Working Paper

Environmental Stress to the Siberian Forests: An Overview

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Foreword

Siberia's forest sector has recently gained considerable international interest. IIASA, the Russian Academy of Sciences, and the Russian Federal Forest Service, in agreement with the Russian Ministry of the Environment and Natural Resources, signed agreements in 1992 and 1994 to carry out a large-scale study on the Siberian forest sector. The overall objective of the study is to focus on policy options that would encourage sustainable development of the sector. The goals are to assess Siberia's forest resources, forest industries, and infrastructure; to examine the forests' economic, social, and biospheric functions; with these functions in mind, to identify possible pathways for their sustainable development; and to translate these pathways into policy options for Russian and international agencies.

The first phase of the study concentrated on the generation of extensive and consistent databases for the total forest sector of Siberia and Russia. The study is now moving into its second phase, which will encompass assessment studies of the greenhouse gas balances, forest resources and forest utilization, biodiversity and landscapes, non-wood products and functions, environmental status, transportation infrastructure, forest industry and markets, and socio-economic problems. This report, by Vera Kiseleva was carried out during her stay at IIASA in 1995 and contributes to the assessment studies in the area of the environmental status of the Siberian forests.

Introduction

The importance of Siberian forests is evident. In a planetary scale, they play a very significant role in maintaining the Earth's climate and atmospheric gas balances. In a regional scale, forests regulate water and permafrost regimes. Siberian forests are habitats for a wide range of animals and plants, many of them are rare and/or endemic. From the economic point of view, they are a large source for the production of timber and non-wood products. In general, they form 20% of the total world forested areas and 50% of the world's coniferous forested areas (Nilsson *et al.*, 1994). Approximately 75% of the Siberian forested area is covered by coniferous species.

Until recently, it has been always thought, that Siberia was huge, its richness was indepletable and it would always provide as much resources, as needed. However, intensive human activities have managed to change the ecological conditions. A rapid industrial development of the territory with no concerns to the ecological problems led to a large-scale mechanical disturbance, to alteration of water and permafrost regimes, to soil and water contamination by oil, heavy metals, phenols, and other substances. In general, according to maps, composed in Russia in 1993, 23 regions in Siberia has "very critical" environmental conditions. Seventeen of them are located in East Siberia and the Far East (Pryde, 1994). Poor air and water qualities, severe health problems, and deterioration of natural ecosystems are characteristic features of these declining regions.

This paper deals with the ecological status of Siberian forests as influenced by both natural and anthropogenic factors. The task of the work is to represent a general estimation of forest decline, to describe the major reasons and tendencies. The influence of industrial pollution is treated in a more detailed manner.

For the analyses, several sources of data were used. The main source was data delivered to IIASA's Siberian Forest Study by the Russian State Committee for Statistics (Roskomstat or former Goskomstat). In addition, data were taken from annual reports of the Russian Federal Service of Forestry and from the USSR National Report on the International Conference on Environment and Development. Difficulties that arose during the work with the databases were partial absence of some urgent data. In addition, experts in different regions of Siberia had different understanding about the ecological changes taken place, which was reflected in the data. Additional information from articles, published in different journals, was included in the analyses and helped to solve the problems to some extent.

To exclude the misunderstanding of terms, some preliminary definitions are needed. The paper discusses both forest die-back and forest damage (excluding dead trees). As a rule, the first case is denoted here directly as forest die-back. The second case is described by the terms decline, damage, degradation, weakening.

The main subjects of this large-scale analysis are the administrative units of Russia – independent republics within Russia, krays and oblasts. For the more detailed studies, administrative units have been divided into so-called ecological regions, or ecoregions, based on natural conditions.

1. General Review of Forest Decline Factors in Siberia

While analyzing the data for the past few years, many reasons of forest damage and decline can be found. They can be roughly divided into two groups: natural and anthropogenic. The most important natural factors are: forest fires, unfavorable weather conditions, insects and diseases. The examination of natural factors as negative ones might be questionable, because, sooner or later, forest ecosystems come to an equilibrium with this kind of disturbances. However, from the point of view of forest management these factors cause regular forest losses and weakening. Anthropogenic factors include different types of human activities, that are not directly connected to timber production (*Figure 1.1*).

In general, one should always have in mind that the influence of different factors is interrelated. For example, stands weakened by fires can be less resistant to some insects or diseases, or weather conditions might intensify pollution effect, etc.

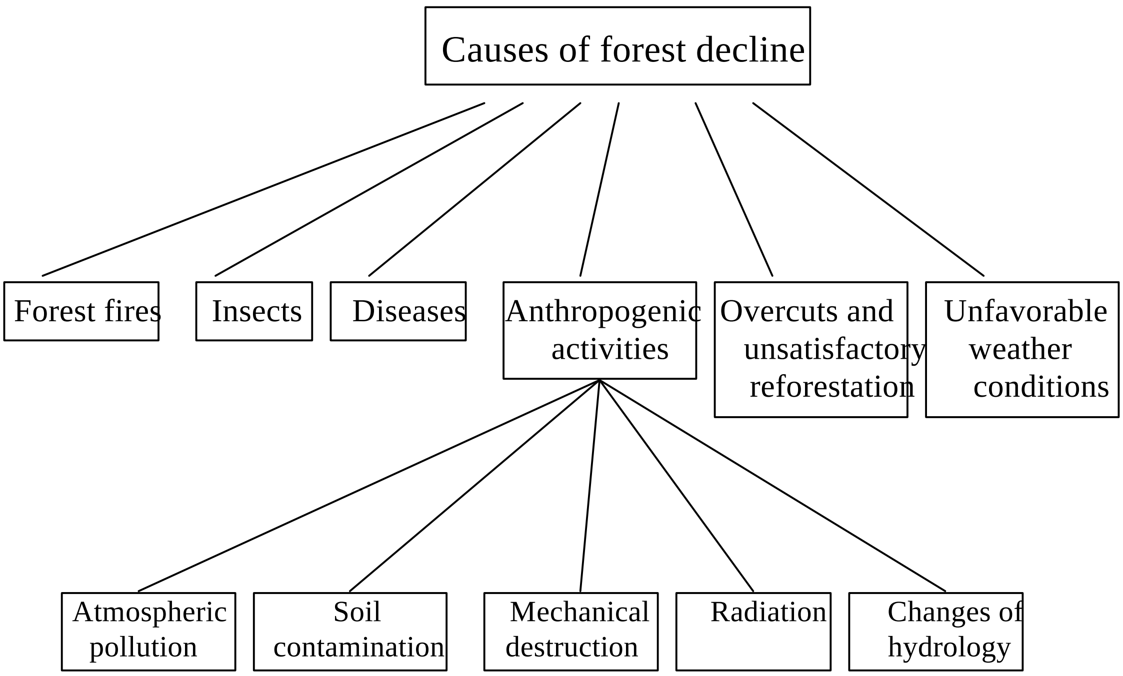

Figure 1.1. Schematic division of forest decline factors.

1.1. Natural factors

According to statistical data for the last 15 years, natural causes of forest decline in Russia as a whole can be ranged by their significance as the following: forest fires (76.8%), unfavorable weather conditions (11.4%), insects (7.7%), damage by wild animals and diseases (4.1%) (*Obzor Sanitarnogo Sostoyaniya…*, 1994).

So, the most important problem is forest fires. According to some estimates, the reduction of forested areas as a result of fires is considered to be 2.5 times higher than that total harvested areas (*Natsionalnyi Doklad*, 1991). Furthermore, the official data on forest decline caused by *fires* are supposed to be severely underestimated. Satellite observations demonstrated that, in fact, burnt areas exceeded those reported statistically by the factor of 2 around Lake Baikal, by the factor of 5–7 in Krasnoyarsk and Khabarovsk krays and even more in Magadan oblasts (*Natsionalnyi Doklad,* 1991). We should also note, that large areas in the northern part of Siberia are not under any systematic fire-monitoring, and many fires in this part are not registered. On other territories, where much attention is paid to forest fires, however, fire protection is problematic due to insufficient equipment and the huge territories to be protected.

Besides the forests burnt immediately by fires, large areas are dried out by the fires, and forest decline occurs there in 3–5 years after the fire occurred (this is especially important for ground fires). For example, in 1990, 23.6 million m^3 of wood was burnt by fires, and 259,400 ha of forest stands died due to drying out (*Natsionalnyi Doklad*, 1991). A correlation was found in the dynamics of forest fires and forest decline, demonstrating a 3-year interval. The most forest fires were observed in 1986 and 1989, and the maximal forest decline (drying out) – in 1989 and 1992 (*Obzor Sanitarnogo Sostoyaniya…*, 1994). This fact gives a possibility to make some forecasts on the decline process.

Figure 1.2 presents the extent of forest fires in 1993 (obtained from *Rosagroservis*, 1994). From the figure it can be seen that the southern part of the Far East is a problematic area from the forest fire point of view, but also the southern parts of West and East Siberia have serious forest fire problems.

Weather is the second and most important factor (after fires) concerning forest decline. The region, where weather influence is most expressed, is in Khabarovsk kray with its special climate (frequent cyclones and storms). During the last couple of years, more than 150,000 ha of forests were lost in the kray (*Table 1.1*), and weather conditions were a dominant factor for the forest decline. Significant forest losses also took part in Krasnoyarsk kray, Novosibirsk oblast, and Primorskii kray.

The distribution of damage caused by insects is of another character (*Figure 1.3*). The most damaged areas are situated in the southern part of Siberia, where warmer weather conditions allow insects to develop. The highest density of insect loca was observed in the Altai region, Novosibirsk oblast, Tuva republic, and Primorskii kray. Relatively high damage is caused by insects in Kemerovo and Omsk oblasts. Taking large administrative units into account, such as Tyumen oblast, Krasnoyarsk kray and Yakutiya, we should note that average values do not represent the real situation. In fact, northern parts of these territories do not exhibit insect invasions because of a severe climate. However, in the southern part of these administrative units harmful insects are quite active. There are several white spots on the map. Most of them are a result of the establishment of new autonomous administrative units, for which data is missing. Another region with missing data is the Magadan oblast, for which there is no proper monitoring.

The highest losses of forests due to insect activities during the period 1989–1993 occurred in Irkutsk, Tomsk and Tyumen oblasts (*Table 1.1*). It is important to note, that, as in the case of fires, a high density of pest loca does not definitely lead to forest die-back. Under some conditions loca can disappear by the influence of other natural factors.

Figure 1.2. Distribution of forest fires in Russia in 1993. Expressed in ha per 1000 ha of forested areas. After **Rosagroservis**, 1994.

Table 1.1. Forest die-back in Siberia caused by different factors during the period 1989–1993 (after *Obzor Sanitarnogo Sostoyaniya*, 1994). Hectares of dead forests of forested areas.

Region	*Damaged by wild animals*	*Damaged by diseases*	*Damaged by human activities*	*Of which air pollution*	*Damaged by insects*	*Damaged by weather conditions*	*Damaged by fires*	*Burnt areas and dead stands** (by 1988)*
Altai Kray	15790	690	0	0	0	0	1132	42000
Altai Rep.*	22	0	3	3	0	579	337	
Amur Obl.	609	0	0	0	0	0	12400	664900
Buriat Rep.	0	0	239	0	0	1622	9072	383400
Chita Obl.	13	0	0	0	0	1212	11349	716200
Irkutsk Obl.	353	44	722	722	2730	352	135242	4428800
Kamchatskaya Obl.	0	0	0	0	0	0	2940	12000
Kemerovo Obl.	6703	0	317	0	18	1817	399	3600
Khabarovsk Kray	50	0	0	0	300	155628	123071	3384100
Khakass Rep.*	0	0	0	0	0	0	0	
Khanty-Mansi AO*	0	0	210	4	0	0	6566	
Krasnoyarsk Kray	0	0	130203	130203	420	55908	131973	3194700
Magadan Obl.	0	0	0	0	0	0	95103	3220200
Novosibirsk Obl.	3911	4	2	2	0	10110	13561	44100
Omsk obl.	0	0	46	46	383	2141	7706	10100
Primorski Kray	1558	0	0	0	0	4316	5327	190200
Sakhalin Obl.	0	0	0	0	0	0	1558	333800
Tomsk Obl.	0	72	17	17	3534	343	21963	280500
Tuva Rep.	0	0	0	0	35	262	13766	215500
Tyumen Obl.	1	0	126	126	18630	572	65631	638600
Yakutiya Rep.	0	0	0	0	0	800	138087	8587500
Yamalo-Nenets AO*	0	0	0	0	0	0	2345	
Total	29010	810	131885	131123	26050	235662	799528	16715200

* – Data only for 1992–1993.
** – After Lesnoi Fond SSSR (1990).

Figure 1.3. Distribution of insect attacks in Russia in 1993. Expressed in ha per 1000 ha of forested areas. After Rosagroservis, 1994.

Figure 1.4. Distribution of forest diseases in Russia in 1993. Expressed in ha per 1000 ha of forested areas. After Rosagroservis, 1994.

The distribution of *diseases* has the same pattern (*Figure 1.4*) – the forests in the northern administrative units do not suffer much from this factor, while southwards the loca of diseases appear. However, a high relative density of damaged forests did not lead to a high extent of forest die-back in this region (*Table 1.1*). The die-back of forests were observed in Altai kray, Tomsk oblast (and with very low loca density) and in the Irkutsk oblast. According to available data, the registered damage by forest diseases is not high. However, the data also probably point out an insufficient monitoring rather than an absence of forest diseases.

1.2. Anthropogenic factors

When an expert estimation of *human impact* was made in Russia, 5 main types of anthropogenic activities were regarded; atmospheric pollution, soil contamination, mechanical disturbances, radiation, and changes of hydrology (*Figure 1.1*). To assess a general ecological status, four degrees of damage were employed: limited damage, less than 10% of studied territory changed; medium damage, when changes had occurred at 11–35% of the territory, severe damage, 36–75%, and extreme; over 75%.

The distribution of anthropogenically damaged areas, as well as the degree of contamination, is uneven across the Siberian territory. In general, some regions of the central and north-eastern part of Siberia do not seem to suffer from any human activities. At the same time, quite a critical situation exists in the Far East or west of Lake Baikal, where a high percentage of forested territories has been anthropogenically changed. Unfortunately, the data about anthropogenic influence, represented in this chapter, are not complete, and it preserves us from any definite conclusions.

Among the administrative units, for which the information is available, it can be seen that the following regions suffer most of all concerning *soil contamination*: Magadan oblast (0.8–1.5% of the forested territory is damaged), the central and southern part of Primorskii kray (1–2.4% of the territory is damaged), Amur oblast (1.6%), and in some ecoregions of Khabarovsk kray, and Sakhalin Island. In Primorskii kray and Sakhalin the scale of damage is sometimes extreme. We should mention extreme soil pollution by heavy metals in Rudnaya Pristan and Dalnerechensk (Primorski kray). In general, heavy metals seem to be the main cause of soil contamination, according to official reports. In Yakutiya and Kamchatka oblast, all the ecoregions underwent changes of forest cover due to soil contamination, however, the changes are not drastic. The data for West Siberia are absent, as well as for Krasnoyarsk kray, where one should expect a high percentage of contaminated soils: in West Siberia – by oil (north of Tyumen oblast), in Krasnoyarsk kray – by gaseous emissions, especially SO_2, and heavy metals (around the cities ofNorilsk, Irkutsk, and Usolie-Sibirskoye).

An important point in soil contamination is *pollution by oil*. Long-term oil spills to the soil leads to the pollution of the whole soil profile, however, horizontal petrol migration is limited (normally polluted area does not exceed 1 km). In accidental cases only the upper soil layers are damaged, however, oil concentrations in soil remain elevated at a long distance from the pollution source (*Natsionalnyi doklad*, 1991). The ecosystems around Surgut and Nizhnevartovsk (Tyumen oblast) are known to be the most problematic area in Siberia from the point of view of pollution by oil.

A specific feature of northern ecosystems is the low intensity of biochemical transformation of organic substances, which is of particular importance in connection with oil pollution. In addition, drastic deterioration of plant cover takes place during oil exploitation, leading to further disturbances of biogeochemical cycles. Critical concentrations of oil products in soils are not established yet, and therefore there are difficulties to estimate the degree of danger.

The set of regions, affected by *mechanical devastation*, is almost the same as the regions discussed above. Among the "leading" regions we should mention Magadan, Amur, Kamchatka, Sakhalin oblasts, and Khabarovsk kray, where the areas of mechanically disturbed forest stands compose from 1 to 2.5% of the whole forested territory. Note that all the ecoregions within these administrative units are involved in mechanical devastation. In many areas, up to 25% of the territory was subjected to extreme influence by mechanical devastation.

In other administrative units, damaged areas are spread unevenly. For example, in Yakutiya the largest disturbed areas are located in the southern part (1.85% of this territory underwent changes). In Tyumen oblast it is the territory between the Ob and Irtysh rivers that is the most damaged (2.5%). The north of West Siberia is not identified in the database, however, as it is one region with intense oil exploitation, mechanical disturbance of natural ecosystems, connected with serious changes of water regimes, involve large territories.

Changes of hydrological regimes seem to be the most wide-spread and the most intensive type of human disturbances. The disturbances are connected with the construction of water reservoirs and hydro-power plants or to road construction and platforms for oil exploitation, altering the runoff. A special situation exists in Yakutiya, where the changes are connected with the gold mining. The Far East territories are altered to the largest extent. In Primorskii and Khabarovsk krays the areas with strongly altered water regimes occupy up to 2.6% of the forested territory, and medium and strong degree of changes prevailing. In Amur oblast 6.7% in the basin of theZeya river is strongly disturbed.

In many other regions (Southern Yakutiya, Krasnoyarsk kray, Sakhalin, Irkutsk, Chita oblasts, Buryatiya Republic) 1 to 2.5% of the forested areas have had changes in the water regimes, mostly to a small or medium extent. In Novosibirsk oblast the percentage of the territory with altered water regime is low, however, two-thirds of the area affected was subjected to extreme changes.

The northern part of West Siberia should also be referred to a region with a high extent of anthropogenic influence. The alteration of water regime is here connected with the construction of roads leading to runoff limitations. The further development of gas and petrol industries in this region might lead to progressing bog formation and serious decrease in forest productivity.

The problem of air pollution will be discussed in some more details later on, however, some general considerations will be mentioned here.

Although industrial pollution is not a major reason of forest decline in general, it is an important item. First of all, forest die-back caused by air pollution contributes to 95% of the anthropogenically induced forest die-back (*Obzor Sanitarnogo Sostoyaniya*…, 1994). Official statistics deal only with forest die-back, and almost nothing is known about the early stages of

forest decline, caused by environmental pollution. Only exceptions are case studies, connected with some big pollution sources.
It is important to point out that most of the Siberian territory has a low potential of self-purification due to unfavorable weather conditions, created in closed valleys. Winter technogenic smogs are quite common. Self-purification of landscapes might proceed through the removal of pollutants with water. In regions with high potential of water flow it might be a basic mechanism (e.g., in the mountainous regions of Altai and Far East). However, in other regions (Trans-Baikal territory) water supply and water flow is limited. East Siberia with its flat plains with limited runoff also has a low self-purification capacity. These conditions lead to a pollutant accumulation within the ecosystems (*Natsionalnyi doklad*, 1991).

1.3. Insufficient reforestation

For all of Russia, reforestation by planting trees takes place at 44% of deforested areas, and with an effectiveness of some 60%. The rest is left for natural generation. Thus, the actual reforestation involves only 25% of cut and burnt areas (*Natsionalnyi Doklad*, 1991). Moreover, primary forests are often replaced by secondary forests by natural regeneration, and the stands thus loose in quality. *Table 1.2* contains a rough description of the situation with the reforestation after harvests. It contains data about territories, left for self-generation, and demonstrates that it is not the most effective way to restore forests. Studies show, that the rate of forest rehabilitation in Russia is 10 times lower than in Western Europe (Quick cash…, 1993).

Table 1.2. Forest regeneration at the territories, left for self-regeneration after harvests (in percent of left areas) (after *Lesnoi Fond SSSR*, 1990).

Oblast	*Regeneration of primary species*	*Regeneration of secondary species*	*Needs artificial planting*
Altai kray	18	60	22
Amur obl.	48	46	6
Buryatiya	28	31	**41**
Chita obl.	29	21	**50**
Irkutsk obl.	39	29	32
Kamchatka obl.	31	30	19
Kemerovo obl.	3	62	35
Khabarovsk kray	57	30	13
Krasnoyarsk kray	35	25	**40**
Magadan obl.	25	0	**75**
Novosibirsk obl.	8	65	22
Omsk obl.	8	57	35
Primorskii kray	60	17	23
Sakhalin obl.	69	10	21
Tomsk obl.	18	55	22
Tuva	24	31	**45**
Tyumen obl.	13	63	24
Yakutiya	47	48	5

Table 1.3. Comparative estimation of damage (including both forest die-back and different stages of decline), caused by natural and anthropogenic factors. In percent of forested areas.

Region	*Insects**	*Diseases**	*Fires**	*Weather**	*Air pollution***	*Soil contamination***	*Mechanical devastation***	*Changes of hydrology***	*Burnt and dead stands, total***
Altai kray	2.11	0.0005	0.01	0.02	0	–	–	0	0.83
Altai rep.	2.18	0	0.01	0.01	–	–	–	–	
Amur obl.	0.05	0.0008	0.13	0	0.40	1.30	1.93	3.57	3.05
Buryatiya rep.	0.06	0.01	0.07	0.001	0.55	–	–	1.15	1.89
Chita obl.	0.06	0	0.04	0.003	0.80	–	–	1.25	2.66
Evenki AO	0	0	–	–	–	–	–	–	
Irkutsk obl.	0.07	0.004	0.24	0.01	0.51	–	–	1.02	**8.75**
Kamchatka obl.	0.002	0	0.01	0	0	0.40	0.60	0.8	0.06
Kemerovoobl.	0.13	0.01	0.01	0.01	–	–	0.70	0	0.08
Khabarovsk kray	0.01	0	0.08	0.02	0.06	0.61	1.91	1.55	**6.93**
Khakass rep.	0	0	0.01	–	0	0	–	–	
Khanty-Mansi AO	0.06	0	–	–	–	–	–	–	
Krasnoyarsk kray	0.06	0.00004	0.06	0.003	0.86	–	–	0.44	3.00
Magadan obl.	0	0	0.21	0.0005	–	1.03	1.60	0.70	**14.56**
Novosibirskobl.	1.01	0.08	0.91	0.04	–	–	–	1.10	1.84
Omsk obl.	0.13	0	0.20	0.01	–	–	–	0	0.40
Primorskii kray	0.96	0.01	0.04	0.004	0.53	1.13	0.59	1.60	1.70
Sakhalin obl.	0.0003	0.003	0.02	0	0.05	1.18	1.95	1.60	**6.27**
Tomsk obl.	0.05	0.001	0.04	0.0003	–	–	–	0	1.65
Tuva rep.	1.09	0.002	0.02	0.01	0.03	0	–	0.80	2.73
Tyumen obl.	0.38	0.25	0.02	0.001	–	–	0.69	0.24	2.46
Yakutiya	0.09	0	0.12	0.0001	0	0.27	1.06	0.97	**5.85**

* – Annual long-term average estimations.
** – Long-term cumulative effect (by 1990, last column – by 1988).

1.4. Comparison of the natural respectively anthropogenic damages

If we compare the extent of the influence on the forests by natural, respectively anthropogenic factors, we find that the latter seem to be of the same magnitude as or even exceed natural disturbance (*Table 1.3*). However, there are several uncertainties. First of all, while the estimations of natural factors on forest decline are long-term yearly averages, the anthropogenic damage was described as a cumulative effect. Thus, the information about separate types of anthropogenic and natural disturbance does not provide the entire picture of ecological conditions. Nothing is known about whether areas with different type of damage are overlaid or not. So, the total percent of forested areas subject to anthropogenic influence cannot be obtained.

According to *Table 1.3*, the regions can be divided into two groups. The first one includes the territories where natural causes of forest decline dominate absolutely. They are Altai kray, Altai, Khakass and Tuva republics. The second group includes the regions where anthropogenic factors play an important part, namely, Irkutsk and Kemerovo oblasts, Krasnoyarsk, Primorskii and Khabarovsk krays, some parts of Tyumen oblast (including new independent administrative units) and Yakutiya.

2. Atmospheric Pollution "Climate" in Siberia

Firstly, it should be stressed that the pollution conditions in Siberia is very unevenly distributed. Regions with developed industry form a belt in its southern part, with one specific exception – Norilsk industrial complex, situated above the Polar circle. On the rest of the territory the pollution is created by small local sources or by long-distance transport.

2.1. Input of different branches of industry

Taking the economic regions (West Siberia, East Siberia and the Far East) into account, it can be concluded that the pollution conditions are different in these three big territorial units. First of all, due to the prevailing branches of the industry. The major part of pollution (by weight) consists of solid compounds (dust of different compositions). The main gaseous pollutants (by weight) are sulphur and nitrogen compounds and, regionally, fluorides or chloral compounds. These latter pollutants are of primary interest, as they might be transported long distances, turning air pollution into a national problem. The share of different components of the total pollutant discharge varies from region to region, depending on prevailing branches of industry, existing in a region.

West Siberia is the major producer of oil and gas in Russia, so the prevailing pollutants (about 20% in 1993, according to Goskomstat) are hydrocarbons. In the late 1980s, West Siberia caused more than 80% of the total air pollution of hydrocarbons in the former USSR (Mnatsakanyan, 1992). In 1993, according to the data of Goskomstat, this value was close to 50%. Chemical industry is highly concentrated in this region, providing 50% of Russian phenol-formaldehyde tars and plastic materials and approximately 30% of caprolactam. As a result, the emission of organic compounds is significant (*Table 2.1*).

In East Siberia, there are two areas with high industry concentration – around Norilsk polymetallic complex (north of the Polar circle) and in the Southern part of the region with

Table 2.1. Branches of industry as pollution sources.

Branch of industry	*Emitted substances*	*Total emitted amounts (1000 tons)*	*Regions with the highest share of the industry with pollutant emissions*
Coal combustion	Solids	746.07	Everywhere
	SO_2	704.27	
	CO	86.96	
Polymetallic industry	Solids	219.90	Chita, Irkutsk, Kemerovoobl.,
	SO_2	1945.73	Krasnoyarsk kray, Yakutiya
Cement production	Solids	43.77	Primorskii kray, Novosibirsk, Kemerovoobl.
Oil refining + oil-chemical industry	Hydrocarbons, volative organic compounds	77.54+2.73 81.66+7.21	Krasnoyarsk kray, Irkutsk , Omsk obl.
Wood and paper production	vol. org. comp.,	8.84	Buriatiya, Irkutsk obl.,
	SO_2	39.37	Krasnoyarsk kray, Sakhalin obl.
Major chemistry	Solids	17.07	Irkutsk, Kemerovo, Altai kray
	vol. org. comp.	7.03	
	NO	2.49	
Steel production	CO	373.47	Kemerovoobl., Khabarovsk kray,
	Solids	86.71	Altai kray
	SO_2	70.15	
Machinery	Solids	53.58	Kemerovo, Novosibirskobl., Altai,
	CO	79.74	Primorskii and Khabarovsk krays,
Fuel industry	vol. org. comp.	113.41	Irkutsk obl., Krasnoyarsk kray,
	CO	605.82	Tomsk, Tyumen oblasts
Transport	CO	249.63	Everywhere

various industries (polymetallic, chemical etc.). The main pollutant of the region (after solid compounds) is SO_2 (10–12% by weight in Russia in 1993). Krasnoyarsk kray, being one of the biggest administrative units, occupies the first place in Siberia by total pollutant discharge to the atmosphere. More than 13 million tons of solid substances, 2 million tons of SO_2, 59 thousand tons of volative organic compounds were released to the atmosphere in 1993. Norilsk, with developed polymetallic industry, situated in the northern part of the kray, provides almost 100% of the total SO_2 emission of the kray. Another pollution center is Kansk-Achinsk polymetallic industry and fuel-producing complex, providing more than 90% of total emission of solid pollutants in the kray. Large fluor release is taking place from the Al-processing complex in Bratsk (Irkutsk oblast), while not mentioned in the *Table 2.1*. The rivers of East Siberia are subject to pollution by oil and organic compounds (especially phenols). Many rivers are used for wood rafting, part of the wood is lost, resulting in high phenol concentrations (Mnatsakanian, 1992).

Pollutant emissions by the administrative units of the Far East is relatively small compared to the two previous economic regions (*Table 2.2*). The major concentration of industry (and pollution, respectively) is in the southern part of Primorsky kray and Sakhalin Island. Dust and

Table 2.2. Emission of main pollutants per unit area (ton/km^2).

Oblast	*Solids*	*SO_2*	*NO*	*Total*
Altai kray	0.66	0.44	0.16	**1.82**
Altai rep.	0.02	0.015	0.015	0.07
Amur obl.	0.13	0.09	0.03	0.33
Buryatiya rep.	0.13	0.10	0.03	0.33
Chita obl.	0.21	0.14	0.04	0.53
Irkutsk obl.	0.29	0.24	0.12	1.01
Kamchatka obl.	0.04	0.04	0.02	0.14
Kemerovo obl.	**2.89**	**1.62**	**1.12**	**11.00**
Khabarovsk kray	**0.77**	0.68	0.16	**1.89**
Khakassiya rep.	0.66	0.33	0.11	**1.81**
Krasnoyarsk kray	0.09	**0.86**	0.03	1.07
Magadan obl.	0.11	0.03	0.01	0.22
Novosibirsk obl.	0.69	0.36	**0.21**	1.64
Omsk obl.	**0.72**	**0.95**	**0.29**	**2.72**
Primorskii kray	0.10	0.09	0.03	1.30
Sakhalin obl.	0.50	0.22	0.16	1.38
Tomsk obl.	0.15	0.05	0.04	0.96
Tuva rep.	0.12	0.02	0.01	0.29
Tyumen obl.	0.03	0.02	0.19	1.38
Yakutiya	0.01	0.004	0.01	0.04
Yevrey aut. obl.	0.26	0.11	0.05	0.56

SO_2 are the main emitted components (by weight), and the sources for their emission are steel and polymetallic industry. Other pollutants are benz-a-piren, NO_2 and formaldehyde from the mechanical wood industry and the pulp and paper production (*Table 2.1*).

Relative emission

Kemerovo oblast, which discharges large amounts of solid particles, gases (SO_2, CO, NO) and volative organic compounds from several big cities, has the highest pollutant emission per unit area. Average total annual emission was between 10 and 20 tons/km^2 in the 1980s (*Okhrana Okruzhayushchei Sredy…*, 1991). According to data of Goskomstat, in early 1990s it remained at the same level, for example, it was 11 tons/km^2 in 1993 (*Table 2.2*, *Figure 2.1*). Kemerovo oblast occupies the first place not only by total relative discharge, but also by the emission of separate compounds per unit area. There is a group of administrative units with almost equal high relative emission, which includes Khabarovsk and Altai krays, Omsk and Tyumen oblasts, Khakass republic. The total relative emission is between 1 and 3 tons/km^2. For most of the regions of the Far East and transbaikalian territories annual discharge does not exceed 1 ton/km^2. High relative emission of SO_2 was registered in Omsk oblast and Krasnoyarsk kray. Relatively high emission of nitrogen monoxide is reported form the enterprises of Novosibirsk and Omsk oblasts.

Within oblasts themselves there are local regions with very high relative pollutant discharge. According to the statistical review (*Okhrana Okruzhayushchei Sredy...*, 1991), relative emission around Norilsk exceeded 20 tons/km^2 in 1990. In the southern part of Krasnoyarsk kray, in Irkutsk oblast and the southern part of Primorskii kray, the emission was between 1 and 10 tons/km^2 in 1990. So, even if the situation does not seem to be critical at the scale of the whole administrative unit, it is quite dangerous around industrial complexes.

Figure 2.1. Total pollutant emissions per unit area, tons/km^2

The least pollutant emission is registered in Yakutiya, Altai republic and Kamchatka oblast. Especially Yakutiya can still be regarded as a relatively clean territory. However, another picture could be obtained if one regards depositions, as long-distance pollution transport might change the situation markedly. While the investigations of depositions in Siberia are very limited, some information is represented in this paper below (see point 2.4).

In 1992, a slight decrease of total pollutant discharge was registered in the Asian part of Russia compared to previous years. In average, the emission volumes were reduced by 5–15%, with the following exceptions: Tyumen oblast (37% increase), Yakutiya (5% increase) and Blagoveshchensk city (16% increase) (*Okhrana Okruzhayushchei Sredy*…, 1993). However, this small decrease did not seem to lead to any changes in the overall pollution conditions.

2.2. Cities

In studying the role of big cities and industrial complexes in creating pollution "climate", we can divide the administrative units into three groups (*Table 2.3*). The first group (one asterisk) includes oblasts where one large point source (as usual, the capital) provides the major part of air pollution. The second group (two asterisks) includes oblasts where the major part of the pollutant discharge is provided by two or several large cities or industrial complexes. And the third group (three asterisks) consists of oblasts where large cities provide the minor part of pollutant discharge, while the most important pollution sources are many small local sources.

In oblasts referred to the first and second groups, local but significant influence on forest ecosystems will be observed. On the contrary, in oblasts of the third group the pollution effect might not be so destructive, however, it might be observed through the whole oblast territory, and creating elevated background pollution concentrations.

During the past few years, official environmental reports in Russia included the list of the most polluted cities. The list includes up to 100 cities where the maximum allowable concentrations are chronically exceeded and where health problems are very serious. Many Siberian cities are mentioned in the list. Some values, characterizing air quality in Siberian cities, are represented in *Table 2.4*. In West Siberia, there are 6 cities denoted as the most polluted: Barnaul, Kemerovo, Novokuznetsk, Novosibirsk, Omsk, Prokopievsk, Tyumen. All of those cities are situated in the southern part of the economic region, having high emissions.

The cities of East Siberia, included in the list of the most polluted ones , are: Abakan, Angarsk, Baikalsk, Bratsk, Chita, Irkutsk, Krasnoyarsk, Nazarovo, Norilsk, Shelekhov, Selenginsk, Ulan-Ude, Usolie-Sibirskoye, Zima. According to the Review of Environmental Status (*Obzor Fonovogo Sostoyaniya*…, 1991), Norilsk and Bratsk occupy the first and third places in all of Russia by the total volume of pollutant discharge.

Five cities of the Far East were included in the list of the most polluted: Blagoveshchensk, Dalnegorsk, Komsomolsk-na-Amure (or Komsomolsk), Khabarovsk, Yuzhno-Sakhalinsk (see *Table 2.4*).

Table 2.3. The share (%) of cities contribution to the total pollutant emissions.

Administrative unit	*Category*	*Solids*	SO_2	*CO*	NO_x	*Hydro-carbons*	*Vol. org. comp.*
West Siberia							
Kemerovo obl.	**	100	80	100	90		100
Novosibirsk obl.	**	90	100	80–90			50
Omsk obl.	*	100	100	100		100	100
Tomsk obl.	*	25	40	100		100	100
Tyumen obl.	***	30–35					< 20
East Siberia							
Buryatiya	**	25	30		0		100
Chita obl.	*	50	100				
Irkutsk obl.	**						
Krasnoyarsk kray	**	100	100	< 10	30		10-15
Tuva	***	20-25					
Yakutiya	***	< 1		0			
Far East							
Amur obl.	*	50-60	90	30	90		
Khabarovsk kray	**	100	90	100			< 20
Primorskii kray	***	20	30–35				< 1
Sakhalin obl.	*	50	60–70				100

Table 2.4. Exceedance of maximum allowable concentrations expressed in times of exceedance in Siberian cities in 1989: average annual concentrations (before slash) and maximum single concentrations (after slash). Data are obtained from Mnatsakanian, 1992.

City	*NO_2*	*NH_3*	*Benz-a-piren*	*Formaldehyde*	*Dust*	*SO_2*	*CO*	*H_2S*	*HCl*	*Phenol*	*H_2SO_4*	*CS_2*	*Methyl-thiol*
West Siberia													
Barnaul	- / 9		3 / 8	2 / 4	1 / 14		- / 6	- / 10		- / 3		- / 4	
Kemerovo	- / 12	3 / 27	4 / 12	5 / 11	- / 8		- / 8		- / 12			- / 8	
Novokuznetsk	- / 15	- / 10	10 / 35	12 / -	2 / 7					- / 39			
Novosibirsk	- / 10	- / 6	4 / 10	4 / 4	- / 10		- / 4			- / 4			
Omsk	- / 21	5 / 30	2 / 6	5 / -	- / 17								
Prokopievsk	- / 8		6 / 24	2 / 8	2 / 8	- / 2		- / 8					
Tomsk	- / 10	2 / 6	3 / 9	2 / -	1.5 / 8		- / 4		- / 6				
East Siberia													
Abakan	- / 3		10 / 29		1 / 3								
Achinsk	- / 8		3 / 7		4 / 8								
Baikalsk												3 / 6	22 / 84
Bratsk*	1 / 28		17 / 124		- / 7		- / 14		- / 2 (Cl)	- / 4		4 / 7	12 / -
Chita	2 / 6		15 / 73	2 / -	2 / 6		- / 7			2 / 3			
Irkutsk	1.2 / 3		11 / 28	4 / 6	12 / -		12 / 8			- / 3			
Kansk			12 / 40		- / 3								
Krasnoyarsk*	- / 15		6 / 22	- / 4	3 / 10							- / 5	
Nazarovo	- / 23		3 / 8				- / 2			- / 4			
Norilsk	- / 15				- / 9	2 / 72	- / 9		- / 5 (Cl)	4 / 49			
Selengingsk	- / 4		7 / 19	3 / -			- / 4					3 / -	8 / 30
Shelekhov	- / 4		12 / 36		- / 2		1 / 8						
Ulan-Ude	2 / 3		13 / 37	2 / -	2 - 11		- / 6			2 / -			
Usolie-Sibirskoye	2 / 9		4 / 17	4 / 4	2 / 4		- / 4						
Zima	- / 8		22 / 64		- /4				- / 4 (Cl)				
FarEast													
Amursk	- / 4				- / 4			- / 4					12 / 69
Khabarovsk	- / 28	3 / 10	6 / 14	6 / 5	3 / 17					3 / 19			
Komsomolsk	6 / 13	- / 10	6 / 30	6 / 5	6 / 22	6 / 13				- / 5			
Magadan	1 / 4		4 / -	4 / -	3 / 5		- / 4						
Vladivostok	2 / 9		3 / 20		2 / 5		- / 5						
Yuzhno-Sakhalinsk	1 / 8		9 / 20		1 / 14		- / 6						

*- concentrations of fluorides, exceeding allowable levels, are reported.

The picture of the emission of gaseous and liquid components in Siberian cities is the following. The most significant S emission (in the form of SO_2 and H_2SO_4) occurs from Norilsk (north of Krasnoyarsk kray). The emission of sulphuric acid is about twice as high in Norilsk, than from any other sources in Russia (*Table 2.5*). The Norilsk complex alone generated more than 20% of the total Russian emission of SO_2 and is the biggest source of pollution in Russia. The same city occupies the first place in Siberia for chlorine emissions. Nitrogen emissions, in the forms of ammonia and nitrogen monoxide, are most severe in Angarsk (Irkutsk oblast), Kemerovo, Novokyznetsk, and Omsk. The last three cities form a powerful source for concentrated nitrogen emissions in the South-Western part of Siberia. In four cities, a very high emission of fluor is registered: Bratsk (Irkutsk oblast), Krasnoyarsk, Novokuznetsk (Kemerovo oblast), Shelekhov (Irkutsk oblast).

Almost all Siberian cities are known to be polluted by phenol and formaldehyde. The largest discharge is registered in Novokuznetsk and Omsk. Bratsk is the city with the highest emission of methylthiol (methylmercaptane), Angarsk suffers most of all from the pollution by formaldehyde and protein dust. The atmosphere of Novokuznetsk and Blagoveshchensk is severely polluted by benz-a-pyrene. In addition, two serious sources of caprolactam exist in West Siberia – Kemerovo and Barnaul.

The analysis of dust emission (*Table 2.6*) demonstrates that all Siberian cities are sources of vanadium pentoxide, manganese, and chrome. The latter is assumed to be one of the most toxic metals, and according to the table, there are several big sources of chrome in Siberia: Krasnoyarsk, Novosibirsk, Barnaul, Omsk, and Irkutsk. Irkutsk is the biggest Siberian source of Cd, in 1993 it discharged more than 100 tons of this very toxic element. Among toxic compounds, we should also mention tetraethyl-lead Norilsk and Belovo (Kemerovo oblast) are the biggest sources. In general, Norilsk occupies the first place for heavy metal discharge. The situation in this city is the most critical, a more detailed description will be presented in Section 5.2.

In addition it should be stressed that air pollution in and around Siberian cities is enhanced by unfavorable atmospheric conditions (*Natsionalnyi Doklad*, 1991) – long-time anticyclones and temperature inversions, locking the air in valleys. In Krasnoyarsk the situation is the worst in winter, when toxic fogs are formed due to water evaporation from the huge Krasnoyarsk water reservoir.

2.3. Pollutant retention

Solid components are subject to an efficient retention in Russia – as a rule, 85 to 98% of the solid compounds are caught by cleaning devices. For the whole country, 77.5% of the solid pollutants underwent cleaning. However, in respect to other substances, mostly gaseous ones, the situation is much worse. *Table 2.7* demonstrates that only 15% of SO_2, 6% of NO_x and 33% of CO emissions are caught in Russia at an average. In Siberia the situation is even more dramatic. In most cases less than 5% of SO_2 are stopped by cleaning devices, the rest goes to the atmosphere. Practically no retention of CO takes place in the Far East and East Siberia. Only in a few administrative units the measures towards retention of nitrogen oxides are undertaken, but even in this case more than 2/3 of NO_x are emitted to the environment. Minor parts of organic pollutants (hydrocarbons and especially toxic volative organic compounds) stay in cleaning devices, as well. For total Russia the remaining values are 20 and 36%, respectively. There are only two exceptions in West Siberia – Omsk and Tomsk oblasts, and

Table 2.5. Emissions of inorganic gaseous and liquid compounds by Siberian cities in 1993 (expressed in tons).

Econ. region	*Town*	*HNO_3*	*NH_3*	*NO_x*	*HCL*	*SO_2*	*H_2SO_4*	*H_2S*	*F*	*CL_2*
West Siberia	Barnaul	3530	239041	14930	2109	38380	26201	230682	1395	210
	Belovo	0	2117	15340	414	18600	4133	2240	63	0
	Biisk	12695	38010	4720	35579	15060	84634	2626	665	39
	Kemerovo	3299	963993	22590	29500	15870	16821	24466	520	1916
	Novokuznetsk	98	980583	29680	26328	53410	149039	602572	1415275	8
	Novosibirsk	3987	117567	28880	22708	45600	16233	6189	4885	1382
	Omsk	372	982464	38700	26677	124780	46126	128682	2185	10212
	Prokopievsk	103	2012	3120	748	3490	1094	18000	3962	0
	Rubtsovsk	2557	32246	990	465	3150	3849	0	428	0
	Tyumen	312	17773	5340	910	4050	4154	55	229	2
East Siberia	Angarsk	308	1025309	42970	1188	92890	213240	231105	1759	91
	Bratsk	8	62651	5770	45199	16040	1023	414507	2463643	36872
	Irkutsk	1274	23268	8690	3274	19110	4136	686	3286	212
	Krasnoyarsk	16048	102014	15080	87176	36090	120824	896951	1850778	68178
	Norilsk	0	0	17440	0	18662850	27710000	159730	0	200000
	Shelekhov	162	1070	1040	432	2960	63	0	866963	0
	Ulan-Ude	140	41609	2890	252	13560	3863	630	255	86
	Usolie-Sibirskoye	6	16000	8350	33434	13060	4590	97	70	11065
	Ust-Ilimsk	0	546	3910	0	5680	5	165335	60	4279
Far East	Amursk	0	1702	1370	588	9840	417	17048	4	1515
	Blagoveshchensk	436	30597	4550	1470	15390	24	3280	15360	0
	Dalnegorsk	0	0	450	0	4450	41200	210	13	0
	Khabarovsk	114	13357	8900	3259	37030	3818	475	2202	0
	Komsomolsk	13762	4685	6740	88	12550	5310	1762	1093	0
	Vladivostok	0	6555	7210	311	28790	2204	4157	541	0

Table 2.6. Emissions of solid inorganic components by Siberian cities in 1993 (expressed in tons).

Econ. region	*Town*	*V_2O_5*	*CaO*	*CdO*	*Mn*	*$CuO + Cu_2O$*	*Ni*	*Tetraethil-Pb*	*Cr (6+)*
West Siberia	Barnaul	28792	0	0	2046	30	4	173	798
	Belovo	0	0	0	255	0	0	12892	20
	Biisk	4610	0	0	1452	404	0	2	96
	Kemerovo	4817	0	0	2787	3	0	103	171
	Novokuznetsk	18	0	0	25593	7	0	62	35
	Novosibirsk	70246	702	2	20118	3488	61	2401	2083
	Omsk	186030	0	0	2339	5	65	62	798
	Rubtsovsk	3535	0	0	576	0	1	5	9
	Tyumen	8406	0	0	1596	137	52	2274	333
East Siberia	Angarsk	4289	9188	0	101	0	0	0	26
	Bratsk	6151	0	0	582	0	0	13	15
	Chita	5658	0	0	259	0	0	706	0
	Irkutsk	9387	781	102	715	1051	0	14	530
	Krasnoyarsk	8600	3452	0	5435	0	315	194	3098
	Norilsk	0	0	0	78470	2469244	1088657	38028	6
	Ulan-Ude	19626	1309	0	1009	99	0	73	270
	Usolie-Sibirskoe	264	413246	0	271	6	0	1	0
Far East	Amursk	4302	0	0	1154	0	0	263	0
	Birobidzhan	355	0	0	1706	0	70	2	13
	Blagoveshchensk	1557	0	0	386	46	0	1	47
	Dalnegorsk	21400	0	0	55	0	0	40	0
	Khabarovsk	114120	0	0	394	0	0	5	357
	Komsomolsk	18185	0	0	580	39	0	21	195
	Okha	0	0	0	630	18	0	0	34
	Vladivistok	20370	0	0	492	30	6	2	68

Table 2.7. Emitted and retained emissions in Siberia in 1993. Emissions are expressed in 1000 tons and retained in percentage. Empty cells indicate no data avilability.

	Total emissions		*Solid compounds*		SO_2		*CO*		NO_x		*Hydrocarbons*		*Vol. org. comp.*	
Oblast	*Emitted*	*Retained*	*Emitted*	*Retained*	*Emitted*	*Retained*	*Emitted*	*Retained*	*Emitted*	*Retained*	*Emitted*	*Retained*	*Emitted*	*Retained*
Russia (average)	109717	77.5	83010.9	94.3	8462.0	14.9	8742.7	32.9	2607.6	6.0	2981.1	20.0	2490.0	35.6
West Siberia														
Altai Republic	8.2	24.9	4.2	48.6	1.43		1.01		1.45		0.01		0.01	
Altai kray	1325.5	76.7	1070.0	89.6	78.8	5.5	114.4	26.7	42.2	35.2	4.8	28.4	3.6	16.4
Kemerovo obl.	5403.8	80.6	4053.2	93.2	207.6	25.1	925.6	50.5	120.2	10.8	37.4		13.4	56.6
Novosibirsk obl.	1333.6	78.1	1158.7	89.3	65.1	1.1	60.7	4.2	38.4	0.05	1.02	8.8	5.7	15.4
Omsk obl.	3037.3	87.5	2405.5	95.8	134.2	1.2	231.4	86.1	40.5	0.1	195.1	69.0	9.6	45.4
Tomsk obl.	889.0	65.8	446.7	89.5	16.6	2.1	177.7	12.3	15.4	7.7	164.9	58.8	65.9	96.8
Tyumen obl.	2019.2	2.2	90.1	48.8	29.0	0.07	676.0		276.7		908.2	0.001	38.6	0.4
East Siberia														
Buryatiya	885.0	86.7	789.1	94.1	55.4	34.3	22.6	0.08	14.8	30.6	0.45		2.4	40.7
Tuva	170.6	70.7	141.2	85.4	4.14		22.6		2.52		0.02		0.02	
Khakassiya	399.6	71.9	325.2	87.4	22.0	5.8	34.5		6.8		0.23		0.3	27.6
Krasnoyarsk kray	15758.4	84.0	13269.2	98.3	2111.0	5.1	159.5	8.7	74.8	1.8	24.2		58.8	75.5
Irkutsk obl.	4071.3	81.3	3318.1	93.2	208.4	12.2	189.1	13.7	91.1	0.7	111.5	90.6	103.6	20.2
Chita obl.	887.7	74.3	749.5	87.6	64.5	4.2	53.4	0.04	17.2	0.8	0.56		0.6	1.5
Yakutiya	491.2	72.3	394.7	89.8	12.8	0.6	51.3	1.0	29.7	0.3	2.93		39.3	
Far East														
Primorskii kray	3999.3	92.2	3810.2	96.6	114.1	1.6	42.3	0.4	25.9	0.3	1.5	0.7	3.0	27.5
Khabarovsk kray	1381.5	82.9	1216.9	93.3	75.8	5.3	41.2	3.0	23.2		19.8	18.7	3.3	38.2
Amur obl.	473.8	74.9	399.8	88.6	32.4	1.3	30.5	0.5	9.9	0.1	0.4		0.4	0.3
Kamchtka obl.	83.5	22.9	37.3	51.2	17.5	0.1	17.9	0.2	9.4	0.1	0.8		0.4	
Magadan obl.	392.3	74.1	341.5	85.1	12.2	1.2	31.2		6.9		0.3		0.1	2.7
Sakhalin obl.	536.2	77.6	458.3	90.5	20.1	4.4	37.8	0.05	14.3		4.6	1.7	0.8	13.1
Yevrey aut. obl.	141.5	85.9	130.7	92.9	4.2	1.0	3.9		1.8		0.1		0.6	16.7

Note: the datadase assumes that the efficiency of cleaning devices is 100% (some authors report a cleaning efficiency of 80–90%).

one in East Siberia – Irkutsk oblast, where organic emissions undergo more or less sufficient purification. However, in Tyumen oblast, which is the main source for organic emissions in Siberia, only 0.001% of hydrocarbons and 0.4% of volative organic compounds are retained.

2.4. Depositions

Data on depositions are limited and quite generalized. Official data deal mainly with the deposition of S and N as it might cause acidification of precipitation. However, in most cases acidification does not occur in Siberia, because the precipitation is alkalinized by mono- and divalent cations from both natural (e.g., sea salts) and anthropogenic sources. Snow acidification has been identified in polar regions, were sulphate and nitrate depositions are caused by long-distance transboundary transportation (*Natsionalnyi Doklad*). In Siberia, increased S and N depositions are observed around big industrial regions, where annual S deposition exceeded 20 kg/ha, nitrate N deposition was close to 5 kg N/ha, ammonium N – up to 10 kg N/ha in 1988–89. Background deposition was approximately 0.1 kg/ha for sulphur and 0.03 kg/ha for the two nitrogen forms (*Obzor Fonovogo Sostoyaniya*, 1992).

Bashkin *et al.* (1995) made general calculations of critical loads of S and N for Siberian ecosystems. According to their research, critical loads for nitrogen do not exceed 100 eq/ha per year (or 1.4 kg/ha N per year) for the northern and eastern part of Siberia and 200 eq/ha per year (or 2.8 kg/ha N per year) for the rest of the territory. Higher values are reported for limited territories. As it has been described above, the emission of N compounds from some Siberian cities is very significant, and as a result, the exceedance of critical loads in some regions was reported. The highest exceedance was found in the Far East near Khabarovsk and Vladivostok and within a large area in the south of West Siberia – around the group of the cities Kemerovo, Barnaul, Novosibirsk, Tomsk.

The lowest critical loads for sulphur are in the Far East and in large territories of West Siberia. The highest critical loads are identified for the ecosystems with soils on neutral and alkaline parent rocks or with chernozems and chenozem-like soils, situated mainly in the southern part of Siberia. The areas, where S deposition exceeds critical loads, are larger than for nitrogen. They include Tyumen oblast, where a high deposition level is created by long-distance transportation from industrial regions at the Urals; a large industrially developed area around Novosibirsk, Tomsk, Barnaul, Kemerovo and Krasnoyarsk; a vast region around Norilsk industrial complex; and almost the whole territory of Primorskii kray.

Examined data demonstrate that the air pollution in Siberia and especially in its southern part can be a serious factor threatening forest health and vitality.

3. Siberian Forest Decline due to Air Pollution

In 1990 the total area of the forests of the former Soviet Union, damaged or dead as a result of atmospheric pollution (as a cumulative effect) was officially estimated to 796,900 ha. During the period 1991–1993, 65,540 ha were added to this area. Currently, the expert estimates indicate 1 million ha of forested areas damaged by industrial emissions. Some 40% of all damaged forests were drying out or dying (this corresponds to damage classes 3 and 4, according to the European classification). Nearly 90% of the damaged forests were constituted by coniferous forests. The dominant part of this damage – 763,600 ha or 95% – was caused by

Figure 3.1. Accumulated (up to 1993) drying out and forest die-back due to air pollutants. Expressed in ha per 1000 per ha of forested areas. After Rosagroservis, 1994.

metal industry enterprises emitting sulphur dioxide (*Obzor fonovogo sostoyaniya…*, 1992). Another expert estimate on the total damage to forests by pollution is even higher – about 7 million ha (Isaev, 1991).

In *Figure 3.1* accumulated data up to 1993 present the distribution of dried out and dead forests due to air pollution. From this map it can be seen that there are serious problems in East Siberia (mainly Krasnoyarsk kray) and in the Southern part of the Far East.

Many chemical substances are known to cause damage to forests. In Siberia, the biggest losses were caused by sulphur dioxide. The most affected region from this point of view is around the Norilsk industrial complex. This is the largest zone of forest decline in the whole Russia.

Fluor is considered to be a dangerous substance. The toxity of fluorides is 30 times higher than that of SO_2. However, the total damage caused by fluor in Siberia is not very drastic. The largest damaged regions are situated in Irkutsk oblast – around Bratsk and Shelekhov.

Other pollutants causing forest decline in Siberia are cement dust and organic compounds. Cement influences are reported for the Novosibirsk oblast. A serious effect of organic emissions is identified around Ust-Ilimsk and especially in the Baikal region, where fir forests affected by pollutants constituted 70,000 ha (*Obzor Fonovogo Sostoyaniya…*, 1992).

In 1991, Goskomstat presented information about the scale of the decline of forested areas in different administrative units. A complete survey was not conducted, however, the data seem realistic. Among the listed administrative units, the most critical damage caused by air pollution was observed in two regions of the Krasnoyarsk kray. In the northern part of the kray, where Norilsk complex is situated, 4.4% of the forested areas had undergone changes, and more than one-third of this damaged territory was influenced to a strong or extreme degree. In the southern part, 2% of the territory was disturbed by the emissions from the Kansk-Achinsk industrial complex, and 20% of the disturbed area was strongly damaged.

Other areas, suffering from atmospheric pollution, are Primorskii kray, Irkutsk and Chita oblasts, where damage to the forest cover occurred at 0.8% of the forested areas. Smaller changes took place at the territories of Khabarovsk kray, Amur, Irkutsk and Chita oblasts, Buriatiya republic.

Table 3.1 presents a list of areas, affected by air pollution around the biggest Siberian cities. The data were extracted from the Natsionalnyi Doklad. The dominating damaged areas are found in Irkutsk, Kansk, Krasnoyarsk, Novosibirsk. The largest damaged area is reported around the Abakan-Minusinsk industrial complexes. However, nothing is identified about the degree of damage for the reported areas.

Analyzing the absolute values of forest losses due to air pollutants,. Krasnoyarsk kray can be identified as the worst area. The total area of dead forests, due to emissions during the period 1988–1993 was some 130,000 ha (*Table 3.2*). All these areas are located around the Norilsk industrial complex (Martynyuk, Kasimov, 1993). During the same period, forest die-back was observed in Irkutsk and Tyumen oblasts (more than 1,000 ha and 142 ha, respectively). Occasional discharges led to forest decline in some other regions (Altai Republic, Khabarovsk kray, Novosibirsk and Omsk oblasts, and in the Khanty-Mansi autonomous district). Forest

Table 3.1. Chronically polluted areas around major Siberian industrial cities in 1990–1991.

City	*Chronically polluted areas, km*^{2}
Abakan-Minusinsk	38560
Achinsk	1540
Barnaul-Novoaltaisk	1790
Baikalsk (Irkutsk region)	698
Blagoveshchensk	1810
Bratsk	3000
Inta	1960
Irkutsk	31240
Kansk	21940
Komsomolsk-na-Amure	4120
Krasnoyarsk	10720
Neryungri	3560
Novosibirsk	13020
Norilsk	7520
Omsk	4580
Petropavlovsk	2220
Tomsk	2020
Tynda	2080
Tyumen	4430
Khabarovsk	2530
Chita	1540

Table 3.2. Areas of dead forests, due to emissions during the period 1988 to 1993 (data were delivered by Russian Federal Service of Forestry).

Region	*Year*	*Dead forests, ha*
Altai Republic	1992	3
Krasnoyarsk kray	1988	331
	1989	68900
	1992	61303
Khabarovsk kray	1988	6
Irkutsk oblast	1988	391
	1991	48
	1993	674
Novosibirsk oblast	1990	2
Omsk oblast	1989	46
Tomsk oblast	1988	10
	1989	1
	1990	1
	1991	15
Tyumen oblast	1988	16
	1990	125
	1991	1
Khanty-Mansi aut. district	1992	4

Table 3.3. Relative rate of different causes for forest losses, expressed in percentage (recalculated from *Obzor Sanitarnogo Sostoyaniya*, 1994).

Region	*Wild animals*	*Diseases*	*Human activities*	*Of which air pollution*	*Insects*	*Weather conditions*	*Fires*
Altai Kray	89.7	3.9	0	0	0	0	6.4
Altai Rep.*	2.3	0	0.3	0.3	0	61.5	35.8
Krasnoyarsk Kray	0	0	40.9	**40.9**	0.1	17.6	41.4
Primorskii Kray	13.9	0	0	0	0	38.5	47.6
Khabarovsk Kray	0.02	0	0	0	0.1	55.8	44.1
Amur Obl.	4.7	0	0	0	0	0	95.3
Irkutsk Obl.	0.25	0.03	0.5	**0.5**	2.0	0.25	97.0
Kamchatskaya Obl.	0	0	0	0	0	0	100
Kemerovo Obl.	72.4	0	3.4	0	0.2	19.6	4.3
Magadan Obl.	0	0	0	0	0	0	100
Novosibirsk Obl.	14.2	0.01	0.01	0.01	0	36.6	49.2
Omsk obl.	0	0	0.4	0.4	3.7	20.8	75.0
Sakhalin Obl.	0	0	0	0	0	0	100
Tomsk Obl.	0	0.3	0.07	0.07	13.6	1.3	84.7
Tyumen Obl.	0.001	0	0.15	0.15	21.9	0.7	77.2
Khanty-Mansi AO*	0	0	3.1	0.06	0	0	96.9
Yamalo-Nenets AO*	0	0	0	0	0	0	100
Chita Obl.	0.1	0	0	0	0	9.6	90.3
Buriat Rep.	0	0	2.2	0	0	14.8	83.0
Tuva Rep.	0	0	0	0	0.25	1.9	97.9
Yakutiya Rep.	0	0	0	0	0	0.6	99.4

* - Data are represented for the period 1992-93.

die-back was also found in Tomsk oblasts, however, forest losses were relatively insignificant compared to the other regions.

It is also important to analyze the role of industrial pollution in combination with other causes of forest decline. *Table 3.3* illustrates that for some regions the industrial atmospheric pollution plays a noticeable part of the forest decline. The situation in Krasnoyarsk kray is very specific. Forest losses resulting from air pollution around Norilsk only are of the same order as the territories destroyed by forest fires in the whole kray. These two factors are the most important causes for forest decline in this kray. In Irkutsk oblast, forest die-back due to air pollution occupies the third place. The damage is dominated by fires and unfavorable weather conditions. In Tyumen, Omsk and Tomsk oblasts, and Altai republic, while air pollution results in forest mortality, it is less important compared to other factors of natural origin (fires, weather conditions, pests, etc.).

Based on the data presented, it can be concluded that required measures for reducing forest decline form air pollution should be directed to the amelioration of local environmental conditions in Norilsk and Irkutsk.

Another important conclusion is that, compared to the scale of air pollution in Siberia, forest losses seem rather small. This is a result due to the fact that the Russian Federal Forest Service deals mainly with forest die-back, and not the early stages of forest decline. However, the analysis of the pollution "climate" allows us to suppose that the damage, caused to forests by air pollutants concerns large territories and might turn into a serious problem in the future.

4. Case Studies of Forest Decline Caused by Air Pollution

4.1. State of forests around Bratsk industrial complex

The environmental pollution around the Bratsk industrial complex has more than a 20 year history. The first indications of forest decline were found in 1968 in the area north-west from the Bratsk aluminum plant. The area of damaged forest has increased gradually and had reached 80,100 ha by 1988 (Martynyuk and Kasimov, 1993).

Thus, the source of pollution is the Bratsk industrial complex, which is constituted by an aluminum plant, wood industry complex, two power stations and a developed transportation net. In average, about 20 types of pollutants are discharged to the atmosphere. The industries emit 170,000 tons of emissions per year and the transportation connected with the industrial production 36,000 tons. The main discharged components are solid particles, sulphur and nitrogen oxides, H_2S, solid and gaseous fluoride, sulphur-organic compounds and methylmercaptane.

Mean daily concentrations of HF and H_2S exceed allowable levels by a factor of 2. The exceedance of maximal occasional concentrations was reported for all pollutants and especially for H_2S, HF and NO_x. Even at a distance of 8–10 km from the pollution source the concentrations of HF are equal to 2.4 the allowable levels (0.012 mg/m^3) (Kasimov *et al.*, 1993).

The Institute of Geography reported in 1988, that pollution of the snow cover was found at a territory of 1044 km^2. The extent of snow pollution by solid particles is presented in *Table 4.1.*

Table 4.1. Snow pollution by solid particles around the Bratsk industrial complex.

Pollution source	*Polluted area, km^2*	*Pollution in snow cover, t/km^2 per winter*
Aluminium plant	47	3475
Wood industry complex + Power stations	26	1650

Among all the pollutants, discharged by Bratsk industrial complex, HF is regarded as the most aggressive towards the forest vegetation. In the composition of melted waters, fluor is represented as a macroelement and composes 41% (in equivalents) of total ions investigated. Fluorides were found at the distance of 60–70 km from the industrial complex. The highest fluoride concentrations were found at a distance of 3–8 km from the aluminum plant, and at a distance of 18–45 km the concentrations exceeded the background emissions by the factor of 17.

Kasimov *et al.* (1993) present a detailed information about ecosystem pollution by zones. Within forest ecosystems, forest litter was subject to serious fluor pollution. Three zones were detected for different degrees of soil contamination. The zone of heavy litter pollution has an area of 3,600 ha (36 km^2), or 4% of the total polluted area, with fluor content in litter exceeding 200 mg/kg. Mean background fluor concentrations are exceeded by the factor of 10–30. The zone of moderate litter pollution occupies 6100 ha (61 km^2), or 6.9% of the total polluted area, with fluoride concentrations of 100–200 mg/kg. The rest 79,500 ha (795 km^2) are referred to the zone with slight pollution.

The zones of litter pollution by fluor tightly correlate with the zones of forest decline, settled after numerous remote-sensing and in situ observations, using special criteria of tree status.

Within the zone of very serious damage (zone 1a), mature pine forests are either dead and cut or found as weakened and drying. After the removal of the dead tree layer, the dominating stands are deciduous and larch-deciduous forests, slightly weakened or almost healthy. At a distance of 1–1.5 km from the Al-producing plant, forests are replaced by bushes.

Within the zone of serious damage (zone 1), severely weakened and drying pine stands prevail. Young pine stands, as well as larch trees, are slightly damaged. Deciduous trees have no visible indications of decline.

At the area of moderate damage (zone 2) mature pine stands are slightly and moderately weakened. Young trees of all species are almost healthy.

Within the zone of slight damage (3) mature pine stands are slightly weakened, while young stands have no visible features of damage.

Rozhkov and Mikhailova (1989) determined 4 degrees of fluor influence on the vegetation.

1. Non-visible damage is caused by low toxicant concentrations, either constantly or periodically. While no external symptoms can be detected, the changes in the physiological processes occur. They lead to the decrease of the increment and wood productivity, however, normal pattern of plant tissue functioning might be restored if the pollution decreases or increases.
2. Cumulative damage is observed under the conditions of long-term influence of low pollutant concentrations. It leads to pollutant accumulation in plant tissues and necroses.
3. Drop-burning damage is identified when necroses points and spots increase in dimensions.
4. Severe damage is observed at high pollutant concentrations (as usual, after accident discharges). Forest decline develops within hours or days after the discharge and the death of the whole canopy occurs.

A solution of the problem of air pollution is only possible with decreased emissions. To calculate allowable emission levels, the existing values of allowable concentrations, elaborated for Baikal region, may be used (*Table 4.2*). Just for comparison, allowable concentrations for cities are presented (*Okhrana Okr. Sredy…*, 1991) in the same table. Special attention must be paid to the abatement of the F emission, due to the fact that F is a very aggressive agent.

A complex of forest management measures was elaborated in order to maintain the functions of the forest cover in the polluted territory. The main task was to create long-living and resistant forest stands, that might carry out their environmental functions under pollution conditions.

Based on the calculations made by Alekseev (1985), the formation of coniferous stands within the zone 1 was assumed to be insufficient. Coniferous trees are not gas-resistant, the lifetime of the mature stands under the given conditions does not exceed 11–16 years. Within zone 2 (moderate pollution) coniferous stands have low increment and are of low industrial and sanitary value, and the impact of forest management is inefficient, as well. Within zone 3 (slight

Table 4.2. Allowable air concentration units of pollutants. (After Kryuchkov (1993), for trees; and Mnatsakanyan (1992), for cities).

Compounds	*Allowable single concentrations, mg/m^3:*		*Average daily concentrations, mg/m^3:*	
	For trees	*For cities*	*For trees*	*For cities*
Nitrogen dioxide	0.04	0.085	0.02	0.04
Sulphur dioxide	0.3	0.5	0.015	0.05
Vapours of sulphuric acid	0.1	0.3	0.03	0.1
Chlorine	0.025	0.1	0.015	0.03
Fluoric acid (HF)	0.004	0.02	0.0005	0.005

pollution) pine growth is possible in mixed stands. The optimal variant seems to be to create mixed pine-larch-deciduous stands. Within zone 4 (almost unpolluted) unaffected growth of coniferous species is possible.

A special harvesting regime must be established. Even in a weakened state, the forests still accomplish their soil- and water-protective functions. If these stands are clear-cut, young stands that will replace them, will not be able to carry out these functions. That is why sanitary fellings are recommended in declining stands within the first zone, under the conditions of immediate reforestation. Special “narrow-corridor” sanitary fellings are proposed for damaged stands.

The success of reforestation depends on a correct choice of the dominating species. Within zones 2 and 3 natural regeneration of both coniferous and deciduous trees is possible. Within the zone 1 relatively long-living coniferous stands can be formed only at the slopes opposite to the prevailing winds. Within zone 1a coniferous stands must be replaced by more resistant deciduous species, both natural regeneration and artificial seeding can be used.

To ameliorate the conditions of forest growth, fertilizers of different kinds can be used.

4.2. The effect of industrial pollution of forest ecosystems in the Subarctic zone (Norilsk)

A very active development of mining and exploitation of fuels take part in the Subarctic zone of Russia. More than 10 million people live in the North. Cities and towns are isolated. Energy is provided by burning coal, liquid fuel, and wood at big and small power stations and in the homes. As a result, significant amounts of pollutants are emitted to the atmosphere, mostly SO_2 and dust. The areas of polluted territories around such towns exceed markedly the territories of the towns themselves (*Zony Zagryazneniya…*, 1988). The transport pressure on fragile northern soils creates additional stresses. As a result the territories around northern towns are eroded and the vegetation cover is severely damaged. A high demand on fuel wood leads to deforestation, which is especially intensive in the northern regions due to the low growing stock (6–20 m^3 per hectare). The total area of anthropogenic tundra, created as a result of deforestation, is about 470,000–500,000 km^2 in the whole Subarctic zone.

The largest area of forest decline due to emissions is situated in Siberian Subarctics, in the south-western part of Taimyr peninsula around Norilsk polymetallic industrial complex (Krasnoyarsk kray), including, in fact, 5 industrial cities. The main component of emissions

(96–98% by weight) is sulphur dioxide. The rest includes nitrogen oxides, CO, chlorides, phenol and other substances. Dust emissions contain copper, nickel, cobalt. According to *Natsionalnyi doklad* (1991), annual emission of sulphur compounds to the atmosphere exceeds 2.2 million tons. In 1993, the emission exceeded 2.7 million tons. The water of the region is also severely polluted. Average annual concentrations exceeded allowable levels by the factor of 115 for copper, by the factor of 30 for nickel, by the factor of 8 for ammonium and by the factor of 4 for organic substances. These conditions have led to serious losses of fish. The enterprises of Norilsk produce annually 1,100 tons of toxic solid wastes, 5 million tons of slag, 12 million tons of ground deposits, which occupy up to 2,000 ha. Based on all these factors, the region of Norilsk is considered to have the most critical ecological conditions.

A seven-fold increase of the area of declining forest was observed during the last decade in Norilsk. The total area of dead forests around Norilsk was 310,000 ha by 1992 (Martynyuk and Kasimov, 1993). According to another estimate, the area with dead forests was 382,000 ha (*Natsionalnyi Doklad*, 1991). Damaged forests were observed at a distance of 200 km to the south from Norilsk. At a distance of 35 km, spruce and larch trees contained 5–10 times more copper than trees outside the affected area. Structural and functional organization of plant communities is altered. At a distance of 120 km, the natural regeneration of trees is absent, annual increment and primary biological production are very low.

The extent of forest die-back varies from year to year (*Table 4.3*). One reason for this variation might be the inventory process itself, as the collection of data about the effect of atmospheric pollution is irregular and fragmentary (*Obzor Sanitarnogo Sostiyaniya*, 1994).

Kryuchkov (1991) made a detailed investigation of the consequences of the northern forest pollution. In fact, it was conducted not in Norilsk, but in quite similar conditions, and the results might also be applied to the description of Norilsk forests. The information about Norilsk itself was not available for publication.

Northern ecosystems are quite specific and forest decline leads to some specific consequences.

Table 4.3. The dynamics of forest die-back around Norilsk (Krasnoyarsk kray).

Year	*Losses of forests, ha*
1988	331
1989	68900
1990	0
1991	0
1992	61303

At deforested territories the climatic conditions became more severe than in typical arctic ecosystems. There is an increase of wind rates, snow density, depth of frozen soil. Changes in air and soil temperatures are observed. After the death of mosses, lichens and undershrubs the upper organic soil horizon is destroyed.

According to Kryuchkov (1991), several bioindicators were chosen and ranged by their sensitivity to describe the extent of subarctic forest degradation (see also *Table 4.4*).

Table 4.4. Plant resistance to air pollution – critical concentrations for different groups of plants, mg/m^3 (after Kryuchkov, 1991).

Plants	*SO_2*	*Ni oxide*	*Cu oxide*	*Dust*	*HF*
Epiphytic fruticose lichens	< 0.003	< 0.001	< 0.002	0.01	0.001
Epiphytic foliose lichens, Sphagnum mosses	0.003 - 0.007	< 0.001	< 0.002	0.01 - 0.02	0.001 - 0.003
Green mosses, crustaceous lichens; Spruce, pine	0.007 - 0.009	< 0.001	< 0.002	0.02 - 0.03	0.003 - 0.004
Larch, ground cedar (*Juniperus*)	0.009 - 0.05*	0.001*	0.002*	0.03 - 0.05*	0.004 - 0.005*
Deciduous trees and bushes – birch (*Betula sp.*) and rowan-tree (*Sorbus sp.*)	0.05 - 0.07	0.001 - 0.002	0.002 - 0.003	0.05 - 0.08	0.005 - 0.007
Bushy forms of willow, aspen, alder; berries - undershrubs; herbs	0.07 - 0.1	0.002 - 0.004	0.003 - 0.005	0.08 - 0.1	0.007- 0.01

* - Second marked values are equal to sanitary normatives.

1. Presence and absence of lichens and mosses.
2. The state of coniferous trees - age, color, necroses of needles.
3. Undershrubs: their diversity and coverage.
4. Completeness and thickness of soil profile.

Five zones of degradation were then identified.

Zone I.

Zone of complete ecosystem degradation. The plants are dead, soil organic horizons are destroyed, mineral soil horizons are exposed to the surface. The whole soil profile is often eroded, and soil cover is represented by parent material. Some fragments of soil and vegetation cover can be found in ravines. Trees are represented by suppressed birch and willow. Single spruce trees can be found, their needles being 1–2-years old (compared to 14–16 years under normal conditions). Local climatic conditions are altered – wind rates increased and the temperature becomes 1–3 centigrades lower. No moss or lichen cover is found at the surface of big stones.

Zone II.

Zone of strong ecosystem degradation. Soil organic horizons are destroyed, “color spot tundra” is formed. Coniferous trees (spruce) are dead, single individuals are alive but dying. Suppressed birch bushes are found at flat and elevated sites. The trees are isolated and cannot form a phytocoenosis. Dwarf forms of spruce and birch with suppression features are common. Lichens are absent. Moss bogs are replaced either by dry valleys or by *Carex* associations. Unfavorable meteorological conditions are very dangerous for the trees in this zone, for example, when there is no wind, no pollutant removal occurs, and pollutant-containing cloud expands and effects more and more trees. Sharp increase of technogenically deforested territories occurs, especially after emergency discharge. After the death of needles or leaves, the temperature and water exchange of a tree is altered, leading to further decline.

Around Norilsk, the territories that could be referred to the zones I and II, occupy the area of 300,000 ha (*Natsionalnyi Doklad*, 1991).

Zone III.

Zone of markedly destroyed northern taiga ecosystems. Its area is about 380,000 ha around Norilsk complex (*Natsionalnyi Doklad*, 1991). Within this zone, the northern taiga forests are transformed into suppressed arctic spruce-birch rarefied forests. Dead spruce forms 30–40% of a stand. Living trees have dry or deformed crowns. The age of needles varies from 2–3 to 6–7 years depending on tree form and degradation stage. Some 30–50% of birch trees have dried crowns. The projective cover of mosses and grasses increases from 20–30% to 60–80%. Small fragments of sphagnum mosses can be found. The retention of pollutant-containing precipitation occurs at crown surface, leading to element concentration and intensified pollution.

Zone IV.

Zone of initial degradation of taiga ecosystems. The main features of disturbance here are drying and deformation of crowns, defoliation, reduction of needle lifetime, leaf and needle necroses, reduced increment, the absence of epiphytous lichens, the suppression of lichens and mosses, and soil cover formations.

Zone V.

Zone of initial degradation. This zone is not subject to constant pollution, however, after emergency discharge and with the absence of winds, pollutant concentration exceed sanitary and especially ecological limits. The age of needles varies between 9 and 13 years. The epiphytic lichens can be found fragmentarily. Zones of initial degradation may occupy large areas.

The destruction of mountainous ecosystems occurs faster compared to plain ecosystems. The technogenic press can be the same, however, climatic conditions are more extreme.

After long-term investigations the following division of vegetation was made for resistance to air pollutants (*Table 4.4*).

Coniferous forests in the taiga zone can survive for a long time at SO_2 concentration in the air being at the level 0.005–0.009 mg/m^3. After a long-term influence of SO_2 at the content 0.009–0.05 mg/m^3, the degradation of epiphytic lichens is observed after 10–15 years, and after 30–50 years the decline of coniferous forests occurs. There is no complete regeneration of forests under such conditions. Taking into account that there is an accumulation effect by other pollutants, the tree lifetime might decrease. At SO_2 concentrations between 0.05 and 0.07 mg/m^3 coniferous trees die after 10–20 years. Only larch and some deciduous species can exist under such conditions.

The input of organic matter and mineral fertilizers can increase forest lifetime. But the most important measure is the reduction of emissions. In 1991, a special program was adopted, including the introduction of new purification technologies. The following reduction of SO_2 emissions was planned, based on the level of 1990: 19% by 1995, 40% by 2000 and 73% by 2005 (*Natsionalnyi Doklad*, 1991). Moreover, water uptake for industrial needs and the discharge of liquid wastes should be seriously reduced. However, for a moment, there is no information available about the implementation progress of this program.

5. Conclusion

Siberian forests are subject to the influence of the whole range of factors leading to forest decline and, in critical cases, to forest die-back. The factors are both natural and anthropogenic. By their significance, natural factors might be ranked as the following: forest fires, unfavorable weather conditions, insect invasions, and diseases. Negative human activities can be ranked as: changes in hydrological regimes, mechanical devastation, soil and air pollution.

In some Siberian regions, natural factors of forest death undoubtedly prevail. At the same time, in many regions the scale of natural and human causes of forest decline are at least comparable (south of the Far East, south of the West Siberia, Krasnoyarsk kray). For some regions the quality of the available information does not allow us to make any comparisons.

The industrial pollution conditions in Siberia are quite different from that described in numerous studies for Europe. In Europe there is a problem at both the national and international scale, and transboundary pollution plays an important role in creating the pollution loads. In Siberia environmental pollution is still a problem at the regional scale. Most parts of territories, damaged by pollution, are concentrated around several huge industrial complexes. In some cases pollution is created around united neighboring pollutant sources, as it happens in Kemerovo oblast or within the industrial region around Krasnoyarsk. At the same time, vast territories are free from pollution influence – Yakutiya, central part of Krasnoyarsk kray, and Magadan oblast. Long-distance pollution transportation does not make any serious contribution to the pollution background in Siberia, with one exception – Tyumen oblast, which is polluted by discharge products from the Southern Urals. In general, it means that severe ecological problems might be solved by ameliorating the “pollution climate” in several specific critical regions.

However, the available information is insufficient to make any definite conclusions and policy recommendations, despite the presence of annual reports, including a review of ecological and sanitary status of Siberian forests. The data represented in the reports are doubtful, especially those concerning pollution causing forest decline. Large forest territories are outside the monitoring of fires or insects. Concerning environmental pollution, only the first attempts have been made to estimate the situation in the Asian part of Russia. The analyses of the pollution conditions in Siberia demonstrated that the damage, caused to forests by air pollution probably should concern larger areas than estimated in the official reports. Case studies, mentioned in the paper, are only first steps in the estimation of real damage of air pollutants to forest ecosystems. Further large investigations are needed to obtain a reliable description of the ecological status of the Siberian forests.

References

Alekseev, A.V., 1985, Ekologicheskie Osnovy Ratsional'nogo Ispol'zovaniya Prirodnykh Resursov (Ecological Bases of the Rational Use of Natural Resources), Leningrad, Leningrad Academy of Forestry (in Russian).

Bashkin, V.N., Kozlov, M.Ya., Priputina, I.V., Abramyshev, Yu.V., and Dedkova, I.S., 1995, Calculation and Mapping of Critical Loads of S, N and Acidity on Ecosystems of the Northern Asia, *Water, Air and Soil Pollution*, forthcoming.

Bolshakov, V.A., Krasnova, N.M., Borisochkina, T.I., Sorokin, S.E., and Grakovskii, V.G., 1993, Aerotekhnogennoe Zagryaznenie Pochvennogo Pokrova Tyazhelymi Metallami: Istochniki, Masshtaby,

Rekultivatsiya (Aerotechnogenic Pollution of Soil Cover by Heavy Metals: Sources, Extent, Recultivation), Moscow, 90 pp. (in Russian).
Boronin, Yu.B., Voron, V.P., and Malyshev, V.V., 1993, Phytotoxic Effects of Sulphuric Anhydride and Aerosols of Sulphuric Acid on Tree Species. In Ekologiya Lesa i Okhrana Prirody (Forest Ecology and Nature Protection), Moscow, p. 63–77 (in Russian).
UN, 1992, Forest Conditions in Europe, 1992 Report: International Cooperation Program on Assessment and Monitoring of Air Pollution Effects on Forests, UN, Geneva, 117 pp.
Isaev, A.S., ed., 1991, Prognoz Ispol'zovaniya I Vosproizvodstva Lesnykh Resursov po Ekonomicheskim Raionam SSSR (Forecast of the Utilization and Reproduction of Forest Resources by Economic Regions of the USSR), Acad. Sci. USSR and State Forestry Committee of the USSR, 994 pp. (in Russian).
Kasimov, V.D., Martyniuk, A.A., Kondratov, V.I., Serdiukova, A.V., Golutvina, L.S., and Ramzevich, G.A., 1993, Status of Forest Stands and the Ways of Increasing Their Resistance Within the Zone of the Influence of Bratsk Industrial Complex. In Forest Ecology and Nature Protection, Moscow, VNIILM, pp.19–34 (in Russian).
Kryuchkov.V.V., 1991, Critical Anthropogenic Loads and the Status of the Ecosystems of the North, Ekologiya, No. 3, pp. 28–40 (in Russian).
Lesnoi Fond SSSR 1990 (Forest Fund of the USSR), Statistical Review, Vol. 1, Moscow (in Russian).
Martyniuk, A.A., and Kasimov, V.D, 1993, Loca of Forest Vegetation Disaster by Industrial Emissions and Forest Management Strategy under the Conditions of Environmental Pollution. In Ekologiya Lesa I Okhrana Prirody (Forest Ecology and Nature Protection), Moscow, p.3–18 (in Russian).
Mnatsakanian, R.A., 1992, Environmental Legacy of the Former Soviet Republics. University of Edinburg, 209 pp.
Natsional'nyi Doklad SSSR k Konferentsii OON 1992 goda po Okruzhayushchei Srede
I Razvitiyu, 1991, (USSR National Report for the UN 1992 Conference on Environment and Development), Moscow (in Russian).
Nilsson, S., Shvidenko, A., Bondarev, A., and Danilin, I., 1994, *Siberian Forestry*, Working Paper WP-94-8, International Institute for Applied Systems Analysis, Laxenburg, Austria.
Obzor Fonovogo Sostoyaniya Okruzhayushchei Prirodnoi Sredy v SSSR za 1990 god, 1992, (Review of Environmental Status in the USSR in 1990), Moscow, Hydrometeoizdat, 71 pp. (in Russian).
Obzor Sanitarnogo Sostoyaniya Lesov Rossii za 1993 god, 1994, (Review of Forest Sanitary Status in Russia in 1993), Moscow, Rosagroservis (in Russian).
Okhrana Okruzhayushchei Sredy I Ratsional'noye Ispol'zovanie Prirodnykh Resursov, 1991, (Environment Protection and Rational Use of Natural Resources), Statistical Review, Moscow, 251 pp. (in Russian).
Okhrana Okruzhayushchei Sredy I Ratsional'noye Ispol'zovanie Prirodnykh Resursov, 1993, (Environment Protection and Rational Use of Natural Resources), Statistical Review, Moscow, 175 pp. (in Russian).
Pryde, Ph.R., 1994, Observations on the Mapping of Critical Environmental Zones in the Former Soviet Union, *Post-Soviet Geography*, **35**(1):38–49.
Greenpeace International, 1993, Quick Cash for Old-Growth: the Loosing of Russia's Forests, Greenpeace International Forests Campaign, Amsterdam, 17 pp.
Rosagroservis, 1994, Review of Sanitary State of the Forests in Russia in 1993, Rosagroservis, Moscow, pp. 126 (in Russian).
Rozhkov, A.S., and Mikhailova, T.A., 1989, Deistvie ftorsoderzhashchikh emissii na khvoinye derevya (The influence of fluor-containing emissions on coniferous trees), Novosibirsk, Nauka (in Russian).
Soloviev, V.A., Alekseev, A.S., Leplinskii, Yu.I., and Lairand, N.I., 1989, Vliyanie Zagryazneniya Atmosfery na Lesnye Ecosistemy (The Influence of Atmospheric Pollution on Forest Ecosystems), Leningrad, 45 pp. (in Russian).
Tracy, L.A., 1994, The Deforestation in Siberia: Economic and Environmental Problems in Russian Forest Management, Forest Industry Lecture Series, No. 32, The University of Alberta, Canada.
Goskomhydromet, 1988, Zony Zagryazneniya Snezhnogo Pokrova Vokrug Gorodov na Territorii SSSR (Zones of Snow Cover Pollution at the Territory of the USSR), Leningrad, 125 pp. (in Russian).

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