3.5. Ecosystems and climate interactions

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Introduction. The climate system and terrestrial ecosystems interact as they change. The interactions enhance and/or moderate the changes making these changes non-lineary. There are theoretical indications that the particular state of the ecosystem may make the history of the global climatic changes intransitive[30]. Gradually, Human Activity (HA) has become a part of these interactions by affecting the atmosphere, hydrosphere, cryosphere, and biosphere. As a working hypothesis we can assume that, in the past, ecosystems were in dynamic equilibrium with climate at the 10^2 –10^3 year time scales (Figures 1.2 and 1.3)[31]. The present situation, however, requires new approaches as the equilibrium has been disrupted and a mounting body of evidence shows changes in the states of both the ecosystem and climate with human impact/reactions contributing to the swiftest of these changes (Figures 2.1, 2.2, and 2.7 through 2.17[32], AGU 2003). Thus, HA have introduced significant transient forcing and feedback to a dynamic nonlinear system, which already has natural thresholds[31]. Contemporary climatic changes in Northern Eurasia are among the largest in the world, are projected to remain so, and may affect the global climate system (2.2.1, 3.3.4.2, and Figures 2.2 and 3.3.2). Ecosystems here are vulnerable to external forcing, especially along their boundaries (in transient zones), and when affected may exercise important controls on the global Earth system (3.1, 3.2). In many parts of Northern Eurasia, the present state of the ecosystems has been sharply affected by HA and is already far from equilibrium (3.1, and 3.4). Thus, it can change without further external impact with unprecedented rates and even in a direction opposite to the climate-induced tendency[33]. Interpretation of the observed

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[30] I.e., a possibility of the multiple long-term equilibriums of the Global Earth System exists under the same external conditions (Pielke 1998). One of the regions of the possible intransitivity is in the Central East Asia desert area (Claussen 1998). Another example is in the boreal forest zone of Northern Eurasia, where a millennium-scale process of paludification, i.e., gradual moss coverage of the surface and mire development could be an autogenous process (Pajula 2000). For example, the surface air temperature and precipitation conditions ~10,000 years ago may be approximately the same as the present at certain locations. But, now we have there a well developed moss cover that insulates the ground while10 to 6,000 years ago the moss cover was absent (or undeveloped) and the entire regional ecosystem (first of all, the soil temperature regime) was different.

[31] There are always ecosystems that are not exactly in equilibrium with the current climate state due to their slow response times. Furthermore, due to a non-linearity of the Global Earth System some of its components (ecosystems, cryospheric and/or hydrological states, ocean and/or atmospheric circulation modes, etc.) may be close to critical thresholds. When these thresholds are crossed during the "linear" way of changes or just by chance, abrupt shifts and trends follow (Rial et al. 2004). The paleoevidence shows that Northern Eurasia experienced such shifts and trends in the past (Neishtadt 1957; Khotinsky 1977; Klige et al. 1998; Kobak et al. 2002; Kozharinov and Puzachenko 2004; Figure 2.18).

[32] Figures 2.7 through 2.18 as well as figures 3.5.4 and 3.5.5 can be found in Scientific Background Appendix.

[33] For example, "greening" of abandoned farmland and pastures in Russia and Kazakhstan in the 1990s (Robinson et al. 2003) occurred while the climate became drier (Figure 2.11).

changes became a more difficult problem, though[34]. Finally, the observed environmental changes affect human society and forces it to react to changes, thus creating the human feedback to ecosystems and climate. This situation raises stakes in our quest for understanding of multifaceted processes that control natural interactions (feedbacks) and forced impacts and systems' responses in Northern Eurasia. The unique features of the region (2.2.2), important controls that it exercises over the global climate and environment (3.2, 3.3, 3.6.1, and 3.6.3), and the scale of observed climatic and environmental changes make the need of this understanding urgent. We must understand them to properly interpret the observations and generate projections of the most plausible scenarios of future changes.

Disclaimer: Direct anthropogenic effect of the fossil fuel burning on climate is not considered in this Chapter. It is sufficiently covered by IPCC (2001). Uncertainties associated with changing the chemical composition of the atmosphere are discussed in 3.2 and 3.6.3. Possible societal reactions to this change are addressed in 3.4. The focus of this chapter is on the feedbacks that emerge when climate and terrestrial ecosystems interact whatever other "external" forcing may be.

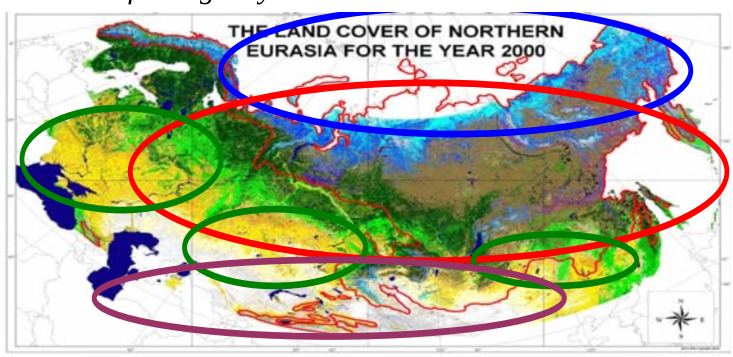

Figure 3.5.1. Present land cover of Northern Eurasia (Figure 1.1), boundaries of Cold Land Regions (thin red line; Figure 3.6.1), and schematic outline of four major ecosystems that will be discussed in this chapter: Arctic desert and tundra (blue), boreal forest (red), steppe/forest steppe/agricultural land (green) and desert and semidesert environment (brown).

3.5.1. Major relationships that define interaction of climate and ecosystems in Northern Eurasia

3.5.1.1 Major feedbacks

Statement of the problem. Terrestrial ecosystem-weather/climate interactions can be interpreted in terms of natural biogeochemical and biogeophysical feedbacks (Claussen et al., 2004). The biogeochemical feedbacks are associated with changes of terrestrial biomass, soil chemical properties, and microbiology and, thus, with changes of the chemical composition of the atmosphere. The biogeophysical feedbacks directly affect surface and near-surface energy, water, and momentum fluxes via changes in surface albedo, roughness, moisture availability for evapotranspiration, etc. More frequently, the biogeophysical feedbacks are the primary processes and are more "visible", while the biogeochemical feedbacks are secondary ones, being the function of biogeophysical processes. This partition is rather conditional: (a) The same process can control different feedback mechanisms[35] and (b) a non-

[34] We observe a summarizing effect, let's say, a decrease of wind over European Russia (Belokrylova 1989; Starkov et al. 2000), but cannot explain whether this is a result of weakening westerlies (cf. Figure 3.3.2) or of changes in landscape (e.g., reforestation). Furthermore, this reforestation in European Russia appears to be anthropogenically forced (abandoned agriculture lands as it is clear from the same figure) instead of a natural forest regeneration.

[35] e.g., the Leaf Area Index (LAI) change or stomatal conductance control both CO_2 exchange and transpiration (Monteith, 1975, 1976; Bihele et al., 1980; Mooney et al., 1999; Baldochii et al., 1996).

linear character of the ecosystem-climate interactions frequently manifests itself as a synergetic effect of all factors and individual feedbacks thus making partition meaningless (Berger, 1999, Ganopolski et al, 1998). But, while biogeochemical and biogeophysical feedbacks could be closely related, their direct interactions could be quite minor (Claussen et al. 2001; Claussen, 2001). There are still a lot of uncertainties in efforts to reveal the synergetic and resonance effects of various feedbacks, the major non-linearities, and areas of local equilibrium in the ecosystem-climate relationships. In different geographical regions, seasons, and times of day, different feedbacks may dominate and the same feedback may be of opposite sign and varying strength. Feedbacks and their dynamics may manifest differently on different spatial and temporal scales and thus determine the long-term climate (ecosystem and biome levels) change and short-time weather (ecosystems) variability in different ways[36]. Short-term variability of ecosystem responses to weather/climate variability (including extremes) is caused by physiological processes in the plant component of the ecosystem[37] and by reversible changes in physical and chemical soil processes. The long-term variability and changes in ecosystem responses to climatic changes are caused by biological processes (growth and loss of above- and below-ground biomass), by decomposition processes within the ecosystem, by stable changes of species composition and vegetation cover structure, and by changes in soil properties. It is clear *a priori* that large scale and long-term changes in climate (biome) should impact biome (climate) (Botkin et al., 1992; Gutman, 1995; Claussen et al., 1998). But, these impacts frequently reveal themselves in short-term events such as fires, dust storms, floods, windthrow, landslides, droughts, excessive soil moisture, thaws, ice jams, etc. Imperceptible accumulation of quantity (e.g., gradual drying or temperature rise) then qualitatively manifests itself in an extreme event (that old-time residents cannot recall) or in a changing frequency of such events. An opposite scenario may also occur. A sequence of strong regional feedbacks during short periods of time (e.g., high vegetation mortality during droughts) may then (a) determine the multi-seasonal and inter-annual variability of both the ecosystem *and* climatic system, (b) enhance spatial gradients and instability of the atmosphere boundary layer, (c) affect the ecosystem stability and its immediate and delayed responses to the climate impact, and finally (d) the changed ecosystem feeds back to the climatic system. Furthermore, feedbacks manifest themselves in interactions of vegetation, atmosphere, hydrosphere, cryosphere, and soil, each having very different inertia (response times to forcing). Thus, the total ecosystem response to climatic changes becomes non-linear and can be unexpected. This volatility makes the study and projections of ecosystem-climate interactions extremely difficult.

Biogeochemical feedbacks. At present, using models and experiments in controlled environmental laboratory chambers, the direct and indirect effects of CO_2 increase on photosynthesis, vegetation growth, transpiration, and mineralization of soil organic matter are sufficiently studied. However, the long-term effects of the CO_2 enrichment at the ecosystem level are still unclear[38]. We still have insufficient information about the synergistic effects of changes in atmospheric CO_2 concentration, temperature, and nitrogen deposition on the ecosystem- and biome-scale responses[39]. According to Claussen (2004), classical biogeochemical feedbacks are based on an assumption that, in a warmer climate, there will be an intensification of bioproductivity, $B+\Delta B$, and thus a sequestration of some fraction of the anthropogenic CO_2 will occur. For example, boreal forest located in the regions of greatest

[36] E.g., Braswell et al., 1997; Pielke et al., 1998; Raupach, 1998; Loehle, 2000.
[37] E.g., Irvine et al., 1998; Maercker-Maier 1998; Varlagin and Vygodskaya 1993.
[38] Schlesinger, 1988; Schlesinger, 1997; Schulze and Mooney, 1992; Hättenschwiler and Körner, 1996; Norby et al., 1999, Mooney et al., 1999; Ellsworth, 1999; Arneth et al., 2002.
[39] Aber and Driscoll, 1997; Churkina and Running, 1998; Lloyd, 1999; Mund et al., 2002.

warming *and* a general surface heat deficit is a primary candidate for this *negative* feedback. But, several constrains (unresolved questions) are attached to this assumption:

- What if the area of the boreal forests changes with climatic change? If the answer to this question is positive, the product of the area of this change, ΔS, and $(B+\Delta B)$ can then be *positive or negative* and will oppose or enhance the effect of ΔB. This alone makes the summarized sign of this particular feedback undefined.
- What if, with the temperature increase, the rates of respiration, transpiration, decomposition of dead biomass and soil organic material, and the rate of release of methane and CO_2 from soil increase (especially from the thawing permafrost, 3.6.1)[40]? Northern Eurasia, and particularly its boreal forest zone, tundra, and wetlands have the largest carbon soil pool in the world (3.1.2, 3.1.3, and 3.2). The changes in these rates may generate a potential runaway scenario of a strong positive biogeochemical feedback[41].
- What if, with time, the influence of some of these factors saturate (e.g., bioproductivity growth), and exhaust (e.g., carbon-rich layers decompose), while others enhance (e.g., changes in forest fire and windthrow areas, thawing of new areas with permafrost)? This raises the temporal factors (dynamics) as a critical issue of actual changes in this feedback.
- What if the forthcoming changes affect biomass and biodiversity of microbiota that control the biogeochemical cycle on various spatial and temporal scales[42]? Not much is known about the consequences of these changes especially for the ecosystems in Northern Eurasia.
- What if the changes in biodiversity associated with changes in both climate and land use affect trophic links within the ecosystems and thus interfere with the major biogeochemical feedback[43]?

And, finally,

- What if other changes in the ecosystems of Northern Eurasia associated with climate change, HA, and biogeophysical feedbacks interfere? For example, a changing rate of disturbances (e.g., forest fires, Figures 2.17 and 3.5.5) and changes in the water cycle (Figures 2.9 through 2.16) directly affect bioproductivity, soil and the wetland carbon pool.

Other substantial biogeochemical feedbacks in Northern Eurasia are related to changes in soil acidity and nitrogen deposition due to industrial pollution[44]. Anthropogenic impact may substantially enhance or weaken the major biogeochemical feedbacks. It may affect N pools and stimulate accumulation in the biomass and soil of phosphorus, sulfur, and heavy metals (3.2 and 3.4). For example, acidification of soils due to a long-term biogenic and microelement pollution at some types of soils can stimulate tree growth (Mund et al. 2002),

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[40] Dadykin, 1952; Grier, 1988; Dyer et al., 1990; Gorhman, 1991; Tzelniker et al., 1993; Inoe et al., 1995; Christensen et al., 1995, 1999; Kirschbaum, 1995; Krankina and Vinson, 1995; Borman et al., 1995; Hobbie, 1996; Ryan et al., 1997; Goulden et al., 1998; Vedrova and Mindeeva, 1998; Liski et al., 1999; Panikov and Dedish , 2000; Janssens et al., 2001; Bird et al., 2002; Buchman, 2000; Valentini et al., 2000; Vygodskaya et al., 2002.

[41] E.g., Moore and Roulet 1993; Schulze et al. 2001; Friborg et al. 2003.

[42] Finlay et al. 1997; Schiemel and Gulledge, 1998; Schiemel and Clien, 1999; Buchman,2000; Santruckova et al., 2000, Wardle 1998, Chernov 1980; Warde 1998.

[43] 3.2, 3.4; Archer et al., 1995; Archer et al., 2001; Baranchikov et al., 2002; Chapin et al., 1996; Collatz et al., 1998; Heywood and Watson, 1995; Hooper and Vitousek, 1997; Lovelock, 1994; Krivoluzky and Pokarzhevsky, 1986; Naeem et al., 1994.

[44] 3.4; Karpov, 1983; Schulze, 1989a; Schulze et al., 1989b; Kuhlusch et al., 1991; Berendse et al., 1993; Godbold and Hutterman, 1994; Kaipiainen et al., 1995; Holland et al., 1997; Berg et al., 1999; Schulze et al., 2000a, 2000b; ; Renn et al., 2001; Gravenhorst et al., 2002; Mund et al., 2002.

but negatively affect lichen and mosses. The anthropogenic impact upon the ecosystems can have cumulative features and reveal itself (and feed back) with a prolonged delay due to biochemical and phitocenogenic structural changes in the ecosystems. Furthermore, changes in the biogenic non-methane hydrocarbons in the atmosphere have an anthropogenic origin (Fexsenfeld et al., 1992; Guentther, 1997). Non-methane hydrocarbons play an important role in catalyzing the formation of tropospheric ozone and photochemical smog and indirectly (via various chemical reactions) influence the resident time of the greenhouse gases in the atmosphere (3.2). *A combination of factors, conditions, and links makes it very difficult to answer the question about the final sign and the magnitude of the terrestrial ecosystems - climate interactions that are loosely named "biogeochemical feedbacks".*

Biogeophysical feedbacks. Vegetation is the most variable component of each terrestrial ecosystem, except deserts. Effects of vegetation and soil changes on the surface energy and water cycles are named "biogeophysical" feedbacks. There are general effects of vegetation on albedo (usually, the presence of vegetation decreases it)[45] and on surface roughness (usually, the presence of vegetation increases it). Vegetation may generate meso-scale effects of advection and turbulence due to spatial heterogeneity[46]. It enhances regional precipitation and evaporation (Rauner 1972; Pielke 2001). It controls the land structure, preventing erosion as well as affects smoothing of the near-surface temperature gradients. Vegetation provides shade, affects surface energy balance (Figure 3.5.2), controls evaporation, runoff, soil

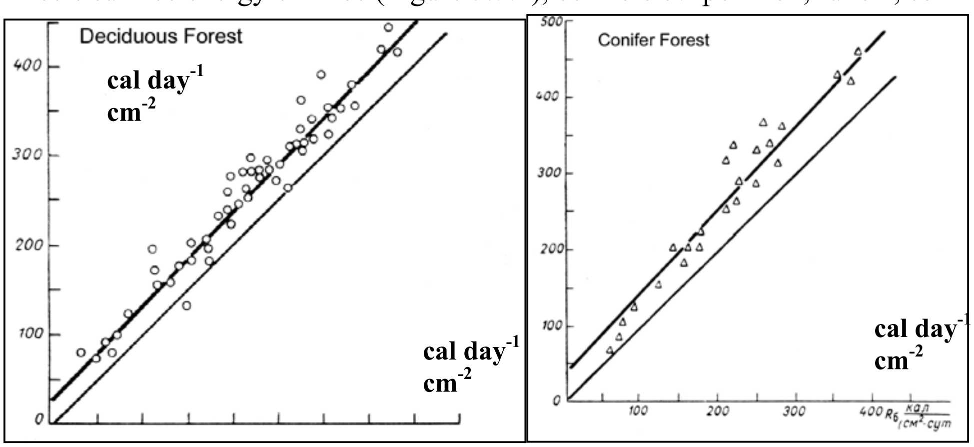


Figure 3.5.2. Radiation balance of forested (RB_f) versus nearby forest-free (RB_0) sites (Rauner 1972). Original units in this graph (cal day^{-1} cm^{-2} = 0.48 W m^{-2}). After conversion in Si units in the regression approximation, $RB_f = a\ RB_0 + b$, parameter values are:
for conifer forest: a = 1.10; b = 20 W m^{-2} and for deciduous forest: a = 1.05; b = 15 W m^{-2}.

moisture, snowmelt, and a partition between sensible and latent heat losses. Vegetation of different species composition, age, and density exercise these effects differently in different parts of the year and different times of the day[47]. The direct effects of changing land cover and spatial mosaic then manifest themselves in temperature, the hydrological cycle, and atmospheric circulation, thus extending the impacts beyond the region where vegetation is

[45] Vegetation decreases albedo of most surfaces except dark wet soil (Ross 1975; Vygodskaya and Gorshkova 1987), but this decrease is the most spectacular for snow-covered surfaces. This feedback is positive: the more vegetation => the more absorbed solar radiation => the further vegetation growth/advance can be expected along the border between tundra and taiga if water and nutrients supply is sufficient (Berger 2001).

[46] Jacobs and Bruin, 1992; Pielke and Avissar, 1990; Fitzjarrald and Moore, 1992,1994; Raupach, 1991,1998; Sogachev et al. 2002.

[47] Geyer and Jarvis, 1991; Galenko 1983; Hollinger et al. 2002; Baldocchi et al. 2001; Kelliher et al 2004; Valentini 2003b; Vygodskaya 1981.

changed[48]. These changes in turn may feed back to vegetation. On a global scale, the biophysical land atmosphere coupling due to (a) interactions between vegetation and snow[49], (b) desertification process (Zolotokrylin 2003), (c) interactions between vegetation and bare soil or between different vegetation types (Charney, 1975; Chase et al. 2000, 2001; Narisma et al. 2003), and (d) variation of sensible and latent heat fluxes (Chapin et al. 2000) are the primary paths of interaction between land surface and the atmosphere in Northern Eurasia. Variable non-linear interactions in the system weather-vegetation-soil moisture cause major feedbacks on a global scale that may contribute to intransitivity of the climatic states (Claussen et al. 2004).

Hydrology-vegetation feedbacks constitute a special subclass because it is impossible to allocate these interactions *a priori* to one of two feedback classes. Water deficit controls the vegetation growth and can completely suppress it causing numerous feedbacks to the surface energy and water cycles (SEWC) and the biogeochemical cycle (BC). The abundance of water above the normal vegetation needs can also be harmful and cause a different set of feedbacks to both SEWC and BC. These feedbacks may be considered as principal ("hot spots"), determining chains of specific biogeochemical and biogeophysical processes depending on regional climate and ecosystem type. A few examples in Box insert 3.5.1 illustrate the volatility and complex character of these feedbacks for the forested land in Northern Eurasia. In the semi-desert, steppe, and forest-steppe zones, the water availability is a major factor that restricts vegetation growth. Thus, hydrology-vegetation feedbacks in these zones are more predictable, although can be non-linear and/or generate an intransitive chain of changes (Claussen 1998; Zolotokrylin 2003). In different ecosystems/climatic zones and under different scenarios of external forcing, these feedbacks manifest themselves with varying strength and sometimes even with an opposite sign. The final consequences (changes) resulting from the climate and ecosystems interactions depend upon all factors and processes involved in the interactions. These processes are interrelated, overlap, may generate similar consequences *initially* and then split off, or may prevent each other from occurring for a while and then may enhance each other. Observations will report the summarized changes, but in order to *explain them,* assess their predictability, *and (if possible) project* into the future we need to have reliable, process-oriented models of each of these feedbacks. Figure 3.5.3 provides an example of when an expected sign of summarized effect due to one feedback changes due to a synergetic impact of another feedback.

Box insert 3.5.1. Hydrology-vegetation feedbacks in forests of Northern Eurasia.

1. In the dry climate of central Siberia, there is a high probability of fire and forest post-fire successions (Stocks and Jynham 1996; Furyaev et al. 2002). If summer temperatures increase here *without an adequate increase in precipitation*, these probabilities would further increase and fire would be the major vegetation feedback to the increasing water deficit. Among the anticipated changes, there will be accumulation of black carbon borrowed temporarily from phytomass and yet, N-pool changes (3.2, 3.6.3; Kuhlbush and Crutzen, 1995; Wirth et al., 2002; Schulze et al., 1999). Thus, hydrology-vegetation feedbacks in this region would cause increased atmospheric levels of aerosols and additional CO_2, biomass reduction in soils and the ground layer (thus, biogeochemical feedbacks to both climate and future vegetation growth), changes in albedo (mostly increase but could also be a decrease in summer, after a strong fire), increase in sensible heat fluxes and reduction in latent heat fluxes, reduction of local surface roughness, and increase the spatial inhomogeneity and thus the regional surface roughness (i.e., biogeophysical feedbacks) [Claussen 2004; Avissar et al. 2004]. It is worth noting that (a) during the past century regional changes followed this scenario (3.5.2) and (b) an adequate increase in precipitation and thus, the reduction of the probability of fire would cause an opposite sequence of feedbacks *and* a set of

[48] Pavlov 1984; Jarvis 1995; Sellers et al. 1997; Baldocchi et al. 2000.
[49] Otterman et al. 1984; Harvet 1988,1989; Bonan et al. 1995; Lynch et al. 1998; Sturm et al. 2001.

new feedbacks would emerge (e.g., changes in decomposition rates of dead above- and below-ground biomass, new successions, and new black carbon pool; 3.1, 3.2, Inoue et al. 1995; Panikov and Dedish 2000; see also item 4 below).

2. In relatively humid West Siberia, which contains the major areas of peat bogs, the same hydrology-vegetation feedback *in the case of the drying climate* would likely reveal themselves in an increase of evaporation (biogeophysical feedback) and the bog water table dropping. These processes would be followed by decreases in biomass, LAI, photosynthesis, and the water use efficiency. The large areas of drying bogs in the boreal forest zone would cause an albedo increase (biogeophysical feedback). Consequently, an increase in albedo and total ecosystem respiration would promote bog transformation from a CO_2 sink into a CO_2 source, a decrease of peat accumulation, and an additional methane release into the atmosphere (thus, biogeochemical feedbacks, 3.2).
3. In the forest zone of European Russia, *in the case of the drying climate*, responses of both forest and bog ecosystems similar to the above may be anticipated (Figure 3.5.3). An increased probability of forest fires could occur here, although, on moist soils of a heavy clay structure, a probability of ignition and fire distribution is low compared to that in Siberia (Korovin and Zukert 2003). Moreover, the non-linear responses of CO_2 exchange in moist boreal forests to droughts may be surprising, going from a CO_2-source to a CO_2-sink (Figure 3.5.4c).

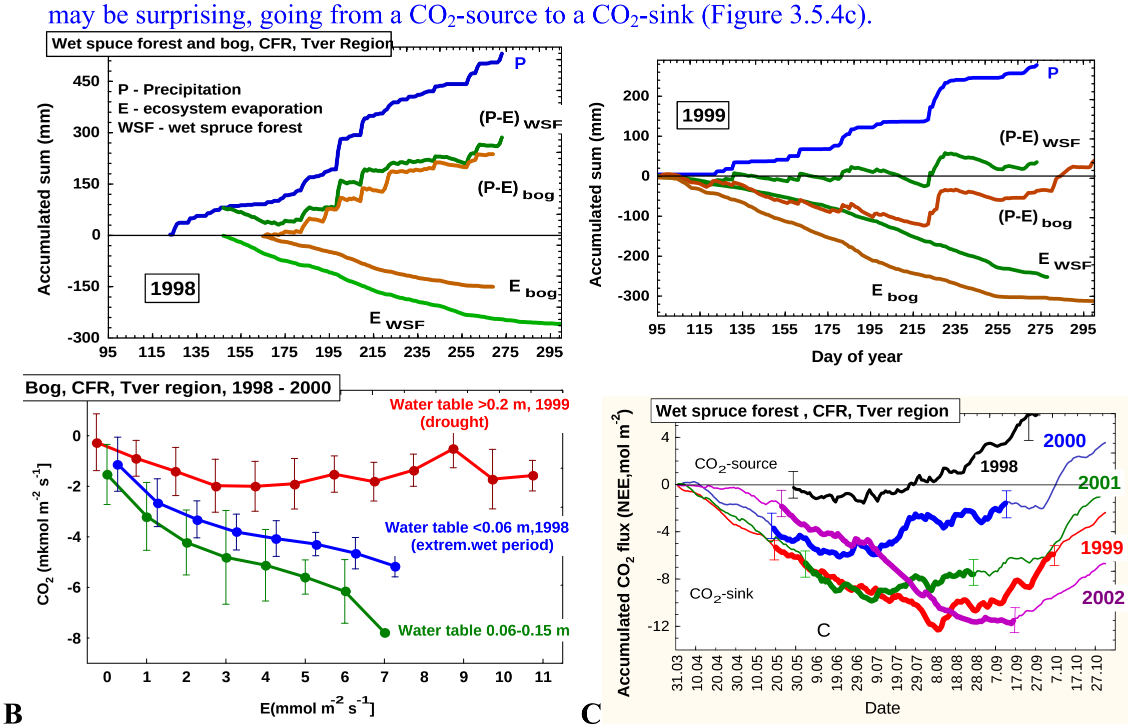


Figure 3.5.3. Two typical boreal ecosystems in wet European southern taiga, unmanaged wet spruce forest (WSF) and bog, during dry (e.g., 1999, 2002) and wet (e.g., 1998) years (Tver', 56^0N, 33^0E, Russia). Interannual variability of ecosystem water balance and evaporation (a), CO_2-fluxes and evaporation rate (b), and Net Ecosystem Exchange (NEE) (c) for 1998-2002; positive CO_2 flux stands for source to the atmosphere (archive of the Eurosiberian Carbonflux Project). In (b) vertical lines depict standard deviations while in (c) periods of active spruce vegetation. Water balance (P-E) is very different in dry and wet years and in dry years evaporation from bog is higher than from WSF while usually the opposite is true. In dry years on bog [P-E < 0; water table is above 0.2 m, red line in (b)], E is high (up to 10-11 mmol m-^{2} s^{-1}), but transpiration and CO_2 assimilation are suppressed. Thus, bog has practically neutral daytime carbon balance and become a CO_2-source due to positive nocturnal CO_2-fluxes. When P-E > 0 and water table is high or average [blue and green lines in (b)] bog is a CO_2-sink. Surprising is the influence of dry conditions on the NEE of the wet spruce forest (c). Opposite to bog, WSF is a CO_2 sink during dry growing seasons (1999 and 2002) when soil water content in the upper 20 cm (root zone) is below 0.4 m^3/m^3 . The different reactions to drought for bog

and WSF are because the lead change in dry conditions on bog is a decrease of the CO_2 assimilation while in WSF with dry soils respiration goes down. During the wet years (soil water content in the upper 20 cm above 0.75 m^3/m^3), forest is a CO_2 source. This result shows that during the growing season overmature spruce forests may act in both ways as CO_2 source and sink.

4. When *weather conditions become wetter*, soil moisture increases and the water table rise causes the bogging of large areas of boreal forests that are on heavy clay soils or on permafrost (Rode 1964). However, ecosystem resistance to heat and water supply alterations depends, to a great extent, on a root system type of dominant species. So, the spruce forests with surface root systems are potentially most vulnerable to soil moisture changes. Bogging combined with local storm winds cause stand destruction (windthrows) followed by secondary successions (Vygodskaya et al. 2002, 2004). Windthrows followed by decomposition of dead wood generate an additional CO_2-source for the atmosphere (Knohl et al. 2002). Therefore, for the regions where the wetter conditions prevail, soil moisture-vegetation interactions become a key feedback. Moreover, the role of these interactions as a potential destructive factor may considerably increase here if the probability of extreme weather conditions increases (Vygodskaya et al. 2002).

3.5.1.2. Areas of sustainable development of ecosystems

A general ecosystems' impact on climate looks like a buffering factor. In high latitudes, vegetation serves as an additional blanket (Figure 3.5.2) that warms the surface. In arid regions, vegetation cools the surface, promotes nocturnal condensation, increases air humidity, and makes life conditions there more tolerable. Autocatalytic effects (positive feedbacks) related to vegetation include wetland and black and podsol soil development, while regulatory effects (negative feedbacks) are observed in the system vegetation-permafrost. Like living creatures, ecosystems generate resilience to extremes or even use them to their advantage in the long run. But, this resilience is not unlimited. When forced, changes in a sequence of successions occur along the following scheme:

> *First, quantitative changes start due to climatic change or changes in the disturbance regime. They affect functional plant ecophysiology and major functional relationships and, thus, the structure of vegetation cover. The species' reaction to the changing environment is defined by their physiological lability. At that time, a replacement of less competitive species by more competitive species occurs under new environmental conditions. Then, finally, stable changes of species compositions and formation of a new ecosystem occur. This looks like a "vegetation shift" because seeds of plants typical of other ecosystems gradually "invade" the area.*

Spatial distribution of ecosystems and their composition is defined by the ability of species to adapt to the environment and to tolerate possible disturbances/extremes. An example of climatic limits of the major boreal ecosystems in Siberia is provided in Table 3.5.1. These types of tables exist for each large region and show typical plant requirements for the main ecological resources - warmth, water, and cold tolerance within each ecosystem. In addition to these basic climate requirements for the ecosystems' survival, bounds for weather variability (its level should be tolerable), air quality (some levels of air pollution are deadly), nutrient availability (3.2), and water supply quality (e.g., level of mineralization) restrict the wellbeing of the ecosystems (3.1). When external forcing and/or feedbacks move a particular ecosystem close to these bounds, they are in danger. If and when one of these limits is crossed, the ecosystem starts degrading and a process of its replacement with a new one accelerates. The follow up changes may have precipitous and, frequently, intransitive character: mountain deglaciation, desertification, forest retreat in refuges, and soil erosion and deflation (Zolotokrylin 2003; Kozharinov and Puzachenko 2002, 2004; Vinogradov et al. 1996; Jaskovski, 2002). In addition to slow changes caused by climate trends, the shift may happen quite swift as a result of disturbances (extreme weather event, prolonged drought or surplus wet conditions, fire, permafrost degradation, windthrow, and/or insect infestation) or anthropogenic impact (logging, ploughing up), after which the old ecosystem does not recover, ceases to exist, and gives way to a new ecosystem.

Models of terrestrial ecosystem dynamics[50] do include these boundaries explicitly. Therefore, the correct input information is a prerequisite for these models. This information will allow tuning models of terrestrial ecosystem dynamics for the region. Then these models can be used for reproduction of the past and present ecosystem dynamics and biome shifts in Northern Eurasia, for assessment of their predictability, and for projections into the future. ***The major task for the future, though, is (a) to collect the necessary input information and (b) to make a viable blend of these models with contemporary global change models that allow all major feedbacks to manifest themselves simultaneously and provide a required synergy of all kinds of interactions.***

Table 3.5.1. Climatic limits for major Siberian ecosystems (Tchebakova et al. 2003). Three basic characteristics: – needs for heat resource expressed in positive degree-days above 5°C (GDD_5), drought resistance characterized by the annual moisture index (AMI, a ratio of GDD_5 to annual precipitation), and cold tolerance characterized by negative degree-days below 0 °C (NDD_0) are presented. The "undefined" limits mean the current absence of climatic conditions in Siberia that draw the ecosystem to the appropriate limit.

Vegetation type	Heat resource, GDD_5		Drought resistance, AMI		Cold tolerance, NDD_0	
	Lower limit	Upper limit	Lower limit	Upper limit	Lower limit	Upper limit
Tundra	0	<300				
Forest-tundra and sparse taiga	300	500				
Northern dark-needled taiga	500	800		<1.5	>-4500	
Northern light-needled taiga	500	800	>1.5			<-4500
Middle dark-needled taiga	800	1050		<1.5	>-3500	
Middle light-needled taiga	800	1050	>1.5			<-3500
Southern dark-needled taiga and birch sub-taiga	1050	1250		<2.25		
Southern light-needled taiga and sub-taiga	1050	1250	>2.25			
Forest-steppe	1250	1650		<3.25		
Steppe	1250	1650	>3.25			
Broadleaf forest	1250	1650		<1.5		
Temperate forest-steppe	>1650		1.5	3.25		

3.5.1.3. Key regions.

In the context of global climate changes, the main attention should be focused on the most vulnerable ecosystems and to "hot" positive feedbacks, or feedbacks which, when initiated, may cause non-linear run-away processes in the climatic system and the biosphere. Larger changes in ecosystem-climate interactions across North Eurasia should be expected at borders of major vegetation zones (in transient zones) like forest-tundra, forest-steppe, and steppe-desert and in mountains where strong altitudinal contrasts allow the presence of a variety of ecosystems at short distances from each other. Historically, the changes along these borders were very substantial (Figure 2.18). The changes in these most vulnerable ecosystems can be better appreciated and understood when compared with "etalon ecosystems" located in the

[50] E.g., Shugart et al. 1992; Kellomaki et al. 1993; Solomon and Kirilenko, 1997; Kirilenko and Solomon, 1998; Kirilenko, 2001; Bonan 2002; Chapter 5.

“center” of biomes where the climate-ecosystem interactions are closest to the equilibrium state.

Tundra-forest. Under climate changes along the boundary of these two zones, *permafrost-vegetation* and *albedo-vegetation* feedbacks will be among the most prominent interactions. Their potential strengths will be different over Siberia and northern European Russia, depending on present-day climate and its trends, and within different regions, depending on moisture conditions, vegetation types, forest tree species compositions, and LAI[51]. In particular, in western Eurasia, temperature does not restrict the northward forest propagation, but excessive precipitation does. In continental Siberia, the tundra-forest boundary is controlled by temperature. Along the Pacific coast, excessive air humidity restricts the forest growth (Puzachenko, 1982). This is one of the reasons why climate impacts and feedbacks along the tundra-forest boundary in Northern Eurasia are regionally specific and asynchronous (Tanfil’ev, 1896). Active layer depth increase that follows the permafrost thaw along the tundra-forest boundary (as well as right in the middle of these zones) may cause various biogeochemical and biogeophysical feedbacks[52] and vegetation shifts in a chain of interrelated processes (Shugart et al. 1992; Tchebakova et al., 2003; 3.6.1). However, the synergism of these processes is still not well studied and, therefore, the resulting changes in the ecosystem-climate system are not yet clear. The most probable change here predicted by the GCMs simulations is a regional albedo decrease when a low tundra vegetation cover is replaced by a higher shrub and forest vegetation (Bonan et al. 1995; Lynch et al. 2003). This increases a regional warming, i.e., provides a positive (biogeophysical) feedback. When forest and forest-tundra vegetation are replaced by tundra vegetation, the same positive feedback accelerates the regional cooling.

Forest-steppe. In southern Northern Eurasia, along the border of steppes and forest, *hydrology-vegetation feedbacks* dominate under the insufficient moisture conditions (Girs and Stakanov, 1986; Zherbatiyk et al. 1996; Khmelev et al, 2002). The forest-steppe transition zone moved depending on both moisture conditions[53]. Leaving the HA aside, a decrease in soil moisture causes forest decline. First, deciduous shrub communities replace temperate deciduous forest. Then, the area of grassland within shrubs increases and, finally, grass communities are established (Archer et al. 1995). These successions are followed by a leaf longevity decrease, decrease in LAI and in the total above- and below-ground biomass (Titlianova and Tisarzhova, 1991; Karpachevsky et al. 1994a; Utehin, 1997). Finally, typical forest soils are replaced by typical steppe soils, with decreased carbon and nitrogen pools and lower evapotranspiration (Bihele et al. 1980). A negative vegetation-albedo feedback (conversion of lower forest albedo to higher steppe albedo followed by a further albedo increase in dry steppes on dry soils; e.g., Ross 1975) should slow this transition down mostly in the cold season. The regional albedo may also decrease due to the ravine development and surface roughness increase under soil erosion. A positive hydrology-vegetation feedback, mostly in the warm season associated with additional precipitation decrease (Rauner 1972) and additional surface warming due to an evapotranspiration decrease with decreasing soil moisture, should enhance the ecosystem changes. The total result of all feedbacks may be different if an increased probability of dust storms will be taken into account (3.6.3). Historical and paleoclimatic records indicate a high variability of this specific transitional zone, thus witnessing a prevailing of the positive feedbacks in the zone (3.5.2). While the

[51] Dadykin,1952; Targulian, 1971; Skatveit et al., 1975; Parmuzin, 1979; Bliss et al. 1981; Puzachenko, 1982; Chapin, 1988; Alekseev,1994; Chapin et al., 1996; Vaganov et al., 1999.

[52] Parton et al. 1981; Lefleur 1992; Pavlov 1994; Christensen et al. 1995, 1999; Zamolodchikov and Karelin 1999; Zamolodchikov at al. 1998; McGuire et al. 2002; Chernov 1980.

[53] Tanfil’ev 1896; Krylova, 1915; Berg, 1947; Piavchenko, 1950; Mil’kov, 1952; Dinesman, 1977) and HA (Kirikov 1979; Osipov and Gavrilova 1983; Vinogradov et al. 1996; Serebryannaya 1982.

mechanisms causing the biogeophysical feedbacks in the forest-steppe zone are quite clear (except, probably, the local water cycle processes along the forest – steppe border line), those causing the biogeochemical feedbacks are not. It is unclear how steppe ecosystem production would change, how the C and N pools would change, how the CO_2 absorption from the atmosphere and ecosystem respiration would change, and how the NO and non-methane hydrocarbons emissions would change (Collatz et al. 1998; Fexsenfeld et al. 1992; Guentther 1997). It is currently unknown how all these processes would manifest themselves at regional and global levels.

Steppe-desert, desertification. Interior regions of Central Asia receive most of their water from remote sources via the atmospheric circulation. Variations of the westerlies and the amount of moisture that they are bringing affect the steppe-desert boundary and initiate its movement (3.3.2, Gumilev 1990). Several important biogeophysical feedbacks enhance and/or prevent this process. Advance of the desert (desertification or increased aridity) is a result of interaction between regional processes of degradation of dry lands with positive and negative feedbacks related to albedo and precipitation changes. The analysis of surface heat balance observations in Northern Eurasia reveals a negative correlation between albedo and surface temperature in arid areas where the radiative mechanism of surface energy exchange is dominating (Zolotokrylin 2002, 2003). Semi-arid areas differ from the neighboring territories by increased variability of energy fluxes and a decrease in correlation between albedo and surface temperature. There is a threshold albedo determined by vegetation of semi-arid areas. If the albedo is above the threshold value, the evapotranspiration regulation of surface temperature is changed into a radiative one, which increases aridity and is a precursor for desertification. This threshold is close to "a point of no return" when desertification begins. Variations of precipitation distribution also control the desertification process, but high boundary layer temperatures make precipitation less probable. Thus, both the decrease of total precipitation and the frequency of low intensity precipitation events predetermine the desertification process. Aeolian erosion of the fertile upper soil accompanies the final stage of desertification causing both biogeophysical (aerosols, albedo) and biogeochemical (e.g., pollution of downwind areas) feedbacks. While steppe areas are a weak carbon sink (Titlyanova and Tesarzhova, 1991), NPP in desert and semi-desert areas is negligible (Bazilevich 1993). While the desertification can occur in a few years, the rates of the reversal of deserts into steppe are unclear. Historical evidence and the past decade in the Near-Caspian lowlands show that grassland advance into desert, when the climate conditions become favorable (i.e., more precipitation), could also be quite quick.

Forest zone. The forest zone is the largest within Northern Eurasia. Its impacts on the global carbon balance (3.2) and on surface water and energy cycles (3.3; Figure 3.5.2) are very strong. The zone occupies several climatic zones: from moderate and moist in Europe, to extreme-continental in Siberia, to monsoon in the Far East. Over the forest zone in Northern Eurasia, seasonal and annual climatic changes were, are, and will probably be of different magnitudes and signs. Numbers of dominant tree and ground plant species in the forest zone are limited. But these species have large ecological niches (habitats) and their distributions overlap each other. As a result of the overlapping of different climates, landscapes, and distances from refuges (Kozharinov and Puzachenko 2002, 2004), a great variety of ecosystem types are found in the forest zone which may be doubled, tripled, etc. by their secondary successions after logging, fires, windthrows, and insect outbreaks. From a global viewpoint, the forest zone may be considered as a powerful terrestrial buffer that stabilizes global biosphere-climate interactions. Its buffer role is in preserving a great amount of carbon in forest above- and below the ground biomass, soils, and peat (Karpachevsky, 1981; Karpov, 1983). Therefore, states of forest soil and bog carbon pools are most critical for global carbon cycles. Hydrology-vegetation feedbacks are among the most prominent here. They are region-specific, though, and controlled by nitrogen deposition (Popova, 1983; Berg et al., 1999). It is problematic to find individual ecosystems that are vulnerable to climate changes and thus to find "hot" feedbacks within the forest and wetland ecosystems. This search should be conducted for large regions within the forest zone, varying by current climate and climate trends and variability (cf., Box Insert 3.5.1). One exception, however, exists: in the forest zone with permafrost (i.e., over more than a half of Northern Eurasia and about 65% of Russia, Pozdnyakov, 1986), the *permafrost-vegetation* feedback is of critical importance (3.6.1).

For the forest zone of Northern Eurasia in the framework of ecosystem-climate interactions and biogeochemical feedbacks, the questions connected to causes and effects of forest fires are currently the most investigated (Korovin and Zuckert 2003). Two less understood topics here require special attention:

- Estimates of black carbon pool and its turnover time and
- The possibility that HA can influence the probability of natural fires caused by lightning from convective cloudiness by changing the spatial-non-uniform mosaic of vegetation cover with timber harvest.

For ecosystem-climate interactions in the forest zone, the following questions are among the least investigated:

- *Reactions of water and carbon balance of the wetland ecosystems to changes of climate, possible area changes, and their dynamics*.
- *Process of bogging in the wet areas of the forest zone*. This process is difficult to reverse (Sjors 1961, Pajula 2000) and it leads to cardinal changes in soil properties, development and growth of plants, and in the carbon, water, and energy balances in general. Depending on prevalence of bogging, this process can cause changing the regional albedo. However, the areas of boggy forests across the territory of Northern Eurasia and their dynamics are poorly studied.
- *The changes connected to change of the dominant species after logging and natural succession of the large areas in European southern and middle taiga*. The replacement of coniferous forest with secondary deciduous stands should lead to podsol soil development, to changes of the components of the water, energy, and carbon balances, and to an increase of regional albedo. The question is closely connected to the problem of the overgrowth of the abandoned agriculture land by shrubs and forest.
- *Forest susceptibility to the windthrow*. We have a few data on the areas with windthrow and their dynamics. A time-lag is not clear of when the windthrow areas turn from a source of CO_2 to the atmosphere (due to a decomposition of the dead biomass) into a sink (when, in the course of succession, the photosynthesis rate exceeds the rate of decomposition). Besides, windthrow areas are problematic for the current remote sensing algorithms of the NPP evaluation due to peculiarities of albedo changes.
- *Influence of the soil eutrophication (nutrient pollution) as a result of technogenic pollution on the growth and development of vegetation* in different areas of the forest zone.

Clearly, the importance of all the above processes and phenomena for regional and global climate changes depends on the size of the areas covered with these processes. These areas, although, are not well known, except the notion that each of them can be quite large.

Besides, for biogeochemical feedbacks and carbon balance in the forest zone, one must pay attention to the large areas (more than half of the State Forest Fund area in Russia) occupied currently by mature and overmature stands. Usually, in calculations of the regional carbon budget, their mean annual net ecosystem exchange (NEE) is assumed to be zero (Isaev and Korovin 1997). In fact, the resulting sign of the annual NEE within this large fraction of the forest zone varies from year to year (Milyukova et al. 2002; Vygodskaya et al.

2004; Knoll et al. 2004). Therefore, this sign will depend on the *future* rates of assimilation and total ecosystem respiration and balance between them as well as on *future* ecosystem-climate interactions.

Managed ecosystems. Managed (agrofields, urban environment) and/or maintained (pasture, fallow, managed forest) ecosystems are created by humans. Sustainability of these systems depends on the ability of the society to preserve these ecosystems in a changing world. Large-scale changes in species distribution have occurred under the HA influence in steppe, forest-steppe (3.1), and even over forested lands (e.g., west of the Ural Mountains as a result of secondary successions after massive logging; 3.1). Most managed ecosystems are on a "slope" and would gradually restore their "pre-anthropogenic" status when the human impact is finished. But, the area of these ecosystems in Northern Eurasia is large, they occupy the most fertile land, and have become part of the landscape. Their properties, including numerous feedbacks to climate, differ from those for "natural" ecosystems and thus, are to be studied separately (3.4).

3.5.1.4. Key question

In 3.5.1.1, we summarized the most prominent feedbacks that affect Northern Eurasia and their most obvious direct consequences. Indirect impacts of these feedbacks, by changing regional and global climate and synergetic effects, are too numerous to list. All of the above clearly indicate that, without synergy of all factors and their interactions, it is impossible to estimate *a priori* the actual strength *and sign* of most of the biogeochemical and biogeophysical feedbacks in Northern Eurasia. The corollary is that a thorough parameterization (process-oriented model) of each process involved in these feedbacks should be conducted, tested, and incorporated into a comprehensive suite of physical and numerical models (Chapter 5). Thus, a major **Question arose:** ***What relationships and/or their parameters that describe the above mentioned feedbacks are not yet well understood, are critical, and should be investigated first of all for Northern Eurasia?***

Empirical parameters of dominant plant species habitats and biome-specific parameterizations are the basis for modeling terrestrial ecosystems dynamics (e.g., 5; Shugart et al. 1992; Kellomaki et al. 1993; Kirilenko 2001). The feedbacks listed in 3.5.1.1 and 3.3.2 have a more "globalized" nature and may affect the Earth system far from the "source" and then return the impact to the ecosystem that caused them in a very different way (e.g., as a changed precipitation pattern). Obviously, palaeo-vegetation and palaeo-climate reconstructions coupled with comprehensive models provide the only possible ways of validation of these global long-term feedbacks. Using ecological limits of modern plant species distribution, spore-pollen analyses, ^{14}C-dating, palaeo-vegetation and palaeo-climate reconstructions, archeological artifacts and other methods provide test samples for validating the modern (and future) models with all their complexity and feedbacks. The richer the palaeo and present evidence is about the environmental and climatic changes and the better the models reproduce these dynamics, the more trust can be placed on these models. Then they can be used for assessment of the predictability of the future, then, hopefully, for its reliable projections and for credible assessing of the possible variants of HA to reveal its future harm as well as for testing the adaptation strategies.

3.5.2. Observed impacts of *changes* in ecosystems and climate on each other

[Section was transferred to the Scientific Background Appendix]

3.5.3. Role of the biosphere-climate systems interaction in the projections of the future changes in Northern Eurasia.

3.5.3.1. Future land cover projections based on contemporary GCM projections. What is missing?

The interactions (feedbacks) between the biosphere and global climatic system play a specific role in Northern Eurasia (3.3.2; 3.5.1) that can substantially change the regional environment and global climate. In the two previous sections, evidence on present and past manifestations of these interactions is given. Here we show what may happen in a changing future.

In Figure 3.5.6, which illustrates one of the climate projections, estimates of the future climate conditions were constructed using one of the IPCC greenhouse gas increase scenarios (a1, see more about these scenarios in IPCC 2001) and the output of the Hadley Centre HADCM3GGa1 run (Gordon et al. 2000). They were used as input to the Siberian bioclimatic model (Tchebakova et al. 1993) to generate a pattern of ecosystem distribution corresponding to a new state of the 2090 climate (Tchebakova et al. 2003). All three, the a1-scenario of increase in the greenhouse gases, the GCM run, and the bioclimatic model do not account for many of the feedbacks discussed in 3.5.1.1. Specifically, a team of specialists in radiative forcing had generated scenarios of its changes due to industrial pollution and its sequestration /decomposition with time (Ramaswamy et al. 2001) (a1 is one of them), then climate modelers used it in their transient runs as an input, and, finally, a carefully regionalized bioclimatic model produced the most probable changes in land cover that would be the result of this scenario and the simulated climatic changes. In Figure 3.5.6, the output of one of the GCMs was used, but the use of several other models gave qualitatively similar results (e.g., Monserud et al. 1996). A brief look in Figure 3.5.6 shows sweeping changes in land cover with the warming anticipated in the last decade of the 21st century:

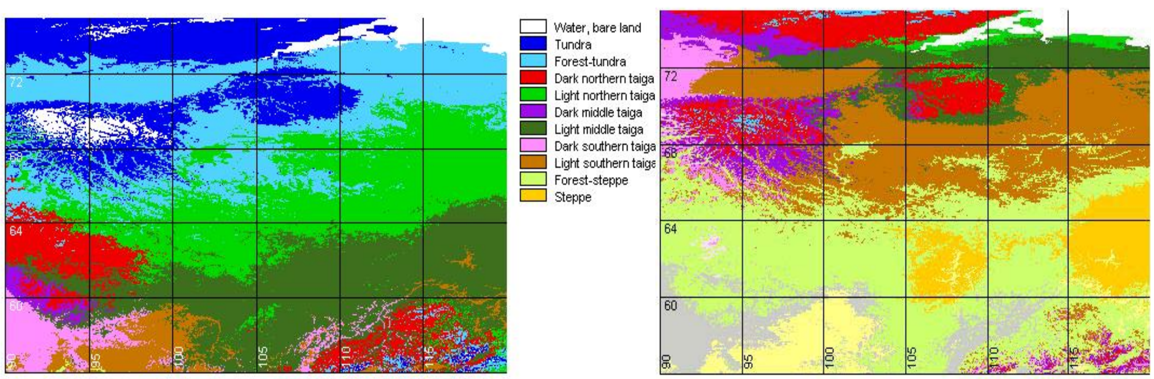


Figure 3.5.6. Major ecosystems distribution in central and eastern Siberia (a) in the current climate and (b) the warmed climate by 2090 derived from the HADCM3GGa1 run (Tchebakova et al. 2004).

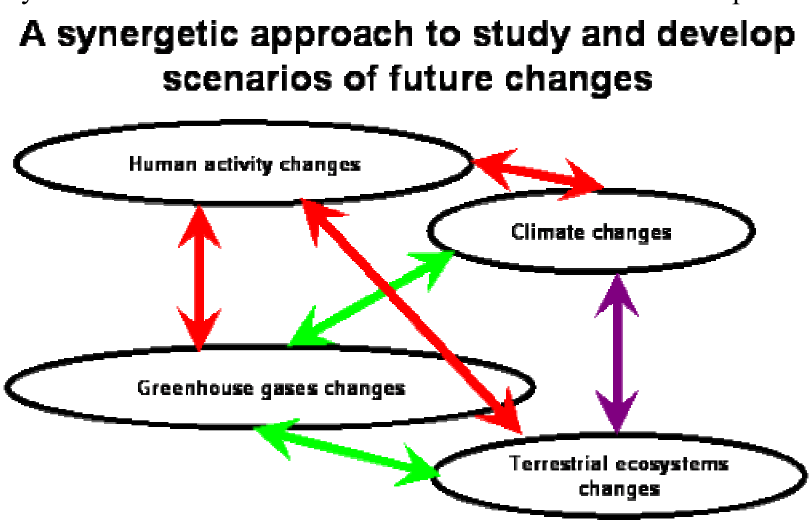
- The tundra and forest-tundra zones (currently ~ one third of the Siberian area) practically disappear;
- Taiga zones (currently about two thirds of Siberia) move northward and reduce to ~40% of the area;
- Steppe, forest-steppe, semi-desert, and desert areas (practically absent now) are projected to occupy up to 45% (forest-steppe) and up to 15% (steppe, desert, and semi-desert) of the area; [large areas of steppe should cover the central Yakutian Plain and the Tungus Plateau, and semi-desert zone would cover a significant area of the Angara Plain].

These estimates broadly correspond to palaeoclimatic reconstructions of two warmer climate epochs of the past: the Mickulin interglacial epoch (122-125K years BP), that was approximately 2°C warmer, and the "climatic optimum of Holocene" (6K years BP), that was approximately 1°C warmer than the present climate (Kobak et al. 2002; the authors suggested that changes in biomes, their areas, and major carbon pools associated with climate warming have occurred quite rapidly as a result of secondary allogene successions). It is unclear if the ecosystem shifts can indeed be as rapid as projected. Probably, the estimates in this figure give us an equilibrium state that would be established if the climatic changes projected by the GCM would be steady. But, it is also clear that there is no such luxury as equilibrium for environmental changes in the 21st century. The climatic system will be on the move, creating instability to the ecosystems' functioning, pushing them toward the other states.

In these projections (and we realize that it is only one of the scenarios that may emerge), it is not clear which effect of land cover changes over the entire Northern Eurasia (tundra-forest transition or forest-steppe transition) will prevail and be more significant for the global albedo. So far, two scenarios may be suggested: (i) higher albedo in southern arid regions would prevail over lower albedo in northern forest-tundra regions with resulting higher global albedo and (ii) global albedo may insignificantly change, compared to current values, if changes in forest-steppe regions will be balanced by changes in forest-tundra. In both scenarios, however, the regional climate conditions should be very different from those generated by the GCM simulation and used to produce Figure 3.5.6. Indeed, a more thorough analysis of this projection clearly indicates that ***for a reliable regional and, probably, global pattern of climate and ecosystem changes, the simultaneous interactive models' runs should be conducted instead of a sequential approach.*** Large-scale changes in land cover (cf., Figure 3.5.6) would generate additional regional forcing (actually, biogeophysical feedbacks), and thus compromising the GCM run assumptions. Furthermore, the changes in biomass, soil and wetlands carbon, and permafrost thawing (that inevitably must accompany such changes) would generate additional and substantial forcings (actually, both biogeophysical *and* biogeochemical feedbacks) on both the GCM forcing *and* the greenhouse scenario itself. In other words, the presently prevailing quasi-linear approach[54] in assessing the future Global Earth System changes:

Human activity changes => Greenhouse gases changes < = > Global Climate System changes => Biosphere changes

should be replaced by a synergic approach (shown in the scheme below) that allows and accounts for numerous feedbacks that modify (and may even reverse) the final state of the Global Earth System as well as affect the modes of HA. The recent attempts to regulate the



This schematic illustrates interactions between components of the Earth system. In this figure, "climate" refers to physical components of the Earth system.

[54] It would be unfair to say that the current approach, including that used in the latest IPCC assessment (2001), is linear. For example, substantial efforts were made to account for the major biochemical feedbacks due to changing climate when terrestrial and ocean sequestration of CO_2 was projected (Prentice et al. 2001, Chapter 3 of IPCC 2001). However, all these estimates were made in an off-line mode with a prescribed climate change "forcing".

greenhouse gases, to control over pollution, changes in agriculture and irrigation practices, and forest management are vivid examples of the changing HA *in response* to the Global Climate System changes. For several reasons outlined above, the amplitudes of the changes in Northern Eurasia in all components of the Global Earth System have been and are anticipated to be among the greatest. ***Thus, a synergic approach for their projections is a must.*** A detailed strategy of this approach is presented in Chapter 5.

3.5.3.2. Transient responses as a new feature of the present century.

When studying the short-term climate- ecosystem interactions, the ecosystem level is appropriate, but for the long-term interactions, scaling-up should be conducted to switch to regional and to global (biome) levels. However, the link between the ecosystem responses to the variability of different time scales is not well understood. It is uncertain how long and intensive the extreme situation or systematic weather/climate anomaly should be in order to influence the inter-seasonal and inter-annual variability of carbon, energy, and water balances. In the changing climate and its future interactions with the biosphere, the conversion of short-term ecosystem reactions into long-term biome responses is among the critical problems[55].

Time is a critical issue while assessing all feedbacks and (in general) the future of ecosystems in the contemporary changing climate. Many of the climate-ecosystem interactions are expanded in time (e.g., slowly developing drought, desertification, growing "new" and old species and their competition, advance/retreat of vegetation). Other interactions occur very quickly (dust storm, fire, windthrow, and flash flood). Some changes are accumulated with time (e.g., lake level and water table, release of methane, thawing of permafrost), while other changes (especially, those associated with HA) follow a step function behavior. Most feedbacks act differently depending on the present state of the ecosystem and the present weather conditions. Timing defines our perspective of future changes (i.e., societal response). For example, one can be pleased to foresee more favorable climate conditions at the end of the 21st century for agriculture. But, if between today and this shining future, the ecosystems (including agricultural fields) would be being non-reparably harmed by soil erosion, industrial pollution, dust storms, forest fires, droughts, surplus wet periods, and floods for several decades, then these conditions will probably be non-beneficial.

Generally, the society should be served by reasonable projections of the future climatic and ecosystem changes decade by decade. Then potentially dangerous consequences of these changes can be mitigated and/or even prevented. Knowing all substantial feedbacks and climate-ecosystem interactions in Northern Eurasia is a prerequisite to these projections for the region and (as it has been already stated in 3.3.2) for the globe. ***Among the major objectives of this Science Plan is a requirement to develop predictive capabilities in order to support informed decision-making and numerous practical applications in the region and thus for the globe. This justifies the major tasks towards this objective outlined below.***

3.5.3.3 Major tasks for studying of the terrestrial ecosystems and climate interactions

These tasks are quite general and seem to not be regional specific. They are, however**,** pressing specifically for Northern Eurasia and important for both the globe and the region, and all five parts of Chapter 3 confirm this (as well as the following part, 3.6, that outlines three more specific areas of research and societal concerns). **These tasks are:**

[55] Continuous long-term direct measurements of energy, heat, water and CO_2 fluxes for major ecosystems (3.2; 3.3; Baldocchi et al., 1996; Lindorth at al., 1998; Joiner at al., 1999; Vygodskaya et al. 2002; McGuire et al. 2002) are required for the realistic solution of this problem. The follow up research should combine these continuous surface flux measurements, the long-term synoptic time series, local process studies, and process-oriented modeling.

- ***To develop an understanding of all major processes and their interrelationship within regional terrestrial ecosystems, climate, cryosphere, and hydrosphere of Northern Eurasia and their interaction with society.*** Particular attention should be paid to the synergy and resonance processes that make this interrelationship non-linear, producing positive feedbacks and run-away scenarios affecting both the region and the globe.

Only having models that reasonably describe and reproduce these processes during the past centuries, we can move forward in the next two tasks.

- ***To establish (restore, develop, utilize) a modern observational system potentially capable to retrieve and properly interpret information about the current state and changes of the environment (ecosystems and climate) of Northern Eurasia.***

Realistically, nobody will substantially change existing in-situ networks and remotely sensed observations. But, the time for simplistic interpretations (such as more precipitation => more runoff; or higher NDVI => carbon sink is occurring) is gone. This system should be based on the understanding of underlying processes with their full complexity. This will show actual gaps in observations and our knowledge and then steps to fill in these gaps should follow.

- ***To develop a regional input (data flux, model blocks, missing parameter values) to contemporary Global and Regional Earth System models, thus allowing for reliable assessment of past and present environmental changes as well as future projections of these changes, and analyses of their impact/interference with society development in Northern Eurasia.***

A particular attention should be paid to areas and ecosystems that are vulnerable and are currently close to the thresholds of their sustainability (e.g., transient zones and most of the man-made systems), as well as to the regions where ecosystem-climate interactions and feedbacks may generate non-linear run-away processes in the climatic system and the biosphere.