Res Lett 4:045013

Lloyd J, Shibistova O, Zolotoukhine D, Kolle O, Arneth A, Wirth C, Styles JM, Tchebakova NM, Schulze ED (2002) Seasonal and annual variations in the photosynthetic productivity and carbon balance of a central Siberian pine forest. Tellus B Chem Phys Meteorol 54:590–610

Luyssaert S, Ciais P, Piao SL, Schulze ED, Jung M, Zaehle S, Schelhaas MJ, Reichstein M, Churkina G, Papale D, Abril G, Beer C, Grace J, Loustau D, Matteucci G, Magnani F, Nabuurs GJ, Verbeeck H, Sulkava M, van der Werf GR, Janssens IA (2010) The European carbon balance. Part 3: Forests. Glob Chang Biol 16:1429–1450

Lyons WA, Nelson TE, Williams ER, Cramer JA, Turner TR (1998) Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires. Science 282:77–80

Magnani F, Mencuccini M, Borghetti M, Berbigier P, Berninger F, Delzon S, Grelle A, Hari P, Jarvis PG, Kolari P, Kowalski AS, Lankreijer H, Law BE, Lindroth A, Loustau D, Manca G, Moncrieff JB, Rayment M, Tedeschi V, Valentini R, Grace J (2007) The human footprint in the carbon cycle of temperate and boreal forests. Nature 447:848–850

Maksyutov S, Machida T, Mukai H, Patra PK, Nakazawa T, Inoue G (2003) Effect of recent observations on Asian CO_2 flux estimates by transport model inversions. Tellus B Chem Phys Meteorol 55:522–529

Manko UI, Gladkova GA (2001) Drying of spruce in the context of global degradation of dark coniferous forest. Dalnauka, Vladivostok, 231 pp

Manö S, Andreae MO (1994) Emission of methyl bromide from biomass burning. Science 263:1255–1257

McClelland JW, Holmes RM, Peterson BJ, Amon R, Brabets T, Cooper L, Gibson J, Gordeev VV, Guay C, Milburn D, Staples R, Raymond PA, Shiklomanov I, Striegl R, Zhulidov A, Gurtovaya T, Zimov S (2008) Development of Pan-Arctic database for river chemistry. Eos 89:217–218

McGuire AD, Chapin Iii FS, Walsh JE, Wirth C (2006) Integrated regional changes in arctic climate feedbacks: implications for the global climate system. Annu Rev Environ Resour 31:61–91

McGuire AD, Anderson LG, Christensen TR, Scott D, Laodong G, Hayes DJ, Martin H, Lorenson TD, Macdonald RW, Nigel R (2009) Sensitivity of the carbon cycle in the Arctic to climate change. Ecol Monogr 79(4):523–555

McGuire AD, Hayes DJ, Kicklighter DW, Manizza M, Zhuang Q, Chen M, Follows MJ, Gurney KR, McClelland JW, Melillo JM, Peterson BJ, Prinn R (2010a) An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. Tellus 62B:455–474. doi:10.1111/j.1600-0889.2010.00497.x

McGuire AD, Hayes DJ, Kicklighter DW, Zhuang Q, Chen M, Gurney RK e a (2010b) Analysis of the carbon balance of boreal Asia from 1997 to 2006. In: Proceedings of the international conference on environmental observations, modeling and information system ENVIROMIS, Tomsk, Russia, 5–11 July, 2010, pp 53–58

Meleshko VP, Katsov VM, Govorkova VA (2008) Climate of Russia in the XXI century. 3. Future climate changes obtained from an ensemble of the coupled atmosphere-ocean GCM CMIP3. Meteorol Hydrol 9:5–22

Mladenoff DJ (2004) LANDIS and forest landscape models. Ecol Model 180:7–19

Mokhov I, Chernokulsky AV, Shkolnik IM (2006) Regional model assessment of fire risks under global climate change. Dokl Earth Sci 411A(9):1485–1488

Mokhov II, Chernokul'Skii AV, Akperov MG, Dufresne JL, Le Treut H (2009) Variations in the characteristics of cyclonic activity and cloudiness in the atmosphere of extratropical latitudes of the Northern Hemisphere based from model calculations compared with the data of the reanalysis and satellite data. Dokl Earth Sci 424:147–150

Monserud RA, Leemans R (1992) Comparing global vegetation maps with the Kappa statistic. Ecol Model 62:275–293

Monserud RA, Tchebakova NM, Kolchugina TP, Denissenko OV (1996) Change in Siberian phytomass predicted for global warming. Silva Fenn 30:185–200

Morishita T, Hatano R, Desyatkin RV (2003) CH4 flux in an Alas ecosystem formed by forest disturbance near Yakutsk, Eastern Siberia, Russia. Soil Sci Plant Nutr 49:369–377

Mukhortova LV, Evgrafova SI (2005) Dynamics of organic matter decomposition and microflora composition of forest litter in artificial biogeocenoses. Proc Russ Acad Sci (Biol) 6:731–737

Nilsson S, Vaganov EA, Shvidenko AZ, Stolbovoi V, Rozhkov VA, MacCallum I, Ionas M (2003) Carbon budget of vegetation ecosystems of Russia. Dokl Earth Sci 393:1281–1283

Olchev A, Ibrom A, Ross T, Falk U, Rakkibu G, Radler K, Grote S, Kreilein H, Gravenhorst G (2008) A modelling approach for simulation of water and carbon dioxide exchange between multi-species tropical rain forest and the atmosphere. Ecol Model 212:122–130

Olchev A, Novenko E, Desherevskaya O, Krasnorutskaya K, Kurbatova J (2009) Effects of climatic changes on carbon dioxide and water vapor fluxes in boreal forest ecosystems of European part of Russia. Environ Res Lett 4:045007 (8 pp)

Oltchev A, Cermak J, Nadezhdina N, Tatarinov F, Tishenko A, Ibrom A, Gravenhorst G (2002) Transpiration of a mixed forest stand: field measurements and simulation using SVAT models. Boreal Environ Res 7:389–397

Onuchin AA (2009) Hydrological role of forest ecosystems of boreal zone. In: Proceedings of the international conference on ecological and geographical aspects of forest forming process, 23–25 Sept 2009, Krasnoyarsk, pp 11–14

Onuchin AA, Burenina TA (2008) Hydrological role of forests in Siberia. In: Prescott AP, Barkely TU (eds) Trends in water research. Nova, New York, pp 67–92

Onuchin A, Balzter H, Borisova H, Blyth E (2006) Climatic and geographic patterns of river runoff formation in Northern Eurasia. Adv Water Resour 29:1314–1327

Onuchin A, Burenina T, Gaparov K, Zyrukina N (2009) Land use impacts on river hydrological regimes in Northern Asia. In: Proceedings of the international conference "Hydroinformatics in hydrology, hydrogeology and water resources", Hyderabad, India, 6–12 September, pp 163–170

Orlov DS, Biryukova ON, Sukhanova NI (1996) Organic matter in soils of the Russian Federation. Nauka, Moscow, 254 pp (in Russian)

Pacala S, Birdsey RA, Bridgham SD, Conant RT, Davis K, Hales B, Hougthon RA, Jenkins JC, Johnston M, Marland G, Paustian K (2009) The North American carbon budget past and present. Chapter 3. In: The first state of the carbon cycle report (SOCCR). The North American carbon budget and implications for the global carbon cycle. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC pp 29–36

Pan Y, Birdsey R, Fang J, Hougthon R, Kaippi PE, Kurz AA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautianen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993

Patra PK, Gurney KR, Denning AS, Maksyutov S, Nakazawa T, Baker D, Bousquet P, Bruhwiler L, Chen YH, Ciais P, Fan S, Fung I, Gloor M, Heimann M, Higuchi K, John J, Law RM, Maki T, Pak BC, Peylin P, Prather M, Rayner PJ, Sarmiento J, Taguchi S, Takahashi T, Yuen CW (2006) Sensitivity of inverse estimation of annual mean CO_2 sources and sinks to ocean-only sites versus all-sites observational networks. Geophys Res Lett 33:L05814

Peng C, Apps MJ (1999) Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. Ecol Model 122:175–193

Pleshanov AS (1982) Insects-defoliators of larch forests of East Siberia. Nauka, Novosibirsk, 209 pp

Pleshikov FI (ed) (2002) Forest ecosystems of the Yenisey Meridian. Publ. House of SB RAN, Novosibirsk

Polykarpov NP, Tchebakova NP, Nazimova DI (1986) Climate and mountain forests of Southern Siberia. Nauka, Novosbirsk, 225 pp (in Russian)

Popov LV (1982) Southern taiga forests of Middle Siberia. Irkutsk State University, Irkutsk, 330 pp (in Russian)

Protopopov VV, Lebedev AV, Bizyukin VV (1991) Water protective role of forests of the lake Baikal basin. In: Proceedings of the scientific conference on problems of water resources of the Far Eastern economic region and Zabaikalie. Hydrometeoizdat, St. Petersburg, pp 298–310

Purves D, Pacala S (2008) Predictive models of forest dynamics. Science 320:1452–1453

Quegan S, Beer C, Shvidenko A, McCallum I, Handoh IC, Peylin P, Rödenbeck C, Lucht W, Nilsson S, Schmullius C (2011) Estimating the carbon balance of central Siberia using a landscape-ecosystem approach, atmospheric inversion and dynamic global vegetation models. Glob Chang Biol 17:351–365

Raich JW, Nadelhoffer KJ (1989) Belowground carbon allocation in forest ecosystems: global trends. Ecology 70:1346–1354

Raich JW, Potter CS, Bhagawati D (2002) Interannual variability in global soil respiration, 1980–1994. Glob Chang Biol 8:800–812

Raich JW, Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B: 81–99

Rautiainen A, Wernick I, Waggoner PE, Ausubel JH, Kauppi PE (2011) A national and international analysis of changing forest density. PLoS One 6:e19577

Rehfeldt GE, Tchebakova NM, Parfenova EI (2004) Genetic responses to climate and climate-change in conifers of the temperate and boreal forests. Recent Res Dev Genet Breed 1:113–130

Rizzo B, Wiken E (1992) Assessing the sensitivity of Canada's ecosystems to climatic change. Clim Chang 21:37–55

Röser C, Montagnani L, Schulze ED, Mollicone D, Kolle O, Meroni M, Papale D, Marchesini LB, Federici S, Valentini R (2002) Net CO_2 exchange rates in three different successional stages of the "Dark Taiga" of central Siberia. Tellus B Chem Phys Meteorol 54:642–654

Rozhkov AS (1965) Outbreaks of Siberian silk moth and measures of their control. Nauka, Moscow, 180 pp

Rozhkov VA, Wagner VB, Kogut VM (1996) Soil carbon estimates and soil carbon map for Russia. International Institute for Applied Systems Analysis, Laxenburg, 44 pp

Santoro M, Beer C, Cartus O, Schmullius C, Shvidenko A, McCallum I, Wegmüller U, Wiesmann A (2011) Retrieval of growing stock volume in boreal forest using hyper-temporal series of Envisat ASAR ScanSAR backscatter measurements. Remote Sens Environ 115:490–507

Scheller RM, Mladenoff DJ (2007) An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. Landsc Ecol 22:491–505

Scheller RM, Domingo JB, Sturtevant BR, Williams JS, Rudy A, Gustafson EJ, Mladenoff DJ (2007) Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecol Model 201:409–419

Schepaschenko D, McCallum I, Shvidenko A, Fritz S, Kraxner F, Obersteiner M (2010) A new hybrid land cover dataset for Russia: a methodology for integrating statistics, remote sensing and in-situ information. J Land Use Sci 6(4):245–259. doi:10.1080/1747423X.2010.511681, Published online 22 December 2010

Schepaschenko DG, Shvidenko AZ, Mukhortova LV, Schepaschenko MV (2011) Soil in the estimation of biospheric role of terrestrial ecosystems of Russia. In: Aparin BF (ed) International conference V.V. Dokuchaev 165 anniversary. Resource potential of soils – basis of food and ecological safety of Russia, Saint Petersburg State University, Saint Petersburg, 1–4 March, pp 511–512

Scherbakov IP (1975) Forest cover of North-East of the USSR. Nauka Publisher, Novosibirsk, 344 p (in Russian)

Schimel DS, Parton WJ, Kittel TGF, Ojima DS, Cole CV (1990) Grassland biogeochemistry: links to atmospheric processes. Clim Chang 17:13–25

Schmid HP, Grimmond CSB, Cropley F, Offerle B, Su HB (2000) Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the mid-western United States. Agr Forest Meteorol 103:357–374

Schmullius C, Santoro M (2005) SIBERIA-II. Multi-sensor concepts for greenhouse gas accounting of Northern Eurasia, Contract Number EVG1-CT-2001–0048, EC Deliverable, Final report, 167 pp

Schneider MK, Lüscher A, Richter M, Aeschlimann U, Hartwig UA, Blum H, Frossard E, Nösberger J (2004) Ten years of free-air CO_2 enrichment altered the mobilization of N from soil in Lolium perenne L. swards. Glob Chang Biol 10:1377–1388

Schulze ED (2002) Understanding global change: lessons learnt from the European landscape. J Veg Sci 13:403–412

Schulze ED, Lloyd J, Kelliher FM, Wirth C, Rebmann C, Luhker B, Mund M, Knohl A, Milyukova IM, Schulze W, Ziegler W, Varlagin AB, Sogachev AF, Valentini R, Dore S, Grigoriev S, Kolle O, Panfyorov MI, Tchebakova N, Vygodskaya NN (1999) Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink – a synthesis. Glob Chang Biol 5:703–722

Schuur EAG, Vogel JG, Crummer KG, Lee H, Sickman JO, Osterkamp TE (2009) The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature 459:556–559

Schwikowski M, Eichler A, Kalugin I, Ovtchinnikov D, Papina T (2009) Past climate variability in the Altai. Pages News 17:44–45

Sedykh VN (1990) Thermal effect in the forest forming process of West Siberia. In: Processes of transfer in natural and artificial covers of the Earth. Tjumen, pp 10–25 (in Russian)

Sedykh VN (2009) Forest forming process. Nauka, Novosibirsk, 163 pp (in Russian)

Shaver GR, Billings WD, Chapin FSI, Giblin AE, Nadelhoffer KJ, Oechel WC, Rastetter EB (1992) Global change and the carbon balance of arctic ecosystems. Bioscience 42:433–441

Sheingauz AS (2001) Forest complex of Khabarovsk Kray. RIOTIP, Kabarovsk, 103 pp (in Russian)

Sheingauz AS (2008) Selected works. FEB RAS, Khabarovsk, 654 pp (in Russian)

Sheshukov MA (1967) On classification of forest fire based on extent of burnt areas. Forestry For Manage 1:53–57 (in Russian)

Shibistova O, Lloyd J, Zrazhevskaya G, Arneth A, Kolle O, Knohl A, Astrakhantceva N, Shijneva I, Schmerler J (2002) Annual ecosystem respiration budget for a *Pinus sylvestris* stand in central Siberia. Tellus B Chem Phys Meteorol 54:568–589

Shiklomanov IA, Krestovsky OI (1988) Influence of forests and forest reclamation practice on streamflow and water balance. In: Reynolds ERC, Thompson FB (eds) Forests, climate, and hydrology: regional impacts. United Nations University Press, Tokyo, pp 78–116

Shiyatov SG (2003) Rates of change in the upper tree line ecotone in the Polar Ural Mountains. Pages News 11:8–10

Shiyatov SG, Terent'ev MM, Fomin VV, Zimmermann NE (2007) Altitudinal and horizontal shifts of the upper boundaries of open and closed forests in the Polar Urals in the 20th century. Russ J Ecol 4(38):223–227

Shugart HH (2000) Importance of structure in the longer-term dynamics of landscapes. J Geophys Res D Atmos 105:20065–20075

Shugart HH, West DC (1980) Forest succession models. Bioscience 30:308–313

Shugart HH, Leemans R, Bonan GB (eds) (1992) A systems analysis of the global boreal forest. Cambridge University Press, Cambridge, 542 pp

Shuman JK, Krankina ON, Shugart HH (2011) Validation of the dynamic forest gap model FAREAST across Russia ecological applications (in preparation)

Shumilova LV (1962) Botanical geography of Siberia. Tomsk State University, Tomsk, 440 pp (in Russian)

Shvidenko A, Goldammer JG (2001) Fire situation in Russia. Int Fire News 24:41–59

Shvidenko A, Nilsson S (2000a) Fire and the carbon budget of Russian forests. In: Kasischke ES, Stock BJ (eds) Fire, climate change, and carbon cycling in the boreal forest. Springer, New York, pp 289–311

Shvidenko AZ, Nilsson S (2000b) Extent, distribution, and ecological role of fire in Russian forests. In: Kasischke ES, Stocks BJ (eds) Fire, climate change, and carbon cycling in the boreal forest. Springer, New York, pp 132–150

Shvidenko A, Nilsson S (2002) Dynamics of Russian forests and the carbon budget in 1961–1998: an assessment based on long-term forest inventory data. Clim Chang 55:5–37

Shvidenko A, Nilsson S (2003) A synthesis of the impact of Russian forests on the global carbon budget for 1961–1998. Tellus B Chem Phys Meteorol 55:391–415

Shvidenko AZ, Strakhov VV, Nilsson S, Sedykh VN, Sokolov VA, Efremov DE (2000) Spatial scale of productivity of Russian forests. For Manage Inf 1–2:7–23 (in Russian)

Shvidenko A, Strakhov V, Nilsson S, Sedykh V, Sokolov V. Efremov D (2001) Productivity of forests of Russia. 3. Spatial scale of productivity's assessment. Forest Management Information, Moscow 1–2, pp 7–23 (in Russian)

Shvidenko A, Schepaschenko D, Nilsson S, Bouloui Y (2007a) Semi-empirical models for assessing biological productivity of Northern Eurasian forests. Ecol Model 204:163–179

Shvidenko AZ, Schepaschenko D, Nilsson S (2007b) Materials to knowledge of current productivity of Russian forest ecosystems. In: Basic problems for going over to sustainable forest management of Russia – forest inventory and forest organization. V.N. Sukachev Institute of Forest SB RAS, Krasnoyarsk, pp 7–37

Shvidenko AZ, Schepashchenko DG, Vaganov EA, Nilsson S (2008) Net primary production of forest ecosystems of Russia: a new estimate. Dokl Earth Sci 421A(6):1009–1012

Shvidenko A, Schepaschenko D, McCallum I (2010a) Bottom-up inventory of the carbon fluxes in Northern Eurasia for comparison with GOSAT level 4 products. Unpublished manuscript. International Institute for Applied Systems Analysis, Laxenburg, 210 p

Shvidenko A, Schepaschenko D, McCallum I, Nilsson S (2010b) Can the uncertainty of full carbon accounting of forest ecosystems be made acceptable to policymakers? Clim Chang 103:137–157

Shvidenko A, Schepaschenko D, Vaganov EA, Sukhinin AI, Maksyutov SS, McCallum I, Lakyda IP (2011) Impacts of vegetation fires of 1998–2010 in Russia on ecosystems and global carbon budget. Proc Russ Acad Sci (Doklady RAN) 441(2):544–588

Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, Thonicke K, Venevsky S (2003) Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob Chang Biol 9:161–185

Smith TM, Shugart HH (1993) The transient response of terrestrial carbon storage to a perturbed climate. Nature 361:523–526

Soja AJ, Cofer WR, Shugart HH, Sukhinin AI, Stackhouse PW Jr, McRae DJ, Conard SG (2004) Estimating fire emissions and disparities in boreal Siberia (1998–2002). J Geophys Res D: Atmos 109:D14S06

Soja AJ, Tchebakova NM, French NHF, Flannigan MD, Shugart HH, Stocks BJ, Sukhinin AI, Parfenova EI, Chapin Iii FS, Stackhouse PW Jr (2007) Climate-induced boreal forest change: predictions versus current observations. Glob Planet Change 56:274–296

Sokolova GA, Teteryatnikova EP (2002) Estimation of dynamics of forests of Russian Far East and Eastern Siberia caused by natural and anthropogenic factors. Research report. Far Eastern Research Forestry Institute, Khabarovsk, 180 p (in Russian)

Solomon AM, Leemans R (1990) Climatic change and landscape ecological response: issues and analysis. In: Boer MM, de Groot RS (eds) Landscape ecological impact of climatic change. Ios Press, Amsterdam, pp 293–316

Stireman JO et al (2005) Climatic unpredictability and parasitism of caterpillars: implications of global warming. PNAS 102(48):17384–17387

Stocks BJ, Fosberg MA, Lynham TJ, Mearns L, Wotton BM, Yang Q, Jin JZ, Lawrence K, Hartley GR, Mason JA, McKenney DW (1998) Climate change and forest fire potential in Russian and Canadian boreal forests. Clim Chang 38:1–13

Sukachev VN (1972) Selected scientific works, vol 1: Foundations of forest typology and biogeocenology. Nauka, Leningrad, 418 pp (in Russian)

Sukhinin AI (2008) Satellite data on wild fire. Available from www.iiasa.ac.at/Research/FOR/forest_cdrom/index.html. Accessed 5 May 2012

Sukhinin AI (2009) Airspace monitoring of catastrophic fires in forests of East Siberia. Unpublished report. Institute of Forest of Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk, 91 p (in Russian)

Tchebakova NM, Kolle O, Zolotuknine DA, Lloyd J, Arneth A, Parfenova EI, Schulze E-D (2002) Annual and seasonal dynamics of energy and mass exchange in a middle taiga pine forest. In: Pleshikov FI (ed) Forest ecosystems of the Yenisei meridian. Siberian Branch of Russian Academy of Sciences Publishing House, Novosibirsk, pp 252–264

Tchebakova NM, Rehfeldt GE, Parfenova EI (2003) Distribution of vegetation zones and populations of *Larix sibirica* and *Pinus sylvestris* in central Siberia under climate warming. Siberian Ecol J 6:677–686 (in Russian)

Tchebakova NM, Parfenova EI, Soja AJ (2009) Effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. Environ Res Lett 4:045013, 10 pp

Tchebakova NM, Rehfeldt GE, Parfenova EI (2010) Vegetation zones to climate types: effects of climate warming on Siberian ecosystems. In: Osawa A, Zyranova OA, Matsurura Y et al (eds) Permafrost ecosystems: Siberian larch forests. Springer, Berlin, pp 427–447

Tchebakova NM, Vygodskaya NN, Arneth A, Belelli-Marchesini L, Corradi C, Kurbatova JA, Parfenova EI, Valentini R, Vaganov EA, Schulze E-D (2011) Energy and mass exchange and productivity of major ecosystems in central Siberia based on the eddy covariance method. Biol Bull (submitted)

Thornley JHM, Fowler D, Cannell MGR (1991) Terrestrial carbon storage resulting from CO_2 and nitrogen fertilization in temperate grasslands. Plant Cell Environ 14:1007–1011

Titlianova AA, Tisarzhova M (1991) Regimes of the biological turnover. Nauka, Novosibirsk, 150 pp

Tumel VF (1939) Changes in the soils and permafrost regimes following vegetation cover burning. Academy of Sciences of the USSR, Moscow/Leningrad. Reports of the Permafrost Commission, Issue VIII, pp 3–80 (in Russian)

Udra IF (1988) Settling and migration of woody plants in temperate belt of Eurasia. Naukova Dumka, Kiev, 200 pp (in Russian)

Urban DL, Shugart HH (1992) Individual-based models of forest succession. In: Glenn-Lewin DC, Peet RK, Veblen TT (eds) Plant succession: theory and prediction. Chapman & Hall, London, pp 249–293

Urban DL, Bonan GB, Smith TM, Shugart HH (1991) Spatial applications of gap models. For Ecol Manage 42:95–110

Usoltsev VA, Voronov MP, Chasovskikh VP (2011) Net primary production of forests of Ural: methods and results of automized estimation. Ecology 4:334–343 (in Russian)

Vaganov EA, Arbatskaya MK, Shashkin AV (1996) History of climate and fire frequency in central part of Krasnoyarsk Kray. 2. Dendrochronological analysis of interdependence of ibcrement of trees, climate and fire frequency. Siberian Ecol J 1:19–28

Valentini R, Matteucci G, Dolman AJ, Schulze ED, Rebmann C, Moors EJ, Granier A, Gross P, Jensen NO, Pilegaard K, Lindroth A, Grelle A, Bernhofer C, Grünwald T, Aubinet M, Ceulemans R, Kowalski AS, Vesala T, Rannik Ü, Berbigier P, Loustau D, Guomundsson J, Thorgeirsson H, Ibrom A, Morgenstern K, Clement R, Moncrieff J, Montagnani L, Minerbi S, Jarvis PG (2000) Respiration as the main determinant of carbon balance in European forests. Nature 404:861–865

Van Der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano AF Jr (2006) Interannual variability of global biomass burning emissions from 1997 to 2004. Atmos Chem Phys Discuss 6:3175–3226

Vaschuk LN, Shvidenko AZ (2006) Dynamics of forests of Irkutsk region. Federal Agency of Forest Management, Irkutsk, 392 pp (in Russian)

Vasiliev SV, Titlyanova AA, Velichko AA (eds) (2001) West Siberian peatlands and carbon cycle: past and present. In: Proceedings of the international field symposium. Russian Academy of Sciences, Novosibirsk 250 pp

Vedrova EF (2002) Intensity of mineralisation flux in forest ecosystems. In: Pleshikov FI (ed) Forest ecosystems of Enisey meridian. SB RAS, Novosibirsk, pp 248–252

Vivchar A (2010) Wildfires in Russia in 2000–2008: estimates of burnt areas using the satellite MODIS MCD45 data. Remote Sens Lett 2:81–90

Vogt KA, Grier CC, Vogt DJ (1986) Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. Adv Ecol Res 15:303–377

Volney MJ, Fleming RA (2007) Spruce budworm (*Choristoneura* spp.) biotype reactions to forest and climate characteristics. Glob Chang Biol 13(8):1630–1643

Voronkov NA (1988) Role of forests in water protection. Hydrometeoizdat, Leningrad, 286 pp (in Russian)

Vtyurina OP, Sokolov VA (2009) Dynamics of forests. In Semechkin IV (ed) Management of sustainability in Krasnoyarsk krai. Institute of Forest SB RAS, Krasnoyarsk, pp 103–123

Vygodskaya NN (1981) Solar radiation regime and structure of mountain forest. Gidrometeoizdat, Leningrad, 261 pp (in Russian)

Vygodskaya N, Schulze E-D, Tchebakova N, Karpachevskii L, Kozlov D, Sidorov K, Panfyorov M, Shaposhnikov E, Solnzeva O, Minaeva T, Jeltuchin A, Wirth C, Pugachevskii A (2002) Climatic control of stand thinning in unmanaged spruce forests of the southern taiga in European Russia. Tellus 54B(5):443–461

Vygodskaya NN, Groisman PY, Tchebakova NM, Kurbatova JA, Panfyorov O, Parfenova EI, Sogachev AF (2007) Ecosystems and climate interactions in the boreal zone of northern Eurasia. Environ Res Lett 2:045033, 7 pp

Weishampel JF, Urban DL, Shugart HH, Smith JB (1992) Semivariograms from a forest transect gap model compared with remotely sensed data. J Veg Sci 3:521–526

Wirth C, Schulze ED, Schulze W, von Stunzner-Karbe D, Ziegler W, Miljukova IM, Sogatchev A, Varlagin AB, Panvyorov M, Grigoriev S, Kusnetzova W, Siry M, Hardes G, Zimmermann R, Vygodskaya NN (1999) Above-ground biomass and structure of pristine Siberian Scots pine forests as controlled by competition and fire. Oecologia 121:66–80

Wirth C, Czimczik CI, Schulze ED (2002) Beyond annual budgets: carbon flux at different temporal scales in fire-prone Siberian Scots pine forests. Tellus B Chem Phys Meteorol 54:611–630

Woodward FI, Lomas MR (2004) Vegetation dynamics – simulating responses to climatic change. Biol Rev Camb Philos Soc 79:643–670

Yan H, Shugart HH (2005) FAREAST: a forest gap model to simulate dynamics and patterns of eastern Eurasian forests. J Biogeogr 32:1641–1658

Yefremov DF, Shvidenko AZ (2004) Long-term ecological consequences of catastrophic forest fires in forests of Far East and their contribution to global processes. In: Forest fire management at ecoregional level. World Bank, Publishing house “Alex”, Moscow, pp 66–73

Yurchenko GI, Turova GI, Kuzmin EA (2003) Consequences of outbreaks of Siberian silk moth in Far Eastern conifer-broadleaves forests. Science background of use and reproduction of forest resources of Far East. Trans Far-Eastern Res For Inst 36:176–193

Zamolodchikov DG, Karelin DV, Ivaschenko AI, Oechel WC, Hastings SJ (2003) CO_2 flux measurements in Russian Far East tundra using eddy covariance and closed chamber techniques. Tellus B Chem Phys Meteorol 55:879–892

Zavarzin GA (ed) (2007) Carbon pools and fluxes in terrestrial ecosystems of Russia. Nauka, Moscow, 315 pp (in Russian)

Zhang YH, Wooster MJ, Tutubalina O, Perry GLW (2003) Monthly burned area and forest fire carbon emission estimates for the Russian Federation from SPOT VGT. Remote Sens Environ 87:1–15

Zhu X, Zhuang Q, Chen M, Sirin A, Melillo J, Kickligther D, Sokolov A, Song L (2011) Rising methane emissions in response to climate change in the Northern Eurasia during the 21st century. Environ Res Lett 6:045211. doi:10.1088/1748-9326/6/4/045211

Zhuang Q, Melillo JM, Kicklighter DW, Prinn RG, McGuire AD, Steudler PA, Felzer BS, Hu S (2004) Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: a retrospective analysis with a process-based biogeochemistry model. Global Biogeochem Cycles 18(GB3010):1–23

Zhuang Q, Melillo JM, Sarofim MC, Kicklighter DW, McGuire AD, Felzer BS, Sokolov A, Prinn RG, Steudler PA, Hu S (2006) CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. Geophys Res Lett 33(17):L17403, 5 pp

Zhuang Q, Melillo JM, McGuire AD, Kicklighter DW, Prinn RG, Steudler PA, Felzer BS, Hu S (2007) Net emissions of CH_4 and CO_2 in Alaska: implications for the region’s greenhouse gas budget. Ecol Appl 17:203–212

Zhukov AB (ed) (1969) Forests of Ural, Siberia and Far East, vol 4, Forests of the USSR. Nauka Publisher, Moscow, 768 pp (in Russian)