Working Paper

Immediate Impact of Logging and Fires on Boreal Forest Soils in Russia

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WP-95-37
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Foreword

Siberia's forest sector is a topic which recently has 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 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-economics. This report, carried out by M. Karpachevsky during his working stay at IIASA, is a contribution to the analyses of the topic of greenhouse gas balances.

1 Introduction

These days there are two very important problems humanity faces which are tightly bound together: global climate change and anthropogenic pressure. Forests and forest soils represent objects of these impacts. Soils, being a central part of terrestrial ecosystems, reflect not only present environmental conditions but also previous ones. Soil is not a living organism, but a medium where organisms live. Transformations of soil differ from plant successions and evolution as well as their buffering capability and tolerance. In turn, the hypothesized global climate change depends mostly on CO_2 concentration in the atmosphere and thus on carbon cycling. Soils are regarded to be even a greater sink of CO_2 than vegetation (and all living biomass). Soil properties shift affects terrestrial ecosystems in many ways, on a local scale as well as influence to the global climate. There is much data about soil pollution or arable land degradation, but only a few works have been done about forest soils transition under clearcuts or wildfires. This is especially true for soil organic matter behavior, the most intriguing and mysterious feature of any soil which is equally important for local site productivity and global carbon cycle analysis. An assessment of these two human impacts to forest soils, as well as dynamics of their properties, is a matter of great concern at the present time.

2 Human Impact on Soils of Boreal Zone

2.1 Interrelationship between soil and human impact

In order to estimate soil change resulting from human impact the following properties must be taken into account (*Figure 1*): ecosystem and habitat type, soil pedon properties (specific soil pit), soil pattern-spatial variation of soil pedons, soil regimes-temporal variation of soil properties. The following properties of pedon are sensitive indicators of the impact:

- *Morphological properties:*
  - Humus horizon thickness;
  - Forest litter thickness and composition;
  - Gleying features;
  - Podzolization features;
  - Sod and peat horizon development.
- *Chemical properties and regimes:*
  - Soil C state, also soil N and P;
  - Nutrient and exchangeable cations state: Ca, Mg, K, Al, H;
  - Soil acidity.
- *Physical properties and regimes:*
  - Soil bulk density and structure;
  - Soil water properties – waterlogging, bogging, drying out.
- *Microbiological properties and regimes:*
  - Composition and amount of microorganisms;
  - Mobile elements dynamics (NO_3, NH_4, P).

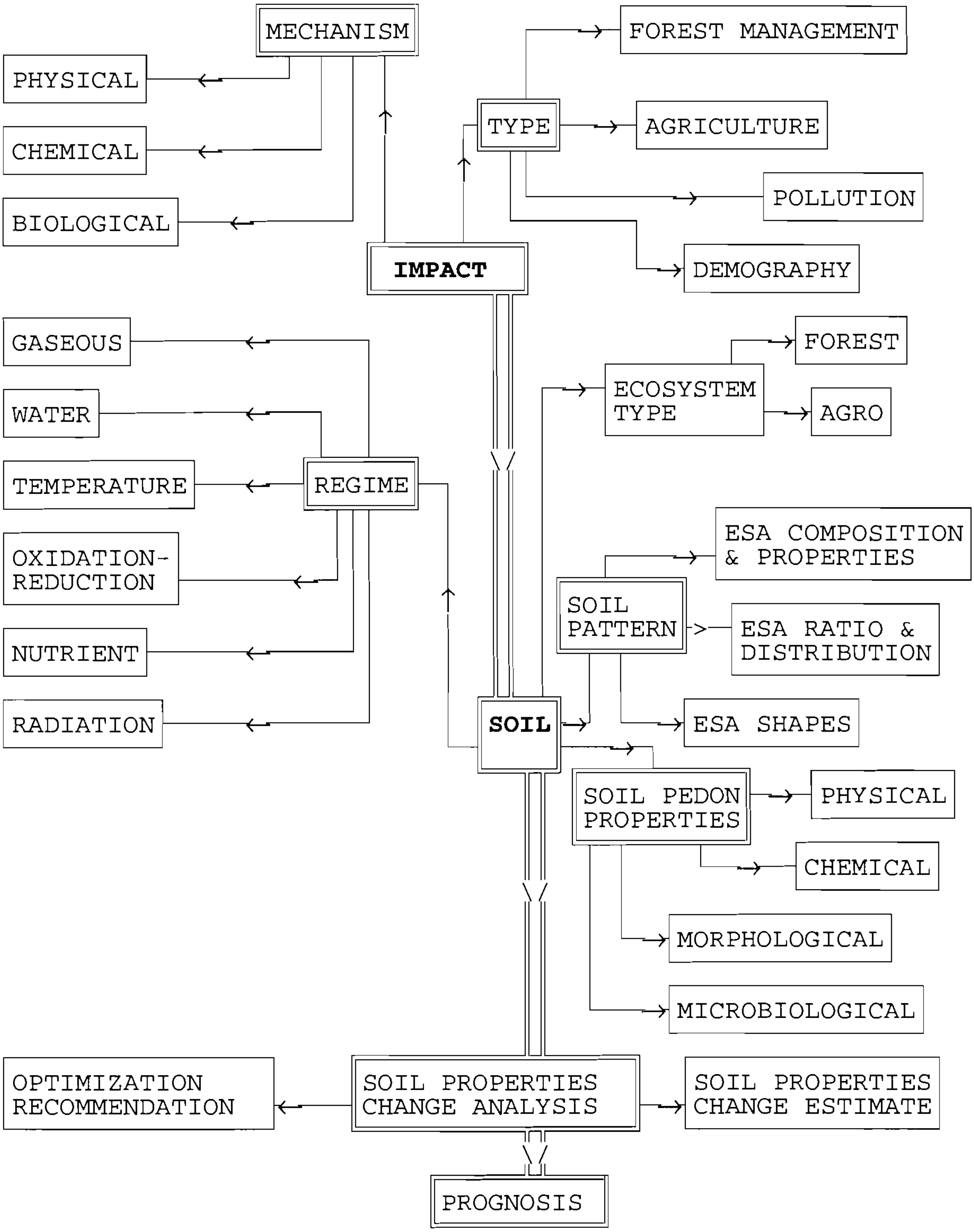

Figure 1. Scheme of relationships between human impact and soils.

Also the impact itself may be characterized by a mechanism of influence. That is, which soil properties are mostly affected, physical, chemical, or biological. The type of impact represents a group of impacts correlating with a specific human activity involved. Besides that, impact severity to soils depends on disturbance intensity and occurrence, area disturbed (point, whole plot disturbance, wide area disturbance), relaxation time or how long it takes for the ecosystem to restore initial soil properties to reduce negative consequences to the same background values. It is also important to estimate the probability of irreversible changes to soil properties.

2.2 Types of human impact

There are four types of human impacts suggested which occur under the following activities: forest management, agriculture, pollution, and demography (*Figure 2*). These types of impacts effect soil differently. For example, logging operation represents a short-term transformation, where chemical pollution may occur for a relatively long period of time producing a cumulative effect. Threshold values are different for various soils and are often unknown which, therefore, makes the assessment of borderline effects very complicated. Thus, negative consequences of recreation emerge when some critical value is crossed – either the amount of people visiting the forest or the amount of hours the soil is subjected to pressure. Besides the negative consequences, this impact might produce a positive effect in certain limits: for example, nitrogen saturation in boreal forests is regarded to be favorable for plants up to certain value of N accumulated.

Forest management includes two such common activities as cutting operations and wildfires subdivided according to procedures applied in the case of logging or according to fire type. Despite the fact that immediate impact can be very strong, post-impact changes of soil are also of great importance. Natural reforestation can produce quite different results than silvicultures planted by humans. Agricultural activity is subdivided into tillage (soil treatments) and grazing. Pollution or technogenic impact combines all types of pollution that occur through atmospheric fallout. Demographic pressure represents activities resulting in the increase of space occupied by humans and roads as well as in intensified pressure to soils used as recreation area or just switching land to another use.

3 Logging Operations and Forest Soil Properties[1]

3.1 Types of logging technology and site peculiarities

In order to estimate the effect of logging operations to soil properties, it is necessary to recognize the fact that consequences of such influence depend not only on the type of logging activity applied, soil conditions and habitat type, but also on spatial peculiarities of the disturbance occurrence. The most significant impact to soils is made by heavy technique; however, this influence takes place only for a short time to evaluate all likely indirect changes

[1] The author thanks Makarova for giving additional material from the unpublished doctor degree thesis (1994) devoted to effect of heavy machines.

I. FOREST MANAGEMENT

1. Logging Procedures

- Clearcutting
- Thinning
- Skidding
- Site Preparation
  - Melioration
  - Soil Treatment
  - Fertilization
  - Pesticides Application
  - Prescribed Burning

2. Wild Fires

- On-ground Fires
  - Steady
  - Superficial
- Crown Fires
- Soil Fires
  - Peat
  - Soddy
  - Litter

3. Forest Regeneration

- Natural
  - Old-field Succession
  - Post-clearcut Succession
  - Post-pyrogenic Succession
- Forest Plantation
  - On Mines Dumps
  - On Cleared Sites
  - On Burnt Down Sites

II. AGRICULTURE

1. Tillage

- Soil Treatment
- Pesticides
- Fertilizers
- Melioration
- Crop type

2. Grazing

III. POLLUTION

1. Atmospheric Pollution

- Sulphur & Nitrogen
- Heavy Metals
- Radioisotopes
- Organic Compounds
- Solid Compounds

2. Ground Pollution

- Mining
- Quarrying
- Oil & Gas
- Waste
- Sewage

IV. DEMOGRAPHY

1. Infrastructure & Construction

- Buildings
- Roads
- Wasting
- Pipelines
- Electric Transmission Lines
- Hydraulic Engineering Constructions

2. Recreation

- Tourism
- Collecting
- Urbanization

Figure 2. Types of human impact on soils of the boreal zone.

of soil properties. Therefore, it must be a subject of very close analysis as occurrences of this effect are increasing.

It is certain that cutting technique determines the type and severity of impact. Habitat properties provide ecosystem tolerance toward impact and also show the direction of further successional changes of vegetation as well as soils. However, published data sometimes reveal quite controversial results of clearcuts for almost all basic soil properties. This supports the idea that we must be very cautious when trying to transfer our previous experience from one ecosystem to another, taking no consideration into shift of natural conditions.

The depth of soil impacted by the logging operation is presently under discussion. Pobedinsky (1973) considers it to be 50 cm for clayey loamy sands (all tree root system layer). Other investigators estimate ranges from 20–25 cm (Danilyuk, 1979; Barantsev and Sannikov, 1990), 15 cm (Shakunas and Bistritskas, 1962), up to 10 cm (Kholopova, 1987). However, it is quite clear that when soil is eroded, the subsurface horizons are exposed or are subjected to transformations.

There are two principal groups of logging activities effecting soil properties in different ways. However, it is more convenient to subdivide logging operations into three groups outlining the intermediate one: weak, medium and strong. The weak impact influences soil properties indirectly, changing radiation regime (less stand basal area), water regime (less evapotranspiration), and also effecting stand composition and structure. The weak impact implies all types of selective cutting, gradual cutting, thinning and so on. The medium impact is made by clearcutting, when no heavy machinery is used. This comprises the most part of known information about soil properties change on a long-term basis. These two types differ very much from the strong impact done by heavy machinery. However, almost all clearcutting is carried out with heavy machinery and it is very difficult to learn the consequences for soils.

The severity of impact and soil evolution also depends on topographical environment (mountains vs. plains), habitat and soil type, occurrence of logging operations, area disturbed, weather conditions, and season of logging (Karpachevsky, 1981; Kholopova, 1987). Clearcuts made in the Tyumen' region showed that on well-drained sandy, loamy sandy and sandy loamy soils, up to 65% of undergrowth is preserved when high productive machinery is applied. Once on wet loamy and clayey podzolic soils with moss on-ground vegetation, and on wet loamy soils where bilberry waterlogging occurs during rainy periods, forest litter is pushed down into the soil and mounds are destroyed, especially in sites with multiple passes and trails (Temporary instruction, 1990).

The role of harvesting season is also of great importance (Ionov, 1935; Melekhov, 1954; Karpachevsky, 1981). It is known that in many regions of Russia, as much as 60% of timber is logged in the period with no snow cover which results in soil making and deteriorates soil physical properties, especially for soils with clayey loamy and clayey texture (Shakunas and Bistritskas, cited by Makarova pers. com.; Danilyuk, 1979). Also, when logs are cut down in summer and removed during winter, this leads to a much weaker disturbance of soil even under heavy machines (Boyle *et al.*, 1973).

3.2 Thinning, gradual and selective cutting

It is confirmed that a removal of trees causes significant changes in soil conditions (Ionov, 1935; Morozov, 1949; Pobedinsky, 1983; Melekhov, 1989; and others), resulting in a cutover radiation regime shift (Morozov, 1949; Melekhov, 1989; Remezov, 1989). Studies carried out by Remezov show that during the vegetational period the temperature of the clearcut is 5–10°C higher, and 6°C lower in cutover than in the forest. Thus, this increases soil temperature at deeper horizons in summer and provides deeper freezing in winter. It can be added that the same effect for permafrost soils may reveal quite different consequences than for forest soils without a frozen layer.

Remezov and Pogrebnyak (1965) consider selective and gradual cuttings to be similar to thinning in impact made to soils. A more significant temperature variation and stronger wind speed at cutover than in forest are indicated, increasing evaporation from the soil surface. However, in general, transpiration and interception decreases more significantly. The increase of soil humidity at 8–10% is reported by some authors. Gansen (cited by Remezov and Pogrebnyak, 1965) found that thinning caused soil temperature to increase to the depth of 60 cm, where Adams reported it to become greater in the upper 15 cm of soil. Also Gansen established that the stronger the cutting is made, the lower N content is determined in needles and litter. The removal of as much as 75% boles strongly increases the near-surface temperature (2.6°C vs. 0.8°C) for spruce-birch forest with soddy podzolic soils (Stefin, 1981). No significant change occurs when 25 or 50% of boles are removed. In deeper soil horizons (20 cm), the temperature is 1°C higher when 75% of boles are removed and more severe after clearcutting (Petrov and Stefin, 1975).

3.3 Clearcutting and heavy machinery application

Peculiarities of disturbance made by clearcutting depend on the felling strips width. Tree stand may effect open cutover up to a distance of 0.5–1 km. During harvesting operations, the most intensive impact to soils is made by heavy machines especially widely applied in the past decades. So, the strong impact is primarily produced by heavy machines which usually affect soil directly compacting it, mixing topsoil up with litter horizon, changing microrelief and initiating erosion. Nevertheless, heavy machinery technique outcomes all types of impact severity, which are unevenly distributed throughout the cutover area. For example, soil changes in skid row are quite different from those at the cutover patch. That is why many authors argue to evaluate the changes of soil properties, not for all cutover areas but for every element recognized (Sabo, pers. com.).

Application of heavy machinery, and specifically skidding, even in the early 1930s, revealed a significant influence to soil properties (Ionov, 1935; Melekhov and Zanin, 1935; Dekatov, 1936; Tkachenko, 1939). Pobedinsky (1973, 1982) divided all soil changes into three categories: improved, slightly changed, and deteriorated based on microrelief, physical and other properties change and also occurrence of seedlings regeneration at skid rows. He also found that it depended very much on soil texture and soil humidity conditions. The following factors, also influencing the disturbance severity, were added by other authors (Ionov, 1935; Melekhov and Zanin, 1935; Dekatov, 1936; Muller and Loeffer, both cited by Shetron, 1988): cutting technique and technology applied, cutting season, and weather conditions.

Heavy machinery, such as cutter pillar tractors, covers as much as 15–20% of the clearcut total area by skid rows. When harvesters, for example LP-19, are applied the total skid row area occupies up to 30–40% (Pobedinsky, 1983; Shakunas and Bistritskas, 1985). Mechanical skidding produces the greatest disturbance (Melekhov and Zanin, 1935; Pobedinsky, 1983; Muller, cited by Shetron, 1988). Harvesters VM-4 move across all the harvesting plot and their specific pressure is 3 times more than those of skidders (Pobedinsky, 1983). Therefore, soil surface is exposed at 90–95% of the total area (Danilyuk, 1979, Pobedinsky, 1982). Three types of disturbances are recognized for the Tver' region cutovers (Tselisheva *et al.*, 1991): strongly impacted – at 40% of the area; medium impacted – 50%; and weakly impacted -10%. The following clearcut sites were studied by Gorbachev *et al.* 1991: magistral and other skid trails, cutover sites impacted by different heavy machines such as VM-4, LP-19, LP-49, LP-18A. Comparatively, slight impact to trails and cutovers is made by MP-5 Ural-2 and skidder TT-4. They form runoff with a suspended flow just on magistral skid rows and the skidder mixes residues up with a soiled layer that decreases its erodability. The most sufficient soil surface is eroded by a combination of VM-4 and 2LP-18A: 80–85% of the total area and 60% to a significant degree that thoroughly destroys and irreversibly affects forest soil. Severe erosion is noted even for relatively sloped surfaces and on areas slightly damaged by clearcutting (15% of the total area). Application of LP-19 and LP-18 reduces erosion at 30-40%. Application of chain saw MP-14 and TT-4 does not disturb more than 15% of area. As a whole, the eroded area was more than 40% due to a bad clearcutting technique. On strongly impacted sites the soil profile is restored after several decades and profile differentiation is accelerated in hydromorphic conditions. Also according to existing data, it is more important to know the number of passes made than the machine type. The most damaged litter was found on the northern slopes where a skidder was applied (Bizyukin, 1983). On the southern slopes, where the narrow strips method was used, litter damaged 48% of the area and fully destroyed 22%.

3.4 Change of forest litter

The removal of litter horizon of gray forest soil results in much less successful planting (18.8% less samplings survived (Botenkov, 1983). In soils covered by light non-transparent plastic, moisture content is 11.3–15.4% more, temperature 1.4–4.0°C higher in the upper 20 cm. In patches with removed litter horizon soil bulk density is 6.3–60.2% higher. Covered soils are marked by a lesser level of nitrification and ammonification than virgin soils. Covered soils have 7.4–14.0 mg/100 g more mobile P in the upper 20 cm when compared with soils with removed layers, noted by the lowest nutritional state. Destroyed litter layer significantly deteriorates soil water-physical properties (Gorbachev *et al.*, 1991).

The litter layer thickness of the Arkhangel'sk region podzolic soils was the same for the undisturbed forest and the logged area undamaged by logs skidding (50% of cleared area) (Chertovsky *et al.*, 1983). It equaled 6.0–7.0 cm (ranging from 3.0 to 11.5 cm), 2.0–3.0 (0.5–5.0) to 5.0–6.0 (2.0–10.0 cm) thick respectively in spruce stand and secondary birch forest of different states. Reserves of litter in spruce forest were 50–65, cutover area 25–38 tons/ha, and birch forests 30–40 and 47–60 tons/ha (absolutely dry weight). Litter density is higher for birch forest (0.12–0.15 g/cm^3) when compared with spruce (0.10 g/cm^3). It ranges at the 1- and 2-year old cutovers in relatively undisturbed patches from 0.07 to 0.10 g/cm^3. Litter decreases water evaporation losses (2–3 times less than on plots without litter). Litter moisture content is 10-fold more than that of bedding mineral horizon. The 1- and 2-year old cutovers have a significantly higher water content than that of forest. It makes up (in parenthesis maximal water holding capacity in mm) in average for vegetation season 215% (40–65) in spruce, 200% (30–40) and 190% (15–29) in 90- and 40-year-old birch stand respectively, and 280–330% for the 1-year cutover. The amount of precipitation for one rain is rarely more than 10–15 mm. Therefore, runoff is absent in spruce stand and likely occurs in birch stand only during snow melting.

At fresh cutovers in the Pre-Baykal region studied by Bizyukin (1983), forest litter was destroyed or mixed up with soil at 43–65% of the total area. The preserved part had the thickness of 2 cm, reserves of 19 tons/ha, maximal water holding capacity was 4.6 mm. After selective cutting the maximal litter reserve is found near bole (*Tables 1* and *2*; see also Stefin, 1981). For the clearcut site it was maximal under crown as well as litter bulk density. This property is the most affected during logging. Bulk density in gaps was even lower than in the control due to topsoil loosening when skidding. Skid row is featured by the greatest litter reserve due to slash residues present, where it is the least for the selective cut plot. Clearcut and skid rows are featured by the increased percentage of hard litter fraction, where it is not changed in the selective cut. Right away the clearcut slash residues play an important role in the regulating of evaporation, however, near-surface temperature is higher. Moisture content, during several years of observations, was the maximal in skid row, somewhat less for clearcut, and almost the same for the selective cut. The 50% thinning reduced litter reserves of soddy podzolic soils, however, the slash residues left behind increased them 4-fold. The litter horizon was not preserved after clearcut. During 3 years, the reserve of forest litter decreased from 10–12 tons/ha to zero. The 50% thinning resulted in an increase of the forest litter reserves due to accumulation of slash residues of birch and aspen. The litter decomposition in cedar stand becomes more intensive after clearcutting and even greater for birch and aspen stands. The litter decomposes during the first 1–1.5 years, restores to modern type during 20–40 years and is differentiated to 0_1 and 0_2 layers by 60 years in the Tver' region (Tselisheva *et al.*, 1991). Fedorets and Sokolov (1983) studied a dependence between litter properties and cutover moisture and observed a litter thickness increasing from 2 to 7 cm and still very variable when moisture content increases. The decomposition rate is very low which is supported by a wide C:N ratio in litter (49–61) in the northern taiga. It is narrower (23–25) for the middle taiga zone. N content is low and varies depending on cutover type from 0.67 to 0.80 in the northern taiga and from 0.77 to 1.8% in the middle taiga. The

Table 1. Litter of soddy calcareous soils (after Stefin, 1981).

	Forest litter reserves, tons/ha			
Plot	Soft fraction	Hard fraction	Total	Thickness, cm
Selective	15.8	2.8	18.6	2.0
Clearcut	15.7	4.3	20.0	1.8
Skidding	33.8	12.2	46.0	3.3
Control	18.9	3.7	22.6	2.2

Table 2. Spatial distribution of litter for soddy calcareous soils (after Stefin, 1981).

Plot	Bole			Crown			Gap		
	Thickness, cm	Reserve, km^2	Bulk density, cm^3	Thickness, cm	Reserve, km^2	Density, cm^3	Thickness, cm	Reserve, cm^3	Bulk density, cm^3
Selective	2.5	2.27	0.91	1.8	1.76	0.09	1.6	1.65	0.10
Clearcut	1.6	1.59	0.1	2.2	3.13	0.14	1.7	1.29	0.08
Control	2.1	2.31	0.11	2.5	2.24	0.09	2.1	2.24	0.11

mobile P and K amount is low and ranges 7–14 and 38–55 mg/100 g of dry weight. When cutover area is burnt down these parameters are lower.

All changes at the 1-year old cutover in Karelia are attributed to movement of organic matter decomposed during the previous vegetational season (Zagural'skaya, 1983). The amount of ammonificators and micromycets decreases once that of oligotrophes increases, comprising 23–60% of the total microflora amount in the litter. Enriched in N, the cutover is marked by an appearance of cellulose decomposers, as well as an increase in anaerobic N-fixing organisms. However, the total amount of microorganisms is low and N cycling ends by ammonia formation (up to 80.5 mg/100 g in patches with preserved ground cover).

Effect produced by thinning and clearcut was estimated by Remezov and Pogrebnyak (1965, *Table 3*). Forest litter, after thinning, was poorer in N and richer in ash elements. During the second year an increase in ammonification capacity was detected. This may result in a decrease of N available. Nitrification was weak everywhere, however it was stronger for thinned stands. Mobile P content (by Truog method) showed an increase when stand was thinned. Nutrient content in litter was observed but did not vary significantly in Scotish soils. However, the maximal litter amounts were found for the least treated plot, where it was maximal at the mostly thinned plot (Wright, 1957). Litter reserves increased in thinned patches (*Table 4*; see also Sviridova, 1959, 1960). Mineralization of litter was faster for thinned plots, and water soluble compounds content in forest litter (K, Ca, Mg) was also higher for thinned plots.

After 10 years, 13% (B), 26% (C), and 38% (D) of the trees were cut down, analyzed and compared with control (A) (Remezov and Pogrebnyak, 1965) in forest-steppe. Thinning caused a decrease in its water holding capacity (0.8 mm for the control and 0.5 mm for 38% thinning stand). This promotes more fully water percolation into soil. Thinning also resulted in an increase of exchangeable K content: A-27%, B-30%, C-38%, D-45%. The NH_4 content also increases with an increase of thinning intensity. Mobile NH_4 and P had the maximal accumulation 10 days after thinning and decreased thereafter. The accumulation was then greater when more intensive treatment was applied. Nitrification was lower and unaffected by thinning.

Table 3. Total N in % in sample dried out under 100°C (after Remezov & Pogrebnyak, 1965).

	Forest litter		
Disturbance	Needles	F layer	H layer
Control	0.55	1.06	0.34
Weak cutting	0.47	1.10	0.25
Strong cutting	0.44	0.98	0.22

Table 4. Change of the forest litter amount by thinning (after Sviridova, 1959, 1960).

Aspen stand, years	Control, tons/ha	Thinning, tons/ha
15	3.118	3.328
30	2.511	2.996
55	2.732	2.762

3.5 Change of soil moisture regime

Clearcuts affect the soil water balance by increasing the amount of precipitation which reaches the soil surface (Morozov, 1949; Karpachevsky, 1981; Melekhov, 1989) initially intercepted by tree crowns. For example, spruce stand is responsible for 55–50% of the annual precipitation interception (Melekhov, 1989). On the other hand, the amount of transpired water declines significantly due to the removal of trees (Koshcheyev, 1954; Melekhov, 1989). According to the data obtained by Koshcheyev, water surplus in the clearcut spruce-broad leaved stand is 300–400 mm per vegetational season due to declined transpiration. Similar figures are received by Karpachevsky (1981) for spruce stand with grass-moss cover. Also physical evaporation is found to be increased. Infiltration rate in cutover is reported to diminish from 33–75 mm/min to 1.2–1.7 mm/min which leads to increased superficial runoff after skidding (Gorbachev *et al.*, 1991).

Water regime of cutovers differs from undisturbed forest, stronger each year during the first years after the disturbance. The reason for this is due to a transpiration decline, an increase of evaporation, surface runoff, and water percolation downward (Stefin, 1981). This is why in fresh clearcuts in the boreal zone, water balance is formed with a surplus of water input over output. All this may result in soil humidity increase as well as waterlogging occurrence (Koshcheyev, 1954), especially in depressions (Dedkov, 1987). Water is saturated with organic-ferruginous compounds sedimentated at the soil surface. Slash residues mixed up with soil give rise to reduction processes (H_2S is detected). Waterlogging occurs not only in cutover areas but also in upward lying parts of slopes, and even in tops with undisturbed forest stand due to groundwater upraising. Post-clearcut gleying features are especially strong during the first years (5–7 years). They gradually die out, but are still present in brown podzolic soils after 13–15 years. Bogging features are found for soils with poor drainage (Karpachevsky, 1981; Pobedinsky, 1983). Undecomposed organic debris is accumulated at the soil surface, especially as iron in clearcuts of wet spruce-bilberry stand. Two crucial stages in soil evolution are recognized (Dedkov, 1987): the first years of disturbance (breaching of bounds between soil and tree stand) and 15 years after disturbance when gleying and sodding are substituted by typical processes and accompanied by the most significant soil properties change. It takes 40 years for soils to restore to their previous state.

3.6 Change of soil bulk density and structure

Much information exists on soil compaction after clearcut (Pobedinsky, 1983; Isayev and Pobedinsky, 1977; Temporary instruction, 1990). Some authors indicate that soil bulk density increases after clearcut to 20–40% (Karpachevsky, 1981), in 1.5 times (Shakunas and Bistritskas, cited by Makarova, pers. com.), in 2.5 times (Danilyuk, 1979). Soil bulk increase is noted up to a depth of 30 cm in soddy podzolic soils by heavy machines and it is strongly compacted up a depth of 20 cm (Stefin, 1981). Soil compaction is responsible for the following negative features for plant growth: worse gas exchange, water percolation and infiltration rates decrease (Kreh *et al.*, 1981; Dickerson, 1976). Increased bulk density decreases volume and height of trees and seedlings (Auspurger *et al.*, Hatchell *et al.*, Youngberg, all cited by Shetron, 1988). The amount of water available for plant growth also declines, especially for soils with fine texture. For example, in soils with bulk density of 1.5–1.7 g/cm^3, the quantity of available water approaches minimal field capacity. Root penetration may be restricted due to compaction effect tree growth and structure. For example, bulk density of more than 1.30 g/cm^3 prevents loblolly pine radicle penetration (Foil and Ralson, 1967); porosity less than 50 (bulk density 1.32 g/cm^3) restricts root growth and penetration (Trouse and Baver, 1962). The nutrient dynamics also deteriorates (Muller, cited by Shetron, 1988). As far as N content is concerned, ammonification, nitrification and often nitrofixation diminish sharply, once negatively evaluated denitrification elevates.

The most severe impact to the soil compaction is produced by skidding operations. Severity and size of its impact depend on technology, skidding distance, number of trips by the machines on the same skidding site, soil texture and humidity. Many authors (Isayev and Pobedinsky, 1977; Karpachevsky, 1981; Tselishcheva *et al.*, 1991) identify specific horizons formed in skidding sites. They are called artificial layers and are featured by the following: heterogenic structure resulted after different soil horizons and slash residues mixing up; compact layering with developed regular clay particles orientation; low porosity; deformed irregular pores, often having different structure. The mentioned changes in horizon morphology are typical for microdepressions (Karpachevsky, 1981).

The bulk density in skid rows increases at 27.7% in the upper 10-cm layer of soil in loamy sand soils (pine stand with variable grass ground cover), and 57.9% to the depth of 25 cm of coarse loamy soils when compared with the control. The bulk density increases at 77.3% in skid row of moistened bound sands in pine stand and up to 169.8% for humid clayey loamy soils when compared with the control (Barantsev and Sannikov, 1990). Already after the first pass of LP-19 the row depth is 4–5 cm, it is 4–5 cm after 10 passes, it then increases to 6–7 cm, and up to 8–10 cm after 20 times. In Western Siberia after 2–3 times the trail becomes almost impassable, therefore the new skid row is used, finally they can occupy almost all the cutover area (Temporary instruction, 1990). Bulk density is increased by heavy machinery in 1.5–2 times, total porosity decreases at 20–30% (Gorbachev *et al.*, 1991)

The data obtained by Shetron *et al.* (1988) for multiple passes and loading during selective cutting shows that the bulk density increases to 0.80 g/cm^3 in a layer of 0–5 cm immediately after tree felling, storing and skidding in places of intensive impact; it was 0.42 g/cm^3 in the undisturbed site. It was established that the first passes were the most responsible for the soil compaction. Reaves and Cooper (cited by Shetron, 1988) observed the maximal compaction in the center of the truck wheel at the depth of 0–7.5 cm. During the year after the disturbance no other significant restoration of the soil bulk density was marked (Shetron, 1988). It was still significant after several years (Dickerson, 1976; Froehlich *et al.*, 1985; Kreh *et al.*, 1981).

Sannikov and Barantsev state that it takes 20 years to restore soil properties after resin collection in the Kirov region. Bulk density of the skid row is restored only to a depth of 5 cm. According to Pobedinsky (1982) soil water-physical properties restoration does not occur even after 25 years. Sabo (pers. com.) estimates the bulk density restoration time to be 25 years for weakly impacted soddy podzolic soils and up to 60 years in heavily impacted. The latter has a worse stand growth and is more susceptible to natural and anthropogenic influences. Leaving of slash residues in skid rows decreases the restoration time to 8 years for the Middle Urals.

Soil structure is also transformed under logging operations. At skidding rows and cutovers microaggregation decreases in the upper layer, and increases in the bedding part of soddy calcareous soils A horizon when compared with the control stand (Stefin, 1981). Water-soluble aggregates were the most abundant in skid rows. There were also somewhat more of them in the 5–20 cm layer of clearcut plot than in the control. Macroaggregation is not changed significantly after cutting. The amount of water-stable aggregates decreases. Water stable aggregates content in the 30 cm layer, and even deeper, increases under 50% thinning and decreases after clearcut. Soil microaggregation reduces after clearcut (dispersion coefficient increased 3-fold). Soil structure becomes worse, and the amount of water-stable aggregates were reduced 5–6 times in the Krasnoyarsk kray (Gorbachev *et al.*, 1991). The amount of aggregates greater than 10 mm increases on eroded sites from 2–5% to 55–60%, where the number of water-resistant ones of more than 1 mm reduces from 25–40% to 8–10%, respectively (Gorbachev *et al.*, 1991).

3.7 Change of soil chemical properties

Data on soil chemical properties change, immediately after clearcut, are very controversial. Actually, logging operations cause no immediate change of soil properties. Instead, they lead to indirect change affecting temperature regime (humus mineralization likely to start), water regime (waterlogging, therefore organic matter conservation). However, when litter and topsoil layers are disturbed the question arises how to evaluate organic carbon losses, because the first is often mixed up with soil after clearcut. Soil compaction may restrict the depth of root penetration and affects water properties, where loosening and removal of the vegetation cover may result in accelerated humus mineralization (Kholopova, 1987), as well as humus accumulation due to more abundant grass vegetation and mixing of slash residues and forest litter with soil (Orfanitsky *et al.* 1959). Soil acidity increases or becomes neutral (Morozova, 1964). Reduced litterfall decreases C input, and plant succession can be, not only accompanied by different patterns for soil organic matter accumulation, but also by a change, to some extent, of chemical composition of organic material input as well as soil humus. This, together with soil peculiarities, yields quite different results for various regions.

Johnson (1992) summed up the material on harvesting alone and with other treatments (13 studies). Soil C change varied significantly from site to site and no main trends were discovered. Most of the studies showed small changes of less than 10% or no effect. Thus, harvesting alone has no or very slight increase in soil C. The main shift is observed only in the top 15 cm of soil. Statistically, significant differences show a more reducing effect. Site preparation may affect soil C quite considerably and depends on the disturbance severity. However, it is very difficult to distinquish changes made due to bulldozing into slash piles or to decomposition. Also, the effect varies with both site and treatment. Sometimes no change was found when chopping, burning, windthrowing, KG-blading, disking and bedding were applied. Site preparation has a positive effect to soil C content.

In slightly impacted soddy podzolic soils the sod horizon develops in topsoil, further transforming into AE horizon similar to the zonal soil (Tselisheva *et al.*, 1991). Soil of undisturbed sites form thicker humus horizon. When compaction of topsoil takes place gleying is found. Strongly impacted soils are bogging up and finally form soils with gleic features. In strongly affected soils of dry habitats the humus formation dominates during first years. Twigs, branches and other residues are mostly humified only after 10–15 years, and they become centers of humus horizon formation. Around them, the main part of the plant roots and fungi hyphens are situated. In more humid habitats (in skid rows) gleic horizons or morphons are formed, or humus horizon is absent, and organic material is carbonized due to eluvo-gleic process. Undisturbed sites are similar to control soils, but litterfall decomposes during 1–1.5 years.

The first years after clearcutting, the maximal humus contents are recognized for undisturbed and medium disturbed soils: 9.6 and 7.2% respectively, where the minimal for soils in skid rows is 5.6% (Tselisheva *et al.*, 1991). Humus content increases in thinned plots on gray-brown forest soils: for the 30-year old stand in the control – 1.48% and 1.86% in thinned; for the 50-year old stand – 2.32% and 2.69%, respectively (Sviridova, 1959, 1960). C and N content of the cutover is two times less, where P is 1.5 times for soddy podzolic soils of Siberia (Gorbachev *et al.*, 1991). Soil humus content increases in all profiles of Trans-Baykal soddy podzolic soils after cutting, with the similar data reported for soddy podzolic soils and gray forest soils (Stefin, 1981). Thinning and clearcutting increases humus content in clearcut up to 18% and decreases exchangeable acidity. Actual acidity is the same in the upper horizon. Montane soddy forest topsoil becomes more acid after clearcut in pine stand. Humus, N, P, and base cations content also decreases. C:N ratio is broader in the clearcut plot. Clearcut larch stand also has more acid in the upper horizon and a decreased amount of P and K but with higher humus content. Yer and Wilde (cited by Stefin, 1981) found soil humus content decreased for soddy sandy alluvial soils after 50% thinning and clearcutting for pine forests, starting from the control value in the upper 15 cm soil layer: 1.93, 1.37 and 1%, respectively. Humus accumulation is not observed after selective cutting in Siberia (the Baykal and Krasnoyarsk), where it was found for the European part.

Total N content increases 1.5–2-fold during the first year comparatively to forest. Acidity becomes much lower (4.0) and depends less on the disturbance degree (Tselisheva *et al.*, 1991). More intensive thinning resulted in less soil C content (Wright, 1957), and also a significant P and Ca and slight Mg and K decrease. Total N content increases and C:N ratio becomes narrower. The author states that the most important is the decrease in the amount of trees at the plot. Easily decomposable N content somewhat increases, where mobile K and P is insufficient in gray forest soil of the Voronezh region after thinning (Remezov and Pogrebnyak, 1965). Exchangeable Ca and K, mobile P slightly increases, hydrolithic and actual acidities decreases. The more significant changes were noted if to recalculate all the data per one tree. The nutrient content became somewhat higher for thinned plots. The amount of mobile nutrient (N, P, K, Ca) increased in forest-steppe soil with more intensive cutting (Remezov and Pogrebnyak, 1965). The nutrient reserves distribution in the 50 cm layer was the same Karelian soils after clearcutting (Fedorets and Sokolov, 1983). Secondary carbonatization is found in the disturbed forest, together with Ca leaching in deep horizons (Stefin, 1981). An increase of leaching occurs after clearcutting on a sun-exposed slope and a decrease is marked on a shady one. The shady clearcut stand is featured by C, N, base cations increase and broader C:N ratio. The soil acidity was lower. Petrapavlovsky (1983) studied a change of forest soils after thinning and clearcutting with 0.7 and 0.5 basal area left. Hydrolithic acidity and cation exchange capacity by Kappen (mg-eq/100 g of soil) are respectively: in a stand of 0.7 – 42.84 and 86.0, 0.5 – 33.60 and 75.88, whole harvesting – 28.54 and 82.0. So, hydrolithic acidity decreases with forest thinning.

3.8 Change of soil microbiological properties

This type of impact is studied to a limited extent. The main part of the work is devoted to the effect of clearcutting, soil microorganisms decomposing, and transforming variable organic and mineral compounds within soil. Clearcutting influences microbiological processes in forest-steppe differently in litter and humus horizon (Yegorova, 1970; Pushkinskaya, 1962). The amount of non-spore bacteria, cellulose decomposers and others, decreases in forest-steppe zone due to drying out, once their number in the soil increases. In the forest zone, it accelerates the decomposition in both forest litter and soil. Shubin and Danilevich (1965) report that small reed clearcuts have much more abundant microflora than meadows of Southern Karelia.

The type of clearcut formed affects microbiological properties as well. Tvorogova (1974) showed that on meadow formed after spruce-bilberry stand clearcut, the amount of ammonificators increased for the first year and declined thereafter. Soil of the Karelian cutover is less biogenic even though it is enriched in mobile N (Zagural'skaya, 1983). Loosened and mixed litter layer has the richest microbic cenose, though when mineral horizons are exposed, the lack of mobile N is observed with total microbiological activity reduced. Degree of disturbance also determines the abundance of microorganisms. Gorbachev *et al.*, 1991 found that the total amount of the microorganisms on control plots is 10–12 times more than those with severe disturbance after VM-4 and LP-18A. Microbiological activity was maximal for 50% thinning and smallest for clearcutting when compared with control (Stefin, 1981). Very low content of H^+ is typical for cutover area (10-fold less). Microbiological processes are higher in cutover and especially in skid row (at 1/3 more than in forest) of soddy calcareous soils (Stefin, 1981). Microbiological activity increases almost 7-fold in the Krasnoyarsk region after clearcut. It is less for the Selenga region, and even less than that in the native forest of the Baykal region. In the Baykal region the maximal decomposition of cellulose was found for 50% selective cutting, where it was for 95% cutting in the Krasnoyarsk region.

These processes proceed differently during the vegetational period depending on soil type, disturbance degree, soil moisture content and clearcut size (Yegorova, 1970). In spring and the beginning of summer they are much more active in forest than in clearcut that loses water faster due to physical evaporation. Narrow clearcuts (35 m) have higher humidity and therefore more abundant microflora when compared with wide clearcuts (50 m). Besides that, microbiological activity is distributed unevenly within clearcut. In spring, there are much less microorganisms in the center of a clearcut than near the forest edge. In summer this relation becomes opposite and microflora is much more abundant in the center than near the edges.

3.9 Summary

Logging operations may be subdivided into two groups according to impact made to soil: (1) all types of thinning, selective and gradual thinning; (2) clearcutting usually accompanied by disturbance made by heavy machinery. The latter is responsible for the greatest physical soil disturbance. The first group affects soils similar to natural processes of tree falling occurring in primary forest. The second group comprises all types of disturbances however unevenly distributed spatially. The more trees removed, the more plant composition transforms and the greater the changes expected for soil properties. Physical disturbance made by heavy machines leads to soil property changes quite distinctive for natural disturbances and unknown probability of irreversible changes. Erosion losses, especially in montane conditions may follow the clearcutting. Permafrost soils change after clearcuts is very unclear.

Litter removal, compaction and disaggregation deteriorate soil physical properties, mainly changing soil erodability, bulk density and water regime. Ecosystem properties (and specifically soil), type of impact, time of logging, and scale of disturbance determine possible consequences of such changes. "Weak" impacts made to "tolerant" soils in favorable bioclimatic conditions likely stimulate soil processes and lead to humus and nutrient availability increase and more thoroughly decomposition of forest litter. Quick reforestation of the plot with slightly deteriorated soil physical properties allows the ecosystem to restore to its previous state. Depending on local conditions, humus content may increase or decrease after impact. In many cases it can be attributed to probability and continuation of waterlogging occurrence. However, the quality of such organic matter accumulated in wet soils, as well as its future fate after gleying features disappearance, is not clear. Strong impact is very unevenly spatially dispersed and intermingled with all other types of impacts. Such soils are expected to have a much longer relaxation time or even featured by irreversible changes in soil properties and ecosystem. Thus, very often it is difficult to estimate the severity of the impact for a particular cutover. A scale of disturbance under clearcutting might result not only in drastic local changes but in regional environmental conditions as well.

4 Wild Fires and Soil Properties

4.1 Forest wildfires

Wildfire is not the impact created by human and persists in some ecosystems for millions of years (Wein, 1993; Clark and Robinson, 1993). However, causes of this disturbance nowadays are mostly human-dependent. For example, the amount of wildfires caused by humans in Russia is more than 80% for last years. Area disturbed by fires is also significant (*Table 5*). Wildfires are usually subdivided into three groups: on-ground, crown and soil. Also among soil fires the following types are recognized: peat, litter and soddy fires. Steady and superficial on-ground fires are distinguished by a character of fire spreading. On-ground fires are estimated to occur at 80% of all burnt areas in Russia, while crown fires refer to about 20%, peat fires to several thousands of hectares annually (*Table 5*; see also Shvidenko *et al.*, 1994). The total burnt area is provisionally assessed to be about 3.5 ml ha, including 1.8 ml ha on forested lands, 0.8 ml ha on unforested and 0.9 ml ha for non-forest lands (Shvidenko *et al.*, 1994).

Table 5. Types of forest fires in Russia and burnt areas (ml ha) in 1988–1992 (modified after Shvidenko *et al.*, 1994 and "White Book", 1993).

	Categories of land			Types of fire			Number of fires, thou.
Region	Forest	Forested	Non-forest	On-ground	Crown	Peat	Total
1988							
Russia		0.76					
1989							
Russia	1.63	1.50–1.51	0.41	1.25	0.25	0.01	21.9
West Siberia	1.13	1.10	0.28	1.04	0.06	0.00	6.6
Far East	0.40	0.32	0.12	0.14	0.18	–	2.3
1990							
Russia	1.37	1.32–1.38	0.30	1.04	0.27	0.00	17.7–23.5
West Siberia	0.72	0.69	0.05	0.48	0.27	–	7.7
Far East	0.61	0.59	0.27	0.52	0.07	–	3.0
1991							
Russia		0.61–0.69					18.0–10.0
1992							
Russia		0.60					18.0
Total		4.81					

Besides the real wildfires, humans use prescribed ones mostly for burning slash residues after clearcut. Scale of that impact influence on soil is under discussion also. Besides that, it is very difficult to separate this type of impact from clearcutting itself. Disturbance to soil made by fire depends on ecosystem properties and also on fire intensity. It is found that the impact of strong fire may lead to quite different consequences than that of weak fire. Steady on-ground fire and crown fire refer to very intensive effects, impacting soil as well as vegetation decreasing its ability to restore quickly after that. The effects of strong fires are similar to those of clearcutting, increasing abiogenic processes such as ferruginazing and secondary carbonatization, where weak fires are not similar to thinning, causing an increase in soil leaching and podzolization. Fire consequences are more variable and, besides climate and relief, depends on soil texture, amount of water resistant aggregates, occurrence rate, and dynamics of every fire event.

Fire frequency occurrence for one plot is a very important value to understand how often an ecosystem is disturbed and what the role of fire is in ecosystem formation. Many authors consider fires to be the main forming factor for many Siberian ecosystems, where forests are unable to reach the climax state due to natural wildfires. Wildfires are regarded to be useful in northern ecosystems on soils with permafrost. These soils have a thick litter layer that is a sink of nutrients becoming a source of them after fires. Wildfires intensify nutrient cycling and microbiological processes and promote trees re-vegetation, increase active soil layer, prevent soils from bogging (Sheshukov *et al.*, 1992). Fires are thought to be a negative feature for conifer-broad leaved stands with easily decomposable litter layer. That is due to nutrient release and leaching following fires, and also tree and seedling damage.

According to Stratonovich, wildfire occurrence is 150–200 years for pine stand and 40–60 years for pine stands of xeric habitats (Remezov and Pogrebnyak, 1965). Spruce forest burns rarer but it is more susceptible to fire. Admixture of broad leaved species diminishes probability of fire occurrence. Occurrence of fires in West and Middle Siberia (*Table 6*; see also Furyayev, 1988) is 135 years for floodplains, 26–55 years for spruce stands of slopes and gently rolling terrace surfaces, 15–25 years for pine stands of slopes and flat terraces. It is 30 years for fir and spruce stands of rolling flat surfaces, where those under pine stands and of steep slopes is 70–85 years. Frequency of fire occurrence only for pine stand varies significantly and depends on habitat type. It is 5–30 years for pine forest on dry sands and on loamy sands wet habitats, and 71–100 years for peaty, humid and bogged pine woods, and more than 100 years for same forest in bottoms (Furyayev and Zlobina, 1983). A review compiled by Wein (1993) demonstrates that for North America fire frequency ranges from 50 years in pine-dominated forests to more than 100 years in spruce-dominated. Consequential plant successions are shown to depend on fire peculiarities in Scandinavia and North America (Furyayev and Kireyev, 1979). Full restoration of dark crown conifers takes place for 180–240 years.

4.2 Change of forest litter

Intensive litter accumulation increases the likeness of fire and its potential intensity, in turn, 5–6 year periodicity of fire suppresses forest regrowth. Fire events may occur several times during the life of one tree generation in the Trans-Baykal region. Thus, the more disturbed plot the slower restoration occurs, the less likely fire event takes place. Near surface

Table 6. Frequency of wildfires in different types forest in the Western and Middle Siberia (after Furyayev & Kireyev, 1979; Furyayev, 1988) and other regions (Wein, 1993).

Frequency, yrs	Dominant vegetation type	Place	
22–110	pine to spruce	S to NW America	Wein & MacLean (1983)
5–20	pine	Minnesota	Clark (1990)
25	pine	NE China	Goldammer & Di (1990)
80	pine & spruce	Sweden	Zackrisson (1977)
100	spruce	N. Quebec	Payette *et al.* (1989)
400	spruce	S of treeline W. Canada	Timoney & Wein (1991)
500	spruce & fir	Labrador	Foster (1983)
400–1200	larch	NE China	Goldammer (1993)
20	pine and spruce	high lacustrine-alluvial fluvio-glacial weakly bogged Kas-Yenisey erosion plain	Furyayev & Kireyev, 1979
110	cedar & pine	elevated lacustrine-alluvial loess and fluvioglacial weakly bogged Ket plain	Furyayev & Kireyev, 1979
70	spruce, cedar & pine	high drained lacustrine-alluvial loess and fluvioglacial weakly bogged Ulu-Yul-Chulym plain	Furyayev & Kireyev, 1979
65	spruce & pine	lacustrine-alluvial loess and alluvial strongly bogged lower Chulym plain	Furyayev & Kireyev, 1979
50	spruce & fir	high lacustrine-alluvial loess and alluvial-deluvial drained Tom'-Yay plain	Furyayev & Kireyev, 1979
52	spruce & fir	elevated drained lacustrine-alluvial loess Chet plain	Furyayev & Kireyev, 1979
40	spruce, fir & cedar	elevated erosion plain	Furyayev, 1988
14	pine & bogs	high drained terrace	Furyayev, 1988
135	spruce, cedar & bogs	small rivers floodplains	Furyayev, 1988
40	spruce	waterlogged terraces with slopily rolling relief	Furyayev, 1988
135	spruce, fir & cedar	modern high floodplains with slopily rolling relief	Furyayev, 1988
30	spruce, fir & cedar	high terraces with slopily rolling relief	Furyayev, 1988
16	pine	streambeds with low sandy terraces	Furyayev, 1988
185	bogs, meadows, willow & poplar	alluvial weakly elevated bogged the Chulym-Key'-Ob' plain	Furyayev, 1988

temperature during the fire ranges from 300–500°C to 600–700°C and can be more. On-ground fire slows down decomposition processes and increases litter accumulation rate. For example, litter reserves increased from 500 to 800–1000 g/m^2 during 3 years following the fire, where in the unburnt site they increased from 800 to 1000 m^2. Strong intensive fire burns down upper layers of forest litter more thoroughly with lower partly decomposed parts becoming significantly carbonized.

Remezov and Pogrebnyak (1965) estimate the soil burnt layer after on-ground fire to be 1–2 cm thick and total C and N losses are found 0.15–0.4 and 0.01–0.02 tons/ha, respectively. Slash residues and tree roots are important sources of organic material input into soil. Post-clearcut burning leads to greater N losses as well as likely K and S. Also Smirnova (1970) found that bilberry barrens formed on burnt conifer stands make water-physical soil properties worse due to a crust formation of burnt mosses. That stimulates surface runoff and water erosion development. After intensive fire at the Far East a fragile crust 1 cm thick is formed from forest litter burnt down (O_3+A) (Sapozhnikov and Kostenkova, 1984). It is transformed into so-called pyromul horizon 2.2 cm thick after 3 years, overlying buried O_2 horizon. Above the first horizon a formation of a new litter horizon takes place (3.7 cm thick). By the 7th year after the fire pyrogenic features still persist. Fulvic to humic acids ratio decreases. It takes 7–10 years for the Far Eastern forests to restore to the previous state. The litter accumulation for 6 years after fire is 800–1000 g/m^2 (Nemchenko, 1983) in the Far East. A litter layer 0–4 cm thick of the control stand nevertheless contained needles and twigs as well as some charcoal, after fire occurred in the Baykal region (Baranov and Stefin, 1978). Weakly damaged stand has a litter layer of 0–2 cm thick (92%), containing charcoal, medium damaged one (strong on-ground fire) has a 0–1 (65% from the initial reserve) cm thick litter layer, twigs and branches are partly carbonized. Strong (somewhere crown) fire destroyed all vegetation, litter doesn't cover all soil surface. A litter layer was 0–3 cm thick (42% from the initial) with a significant content of ash and charcoal. Grass vegetation covers burnt-out within 2 years after the fire.

The amount of litterfall increases after fire due to trees dying off. During the first two months after spring on-ground fires the post-pyrogenic litterfall is 4–5 times more than for the control forest, this contrast is much greater for needles. In July the difference decreases, but it is still 150% for total litterfall and 200% for needle fraction. No difference is found for twigs, cones, and bark. At the end of the first vegetational season, the post-fire litterfall is the same as in the control stand, if no significant stand thinning occurs (25–30%).

The strongly fire-thinned stand produces much less litterfall – 40–60% of the initial amount during the second post-pyrogenic season. The annual litterfall of needles is 15–20% of their total amount on trees. Thus, it takes more time to restore the previous amount of litter reserve after intensive on-ground fires. After a weak on-ground fire, pyrogenic fir stand of ferruginous Baykal soils can have greater litter reserves than long-time undisturbed stand with lower closed canopy (19.43 vs. 12 tons/ha). Stands with fully destroyed forest litter reserves are lower. Litter thickness increases after wildfire, especially right after fire due to abundant dead treefall: for fir stand – 0.110 vs. 0.66 g/cm^3 in control stand; and for birch burnt-out – 0.96 vs. 0.56 g/cm^3. Firsova (1960) showed that weak fires destroy not more than 30% of forest litter in the Urals, where 50% of litter reserves is lost after on-ground fires (Popova, 1978, 1979) in Krasnoyarsk kray. Pyrolysis resulting from forest litter reserves reduced from 5.2 to 6.7 t/ha after weak fire. The thickness reduced from 2.36 to 1.25 cm, bulk density 0.069 to

0.055 cm^3. The amount of forest litter reaches 12.5 t/ha for 3–4 years (the average many-year level is 14.7 t/ha). Its fractional composition mostly restores the previous level, but needle fraction is higher where semi-decomposed debris is lower comparatively with unburned site. Litter reserves of montane podzolic soils were 15.16 before and 9.6 tons/ha the 2nd year after the fire (Stefin, 1981). The amount of soft fraction increases after fire, however it becomes much rawer. Also, forest litter reserves distribution of ferruginous Baykal soils is modified after fire, depending on strength and time since it happened.

The distribution of forest litter in fire-unaffected montane podzolic soils becomes more even or reversed after the fire (Stefin, 1981). Sites with maximal litter reserves were burnt down more thoroughly. Litter pH increased after fire to 0.7 unit, bulk density was twice as much after fire. Soddy taiga deeply frozen soils, characterized by litter reserves, decrease from bole to gap in the undisturbed forest, which is reversed for the burnt down site. The litter is burnt down much stronger in gaps, and bulk density becomes higher there, especially in lower parts of slopes due to fine material input from upper part of slopes, which also increases litter bulk density. In areas with poorly recognized parcel structure fire produces more even spatial impact. Their maximum may occur in gap or near tree bole for poorly birch regrown year old stand. It has almost the same distribution as for well regrown stands, however, its reserves are much lower. Litter distribution in old burn-out with regrowing birch stand was similar to that of softwood stand with 50% thinning. It is featured by a greater litter accumulation beneath tree bole and crown due to sparse of stand. Litter material is decomposed more intensively for burnt-out even 10 years after fire event.

The ammonium content reaches 89–99 mg/100 g after an on-ground fire (Popova, 1978, 1979). Right after a fire, litter acidity decreases: 5.3–5.6 vs. 5.1–5.2 for weak fire and 5.9–5.7. After a strong fire, distinctive heterogeneity is found in pH values even after 2 years. By the 4th year, pH value is almost levelled with the control after strong fire and within 2 years after weak fire. Weak fire causes a slight increase in exchangeable Ca content, this is much stronger after a strong fire and recognizable after 4 years. N content is optimal right after the fire, but becomes equally low by the 4th year. A weak fire stimulates microbiologic processes which are depressed after strong fires.

4.3 Change of soil physical properties

Absence of litter layer leads to disaggregation, poorer aeration and porosity, and also increases soil bulk density in 2.5 times (*Table 7*; see also Gulisashvili, cited by Remezov and Pogrebnyak, 1963). Burning of litter layer changes soil water and temperature regime. Soil temperature in burnt down place is 4° higher than for unburnt, at the depth of 10 cm (Sheshukov *et al.*, 1992). Strong fires increase soil active layer up to 50% (10–25 cm) due to permafrost thawing in frozen soils of the Far East. It is also 30–40% more for 1–2-year old burnt-outs when compared with control. Permafrost layer decreases due to insolation increase on burnt-out to 40–150 cm (Furyayev and Kireyev, 1979). All of this may result in thermokarst features, solifluction and landslide development in hilly relief. Mineralized strips were observed to give rise water channel formation 50–80 cm deep. Depressions and mounds are formed on burn-out. Thermokarst features may persist during 40 years after fire.

Table 7. Different rate of infiltration of 100 mm water column by top-soil (after Remezov & Pogrebnyak, 1965).

Stand	Infiltration rate in 1 min	
	In forest	In burnt-out
Spruce-beech (Bakuriani)	7.6	30.5
Oak-pine (Akhiidabi)	10.5	62.6
Fir (Upper Svanetiya)	6.2	57.6

Kiseleva and Lebedinskaya (1984) refer absence of forest litter, soddy and gleying features, to post-fire changes as well as to a shift in soil physical properties and water regime in soils of the Primorsky kray. Soil temperature and moisture content increases in A horizon after fire in the South Urals (Kucherov and Mukatanov, 1978). All soil properties were not subject to changes in deeper horizons. Content of water-stable aggregates (>2 mm in diameter) decreases two-fold in all stands in a 0–30 cm layer. Amount of all water-stable aggregates is the same for the control and strongly damaged soils, and 20% less for medium-disturbed.

Gulisashvili and Stratonovich (cited by Furyayev and Kireyev, 1979) show post-fire soil compaction, moisture content increase and partial bogging in slightly podzolic soils. No such changes are found for strongly podzolic soils. Post-fire increase in podzolic soil density is driven by the fact that holes caused by burnt roots are filled up (Stefin, 1981). However, right after the fire, bulk density is much less for burnt down soils in 0–5 cm layer. It is accompanied by deterioration of soil microaggregation in the top 5–10 cm after strong fire. The latter was unaffected by medium fire and even became better when the soil surface was fully mineralized. The amount of water-stable aggregates increased under weak fire and decreased under strong fire. Very strong fire produces small macroaggregates compensating a decrease in large water-stable aggregates. In pine stand, post-fire changes of soddy podzolic soil structure are insufficient. The amount of microaggregates increases in the very top 1–2 cm layer of soil. Laboratory experiments testify physical properties change after burning under 250°C up to a depth of 4 cm. However, the amount of water-stable macroaggregates decreases significantly and especially in a strongly disturbed site. Soil bulk density was found to increase significantly in the upper 10 cm and varies much less spatially due to even fire effect.

Soil microaggregation is higher in unburnt stands with ferruginous pyrogenic soils (Stefin, 1981). Burnt soil also has more large water non-stable aggregates. However, later the amount of water-stable aggregates increases more significantly in burnt-outs. There is data that fire may destroy alumosilicates of soil and thus increases exchangeable Al content within soil. Bulk density increase is noted for almost 50 cm soil layer after fire. It is more clearly observed several years after fire. Soil moisture content on the burnt site tends to fluctuate much more during the summer; it is more humid during spring rains and drier due to evaporation and runoff after showers in hot periods.

4.4 Change of soil chemical and microbiological properties

Johnson (1992) considers that prescribed burning and wildfire cause a reduction in litter horizon weight and have no effect or even increase the amount of mineral soil organic C. Often the invasion of the N-fixing species causes an increase of the C content on a long-term basis. There was no significant increase found in soil C content after 25 years after broadcast burning in 34 plot pairs in western Washington and Oregon. It was observed that there was a significant increase in soil C in sites occupied by N-fixing Ceanophytes. There was no change of soil organic matter but a significant decrease of forest floor occurred 1 year after a wildfire in Maine (Johnson, 1992). Sampling of soils within 1 week after a wildfire in interior Alaska revealed forest floor losses varying from 5 to 80% and ranging from +16 to -18% top 5 cm of soil depending on fire intensity. So it can significantly shift the soil C content. Intensive fires deteriorated conditions of forest growth and resulted in N and other losses, and an increase in soil erodability. All this affects soil carbon pool on a long-term basis.

Steady on-ground fire produces up to 2.5 tons/ha of ash (21 kg of Ca, 48 kg of Mg, 61 kg of K and 17 kg of P). The most content of these nutrients is found during the first 2 to 4 months (Popova, 1978) in Krasnoyarsk kray. They are above mean values after 2–4 years according to observations by Sheshukov *et al.* (1992) in Far Eastern soils. N losses are significant (up to 1 tone/ha), however, they are compensated by increased N-fixation by Ceanopnytes and better plant growth. Soil pH increases in acid poor-drained, fine-textured soils. Thus, in larch stand the pH increases from 3.9 to 4.3 in lower litter layers after a medium intensive on-ground fire and from 4.4 to 4.7 in humus horizon.

Stefin reviewed the literature and considers that stronger fires cause a greater loss of C as compared to N, where moisture conditions affect the N losses with mobile forms accumulated within the soil. Great losses of C and N with smoke and percolation shade the role of microbiological processes. The ash content of Baykal podzolic soils is higher after a fire, where N, P and K content decreases (2.4–1.4 times) due to burning, leaching and runoff (Stefin, 1981). As a whole, hydromorphic soils of the Trans-Baikal region have a more narrow C:N ratio after weak fires. It becomes wider after strong fires and medium fires for well moistened areas. The influence of fires to soil properties depend very much on the intensity of the first fire. Post-fire water erosion is not common, due mainly to the presence of a significant stony skeleton. Fire causes some increase in actual soil pH if there are no carbonates in soil. The author hypothesizes that fire can accelerate typical soil processes especially in the lower parts of slopes. Post-fire losses of nutrients are significant: with water streams, about 3 tons/ha of P_2O_5 is lost in conditions of unpercolated water regime for Minusinsk (Chagina, cited by Stefin, 1981). According to these figures the loss of P of forest litter is equal to 50 years of P accumulation in soil. Claton found that the amount of nutrient in surface runoff per week after the fire was more: Na, 70.6 times; K, 37.7; Mg, 27.1; Ca, 19.2; and N, 21.1. Amounts of some nutrients discharged two years after the fire into Lake Minder (Minnesota) was for K – 265% and for P – 93% more comparatively with a neighboring lake. These losses are higher than those found for prescribed fires. Some authors report N increase in burnt down soils (for soddy taiga soil in pine stand in the Baykal region, Trans-Urals (nitrates accumulation) and East Siberia-Middle Pre-Angara region).

The C:N ratio becomes wider after a fire in the upper horizon due to N loss, and becomes lower in subsoil horizons because of increased humus mineralization under other microclimate conditions. Soils affected many times by non-intensive fires, nevertheless, have a narrow C:N ratio, even narrower than those unaffected by pyrogenesis. The narrowest ratio is found for the most moisture soils at the bottom of the slopes with a slower nutrient cycling. After a fire, the pH becomes greater, humus content decreases (from 58.3 to 51.0 tons/ha in burnt-out in upper 20 cm of soil) with significant N losses. Losses of N and P are more than 2 times as much, K – 1.24 times more. Soil acidity of soddy taiga soils decreases only in the burnt part of humus horizon, and increases in the lower horizons. On the lower part of the slope, the increase of humus content is attributed to soil material input from the upper part. In burn-out, N content is higher in 1.7 times. Narrower C:N ratio confirms the post-pyrogenic increase of N. The same was reported by Grishin (1973) for soils of the Pre-Amur region. However an increase of the C:N ratio is recognized for the Angara-Lena interriver basin (Kolyago and Sazonov, 1975). In this contradiction, the author refers to the narrowing of the C:N ratio right after fire. It becomes much wider due to fresh litterfall afterwards, especially for coniferous trees (Duchaufour, 1970). Ferruginous pyrogenic soils (Stefin, 1981) have a broader C:N ration in topsoil and a narrower one in subsoil. That distinguishes from undisturbed. This is due to N losses from upper horizons and increased humus mineralization in lower. Weak multiple on-ground fire in fir-cedar stand did not cause N losses in the A horizon and did not change soil structure. C:N ratio is even slightly narrower when compared with the unburnt stand. The narrowest C:N ratio and maximal C content are observed in waterlogged soil (C – 9.5% and N – 0.43%). This can also be due to material input from upper lying burnt-outs.

No significant changes occur with a humus horizon apart from small carbon particles formation (Sapozhnikov and Kostenkova, 1984). The amount of humin has increased, but fulvic to humic acids ratio increases. However, the high content of humus is still typical. After more intensive fires, a content of the humic acids 3-d fraction increases and the 1-st fulvic acid fraction decreases. Popova (1979) indicates that after the weak fire the humus content and soil acidity (5.9–6.1) are not changed for soils of the Krasnoyarsky kray. The cation saturation slightly increases from 5.08 to 5.46 mg-eq/100 g. For the first two years, the amount of ammonium nitrogen increases in the 0–5 cm layer: the studied plot, 3.2 during the first year and 4.9 mg/100 g by the next year; for the control, 1.7 and 1.8 mg/100 g, respectively. During the first four years after fire event, the rate of cellulose decomposition is higher for disturbed soils, especially for the surface layer. The weak fire decreases soil acidity in 0-5 cm layer and results in an increase of mobile N and P content. Medium fires cause soil reaction to approach neutral in some patches of upper horizons. The exchangeable bases content increases up to 11 mg-eq/100 g as well as the ammonium one. The strong intensive fire increases ammonium content significantly to 56–70 mg/100 g. The soil acidity and ammonium content (6–17 times as much) increase many times under burnt fallen down logs. Therefore some cations are lost with smoke and runoff.

Furyayev and Kireyev (1979) (citing Trutneva and Bylinkina) demonstrated the soil pH increase in different conditions: from 3.8 to 5.0, from 6.0 to 6.5 and from 4.8 to 5.5. Simultaneously P_2O_5 content increased from 1.75 to 9.0 mg/100 g, K_2O-from 11 to 17 mg/100 g, MgO-from 16.5 to 28.5 mg/100 g. Increase of these compounds as well as mobile N was also detected by Ivanov and Aref'yeva, Ponomarev, and Firsova (all cited by Furyayev and Kireyev, 1979). Many authors identify that soddy process development, humus and nutrient status increase. Also a decrease of the total humus content is often reported for the first 3–4 years after fire. It increases in litter and upper 10 cm layer as well as CaO (2–3-fold), MgO (1.5–2.0-fold), K_2O (1.3–1.5), P_2O_5 (1.1–1.5-fold), NH_4NO_3 (1.5–3.0-fold). The initial total N loss is compensated due to the intensive ammonification and nitrification. Nutrient losses due to leaching in burnt down areas are sufficient. They are 2 times more in the burnt down site for Ca, Mg, Na, K, and P. Water runoff is also 1.9 times greater (Lewis). The soluble Ca content after a fire was 20 times more, Mg – 10 times, K, Na, P and N – 2 times [Grier, all cited by Furyayev and Kireyev (1979)].

Remezov and Pogrebnyak (1965) reviewed literature on the microbiological situation after fire. Sushkina determined no change of microbiological activity after slash burning found in pine stand. In the second site, the microbiological activity was higher in the forest, and some organic matter mineralization was marked. Decrease of pH in topsoil was observed, and it reaches deeper horizons in weak form after 1–4 months. Topsoil pH was 5.2–5.6 in unburnt site and 7.4–8.2 in burnt. The same microbiological activity is identified for the Southern Urals burnt and unburnt soils (Kucherov and Mukatanov, 1978). The A horizon humus content is 7.5-15.35% after fire (4.48–6.63% initially), Ca-8.5–21.5 mg*eq/100 g (3–8.5%), Mg-9.5–25 mg*eq/100 g (10.5–16.5%). Hesselman found nitrification to increase after slash burning, and the weak burning to be especially effective in this respect. Nitrification was absent in conifer-moss stand, and 5 years after burning 24 mg of nitrate was accumulated. Growth of Polytrichum prevents nitrification development. Data obtained by Sushkina supported his conclusion. Russel and Hutchinson demonstrated that weak heating of soil (up to 98°) intensified ammonification and nitrification (by 12 times).

Pershina (1935, *Tables 8, 9*) studied the effect of cutover cleaning ways to chemical properties of soddy podzolic soils. No reliable changes were found and soil pH ranged from 4.7–5.8. Burnt areas were the only exclusions and had a pH of 7.8–7.9 which decreased in fall to 7.4. More Ca and mobile P was found after slash burning. Also some nitrates were recognized absent in the unburnt site. Burnt moss cover increases soil aeration, and decreases acidity and amounts of organic compounds toxic for microbes.

Transition of original spruce forests into other coniferous after a fire does not change the soils' properties (Kiseleva and Lebedinskaya, 1984). However, the significant difference is detected for the birch stand humus horizon: the content of mobile H and Al is 2.3 times less. The C:N ratio is high – 20, the humus content increases with an increase of moisture content in at least the 30 cm layer due to poor decomposition conditions.

Table 8. Influence of slash residues burning on the soil exchangeable Ca content (after Pershina, 1935).

Plots	Exchangeable Ca, mg-eq/100 g of soil				
	O	A^1	A^2	E	B
Fireplace	–	19.7	9.7	1.8	20.9
Cutover	39.9	5.6	1.1	1.0	1.0
Forest	41.7	6.8	2.3	1.1	1.2

Table 9. Influence of slash residues on the exchangeable acidity (after Pershina, 1935).

	Exchangeable acidity, mg-eq/100 g of soil				
Plots	O	A^1	A^2	E	B
Fireplace	–	no	0.2	0.2	0.1
Cutover	12.8	1.8	0.5	0.2	0.1
Forest	9.7	1.1	0.5	0.2	0.2

4.5 Summary

Two groups of fires are necessary to distinguish according to impact severity: (1) weak impact, incorporating peat, sod, litter, superficial on-ground fires and a part of steady; (2) strong impact, comprising crown and the most intensive on-ground fires. The first group has slight or no effect to the ecosystem and soil properties, implying that it does not affect natural successional patterns. The second group produces the most significant effect to soil properties and the ecosystem, and also may transform the ecosystem into another type.

Wildfires result in loss of nutrients and organic carbon during the impact and thereafter. Litter horizon is often partly burned once its bulk density increases. During the first years, ecosystems, if not bogged, contain greater amounts of nutrients available and are featured by pH increase. Post-fire compaction and changes in soil structure are found. Also, erosion hazard can be very serious, but it is much less than that produced by clearcutting. The reason for this is the more spatially "stochastic" appearance of wildfires. Habitat type and soil properties determine all post-fire changes. Wildfires in northern (conifer) taiga soils are considered to be "useful" in accelerating nutrient cycling and making them more available for trees, as well as increasing soil layer for frozen soils. Wildfires in mixed stands are thought not to have such a positive effect.

The most part of the stated refers to weak fires. The effect of intensive, multiple fires occupying vast areas may result in negative, irreversible changes in ecosystems. Post-fire evolution of such soils may have other directions than just restoration to its previous state. The effect of intensive fire is thought to be similar to that of clearcutting, where weak fires are not similar to weak logging procedures, and produce various effects in different conditions. An increase of fire occurrence scale with burnt-outs covering significant areas may significantly change the ecological situation in such regions.

5 Soil Carbon State as Ecosystem Integrated Indicator[2]

5.1 Soil carbon state change

There are uncertainties about the role of natural undisturbed forest soils in the organic carbon cycling within terrestrial ecosystems. However, felling and forest fires cause considerable

[2] This chapter is compiled partly using the material kindly given by Rozhkov and Travnikova.

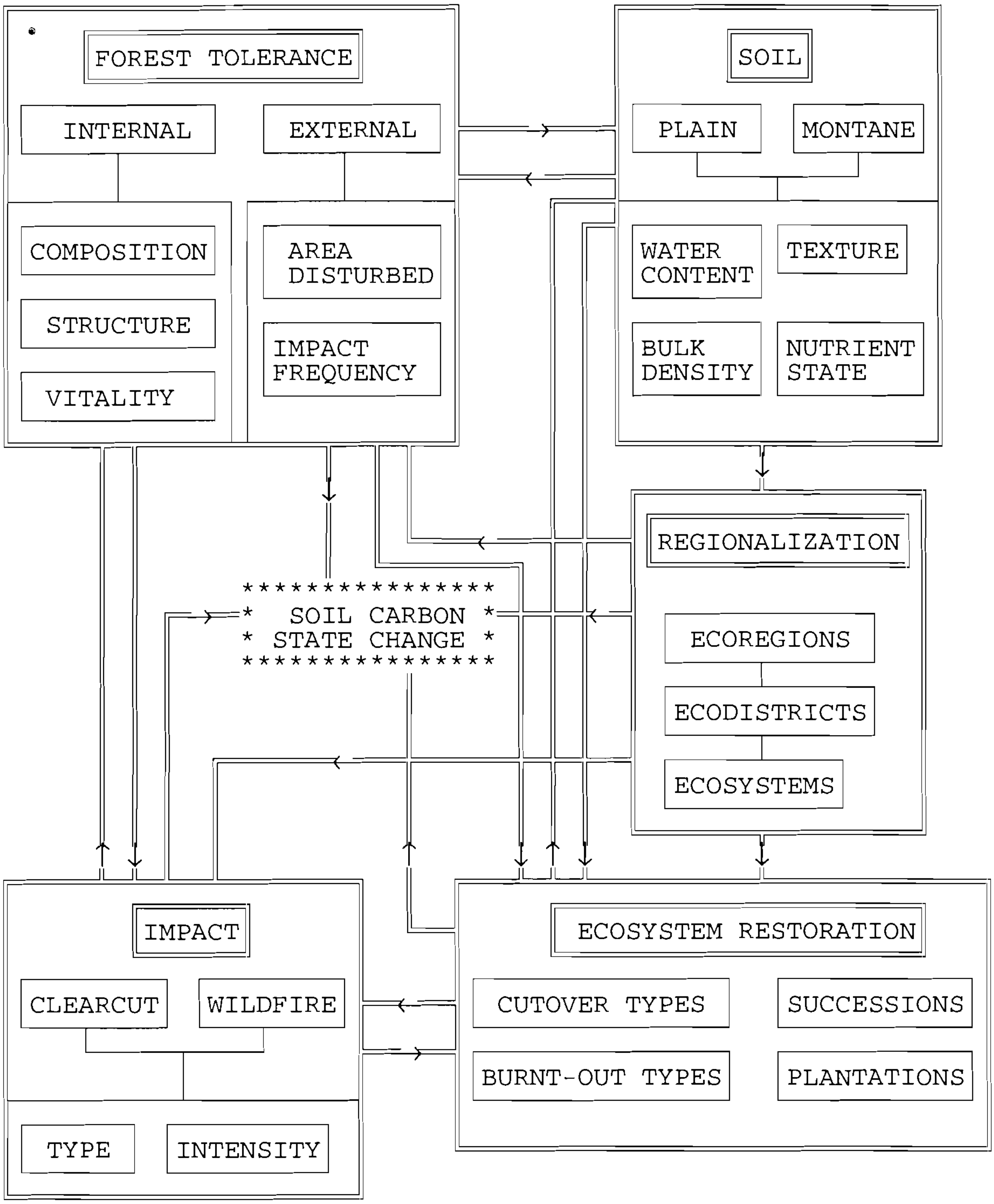

Figure 3. Factors effecting soil carbon state change in boreal forests.

changes in carbon flow between the forest ecosystems and the atmosphere. In turn, soil C reserves, by some estimates, are considered to be 2/3 of the total amount of the Earth's total biomass (Reyntam, 1986). Nowadays, when significant areas are under anthropogenic pressure, it changes during impact and afterwards due to ecosystem disbalance. That is why the assessment of such a carbon cycle must be made for both disturbed and undisturbed forest ecosystems. Change of organic carbon state in the forest ecosystem under human impacts is driven by many factors (*Figure 3*). Of course, intensity and type of disturbance are of primary importance in this respect. Soil properties such as texture, bulk density, humus and nutrient states, litter reserves as well as site location in plains or in mountains, determine many possible consequences of impacts affecting the soil organic matter state. The ecosystem itself possesses some tolerance toward impact due to plant composition, state (vitality) and structure. This ability to withstand is restricted by the size of the area disturbed and frequency of disturbance. Consequential changes of soil humus also depend on cutover or burnt-out types formed and possible mechanisms of forest cover restoration: afforestation, reforestation, plantation. All this can be included into the ecoregional subdivision of Russia at different levels.

Human impact, for example, clearcutting or wildfire, changes the physical conditions of the environment: radiation balance, temperature and moisture regimes, water content, and biological conditions: microbiological activity. This causes humus content to change. Besides that, soil carbon content correlates with bulk density, which is often shifted under clearcutting and wildfire, and indirectly by a pattern of the further humus fate in soil determined by plant composition and structure. The change of soil conditions due to human impact may cause accelerated humus decomposition and nutrient release. In addition, humus accumulation is sometimes found to indicate more favorable conditions for plant growth especially under "weak" impacts.

The soil C change can be attributed to organic matter modification and (or) topsoil material losses which resulted from soil erosion (input) after disturbance. If we consider the latter to be of zero value (which is not quite correct in many cases), it is possible to attribute all the soil C negative change to its decomposition. Reflecting actual processes taking place within soils, soil organic matter represents not only a specific group of organic compounds but a broad variety of quite different dead and alive, fresh and deeply decomposed substances united in one group, due to a presence of organic C in their composition. Thus, soil C change within soil profile, together with geographical heterogeneity of its composition, must be treated not only in general, but also according to peculiarities of its compartments alternation.

5.2 Overview of soil organic carbon compartmentation

It is well established that the rates of synthesis and decomposition depend on the chemical composition of plant litter (lignin, waxes content and C:N ratio), as well as on temperature, water regime, soil pH and metabolism inhibitors, waterlogging occurrence, permafrost depth, and also on soil depth. The last factor is often underestimated in modelling of the soil C change, however, the amount of microorganisms and thus their respiration dies out with depth (Zak, personal communications). The fact is that the decomposition rate of the soil organic matter (OM) depends on the composition of soil microorganisms and the amount of 0_2 available for oxidation. The range of decomposition rates variations is determined by conditions of bioclimatic zones and the type of ecosystem. This is testified by the fact that the climatic parameters are greatly changed in different latitudinal belts and that the mineralization of OM seems to be diverse in soils of forest, meadow, wetlands and agrocenoses.

The data on OM mineralization under field and laboratory conditions show that the OM is diverse in its composition and some parts or pools may decompose slower than others.

According to Sauerbek and Gonzales (Rozhkov and Travnikova, pers. com.[3]) two groups of the OM there exist: labile fraction comprising plant residues and humified products of their cycle, as well as stable fraction which contain the remnant part of humus substances. The model, which accounts for two components, was elaborated by Jenkinson (Jenkinson *et al.*, 1991) in 1977 and represented as the following equation:

$$C = 71 \cdot e^{-2.83 \times t} + 29 \cdot e^{0.087} \quad (1)$$

which makes it possible to show the OM decomposition in arable soils during the first years.

The long-term experiments carried out by the Rothamsted station provided information on changes in soil OM, its age, the amount of microbial biomass and velocity of decomposition. In this respect Jenkinson and Rainer (cited by Jenkinson *et al.*, 1991) proposed the subdivision of OM into 5 groups as follows: (1) easily decomposed plant residues with half-life of O.165 years; (2) heavily decomposed plant residues (2.31 years); (3) biomass (1.69 years); (4) physically stabilized OM (49.5 years) and (5) chemically stabilized OM.

On the contrary, Paul and Van Veen (1981), proceeding from the assumption that the physical stabilization and chemical resistance of OM are not properties of separate fractions, offered to divide OM into plant residues without lignin and its similar stable compounds, lignin-containing plant residues, easily decomposed natural organic substances and stable natural OM. Two last groups are subdivided into physical stable and unstable organic substances.

Using the notion on the role of the OM cycle based upon data available to determine natural radiocarbon, Gije proposed to classify OM as follows: (1) quickly decomposing fresh plant residues, (2) labile substances enriched in nitrogen, especially easily hydrolyzed fractions of aminoacids, which are highly subjected to biodegradation and characterized by intensive cycle, and (3) inert organic substances poor in nitrogen, including aromatized polycondensates of humin and humic acids as well as stable fragments of plant tissues and substances connected with phytolithes.

Kurtz *et al.* (1992) suggests three pools of the soil OM: fast, medium, and slow. The fast pool is supplied by fine plant material such as softwood and hardwood foliage, submerchantable and other material, with half-lives of 3–20 years. They are composed by material less than 10 cm in diameter. The medium pool is provided by softwood and hardwood merchantable material. It consists of detritus greater than 10 cm in diameter. The slow turnover pool is characterized by half-lives greater than 100 years and consists of humified soil OM. Peatlands with an organic layer greater than 50 cm is handled separately. Three decay rate parameters are recognized for each of the fast and medium pools. The decomposition rate depends on mean annual temperature, forest type, and stand development. The slow pool decomposition rate is assumed to be independent on the amount of the stand biomass and time since disturbance. The dynamics of the slow soil carbon pool are attributed to a change of material input from the medium and fast pools.

[3] All other references without indication of sources are represent results of personal communications with Rozhkov and Travnikova.

Based on their own investigations and on published data about the nature and structural peculiarities of OM and its stable links with the soil mineral part, Anderson and colleagues distinguish the two following groups of humified OM: (1) labile, enriched with nitrogen and connected with fine clay (<O.2 mcm) of fulvate type and slightly aromatized forms of humic acids, and (2) more stable organic substances resistant to acidic hydrolysis connected with coarse clay particles and light silt, including the most aromatized organic substances of humate type. According to the authors' the first group corresponds to the physically stabilized fraction, and the second, to chemically stabilized organic substances. Campbell *et al.* (1967) and Trumbore (1988) suggest three groups of organic substances: dense residues (>1.6 cm^3), base, and alkaline-soluble. Residues revealed the longer mean residence time (MRT) than those of the base after acid hydrolysis.

Chemical and physical subdivisions of OM are separated according to mean residence time (Campbell *et al.*, 1967; Goh *et al.*, 1976). The mean residence time for soil humus is reported to range from years to several hundred thousand years, with mean residence time increasing with depth in the soil profile (Sharpenseel *et al.*, 1968). Once the C reserve decreases downward to the soil profile, its MTR time gradually increases for Mollisols (from 1000–1800 years at 10 cm to 5000–7000 years below 70 cm) and Ultisols (from 1000 years at 10 cm to 6000 below 125 cm) (Trumbore *et al.*, 1990). Podzol soils show the local maximum in the C reserve and the minimum of MRT in B horizon (E horizon: 2000–4000 years at 0–20 cm;

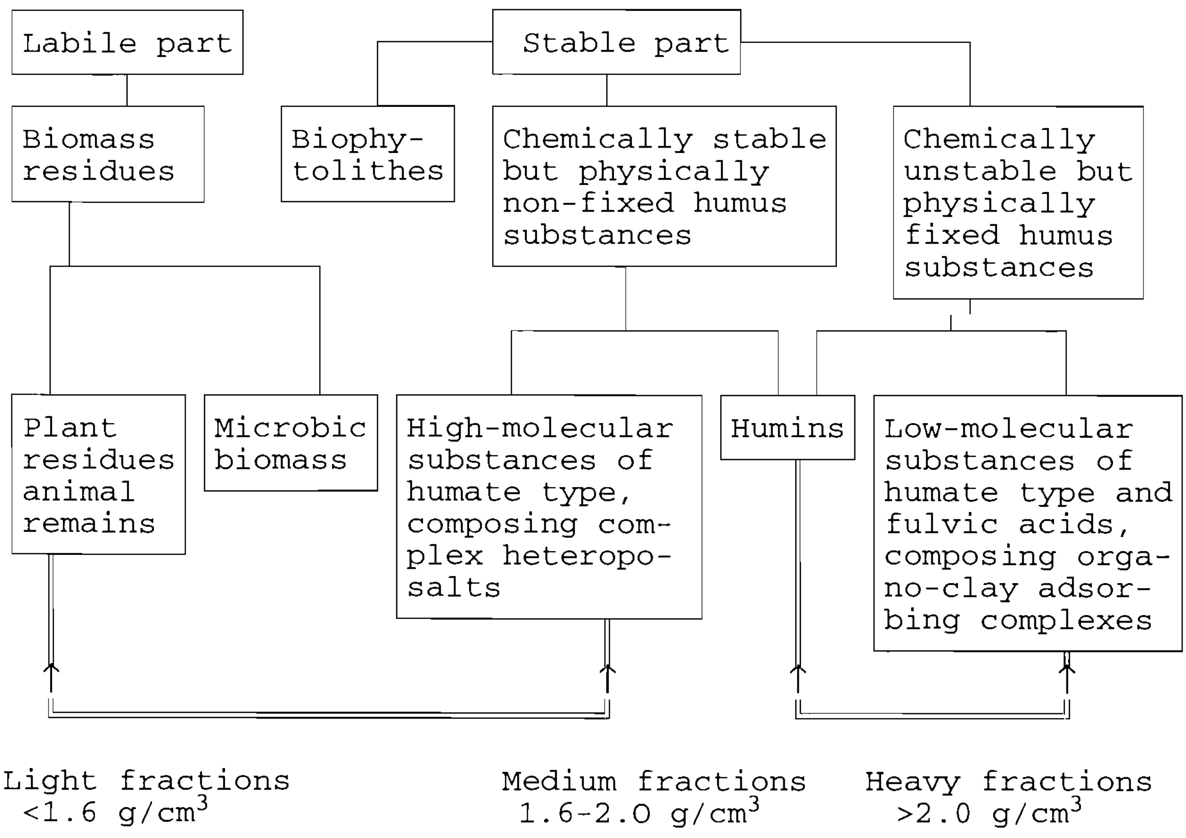

Figure 4. Soil carbon compartmentation according to the decomposition rate.

B1: 2000–3000 years at 30 cm). It is significantly more at a depth of 70 cm (12500 years). Animal origin is found to be the most active fraction of the soil OM. It is not connected with the soil mineral part and the chemical composition determines its resistance to degradation.

When analyzing the published data, one may notice the common regularities that allow the distinction of OM due to its activity. Such grouping is schematized in *Figure 4* (modified after Rozhkov and Travnikova).

Detritus represents humified fragments of plant and animal origin. The mineralization rate ranges from some months to several years. The proper humus substances are less active, slowly renewed and their age reaches some thousands of years. This is explained by their complicated chemical composition as well as by tight bounds with the soil mineral part. As a result, these organic substances proved to be more stable and resistant to biodegradation. The most inert are substances of coal type, which, unlike detritus, are not bound with the soil mineral part and the resistance to biodegradation is also determined by their chemical composition. The activity decrease can be placed in the following order: detritus-humus substances – coal-like substances, thus showing the "chemical stabilization" of these substances. Humus substances can be more stable due to their connection with the soil mineral part, it means that "physical stabilization" takes place.

5.3 Soil carbon decomposition rate

When the dynamic equilibrium of an ecosystem is disturbed the mineralization rate of soil OM may fluctuate depending on duration of its composition cycle. It is testified by a number of publications concerning dynamics of changes in the carbon content resulted from the plowing of virgin soils. The data for forest soils is almost absent. It has been established that in the first years of ecosystem change, the plant residues and animal remains of microbic biomass begin to be intensively mineralized, and after that only humus substances connected with clay fraction in the form of adsorbed complexes (those parts which are adsorbed by the surface of clay particles) are mineralized. The so-called "free" fraction of high-molecular humic acids remains unmineralized for a long time, and is the most stable humin fraction.

Examination of the soil OM transformation is made by conceptual and mathematical models that are widely adopted now. Different mathematical equations were offered for reflecting the soil biological processes, among them the equation offered by Michaelis-Menten is considered to be the most suitable for application (2).

$$V = \frac{\partial S}{\partial t} = \frac{V_{max} \times S}{K_m + S} \qquad (2)$$

where V - reaction velocity, V_{max} - its maximum, S - initial substratum concentration, K_m - Michaelis's constant which is equal to substratum concentration to reach the velocity of ½ V_{max}.

This equation is usually applied to describe reactions of the second order kinetic mechanism. The following first-order equation (3) exists.

$$\frac{\partial S}{\partial t} = kS_o \qquad (3)$$

where S_0, t and k are the initial substrate concentration, time and metabolism velocity respectively.

To explain the influence of different soil properties to the reaction velocity, for instance, Arrenius's constant reflecting the temperature impact, the other known formulas are employed, as well as regression equations. The assessment methods of the carbon cycle in soils are developed as related to the idea about the state and transformation of soil OM. The simplest model of carbon cycle (Jey, 1941; Woodruff, 1949) is based on equation (4). This model was used to explain a change in the content of OM in croplands. It is able to show adequate changes in the carbon cycle for several years but cannot be used for long-term predictions.

$$C_t = C_e + (C_o - C_e)e^{-kt} \qquad (4)$$

where OM is represented as one component: C_t, C_e, C_0 - the content of OM in the given time and initial state.

In the last 20 years, many models, designed to show the decomposition of the soil OM, have been described based on its multi-component composition. Much attention is paid to the initial stage of decomposition accounting for days, weeks and months (Smith, 1979; McGill *et al.*, 1981; Van Veen *et al.*, 1984; Buyanovski *et al.*, 1987; and others), when the physical state and chemical composition of the soil OM appear to be decisive. These models are mainly elaborated by using experimental data about the incubation of plant residues or short-term field experiments. There are also models to simulate the carbon cycle in a long space of time (from several years to some hundred years period). As a rule, such models are based on materials of long-term incubation of OM with labelled C. Long-term field experiments carried out to study changes in the carbon content depending on climate factors, soil types and land use (Russel; Jenkinson and Rainer, all cited by Jenkinson *et al.*, 1991) are supporting this model development. In the majority of such models, the constant of mineralization velocity is usually multiplied by one or several coefficients of the "modification velocity" characterized by change in this constant, and induced by alteration of temperature and moistening.

Among such models, the most suitable is the model offered by Jenkinson (1991) from the Rothamsted Experimental Station, which embraces the following components: decomposed plant residues, microbic biomass, humified OM, inert substances, resistant to biodegradation. The model well agrees with experiment data on the content of organic carbon in soils of two classic experiments.

Under special discussion now is the question about the ratio between labile and stable fractions of the soil OM since only these values are used to calculate the net flow of carbon in the soil. At present, it is obvious that the labile fractions account for 1/3 and stable ones-2/3 (Kobak, 1988). However, Schlesinger (1984) indicates that the ratio between these fractions varies greatly. Nowadays the most widespread models permit the simulation of two components of OM in plant residues and in soils. In this respect, values of carbon net flow have been calculated for terrestrial ecosystems throughout the world (Kobak, 1988). The same coefficients proposed by Oberlander (1965) and Kononova (1984) were applied for soils of all ecosystems: 6% for estimation of the total amount of humus resulting from decomposition and 2.5% for stable humus amount. This method can be used to assess the carbon balance in terrestrial ecosystems at the former USSR territory, taking into consideration that the humification coefficient varies greatly due to changes in hydrothermic conditions.

In stable compounds the OM content is relatively constant. As a result of essential changes of physical, chemical and biological factors driving the activity of microorganisms, a new equilibrium concentration is established, because the amount of OM produced in soil is always equal to that which has been decomposed (5):

$$\frac{\partial OM}{\partial t} = \frac{\partial S}{\partial t} - \frac{\partial D}{\partial t} \qquad (5)$$

where OM - the content of OM, S and D - its synthesis and decomposition rates depend on physical and chemical conditions. In the case of the equilibrium state, the amount of organic matter maintains its balance (6).

$$\frac{\partial S}{\partial t} = \frac{\partial D}{\partial t} \qquad (6)$$

As for boggy soils, they are able to accumulate great amounts of OM including decomposed residues, with a small half-life period. The aeration improvement may provide for more intensive mineralization as compared to mineral soils.

When there are elaborated models of the OM transformation in soils, it seems reasonable to divide it into the most informative components. However, a routine method of humus fractionation in alkaline and acidic solutions is not always applicable for the separation of such fractions. An alternative model would be to use the density and the particle size fractionation which would permit us to obtain fractions which are more sensitive to biodegradation. The granular-densimetric fractionation elaborated by Travnikova in the Dokuchaev Soil Institute in Moscow allows us to distinguish more labile and more stable fractions of OM. The more stable fractions proved to be decomposed at higher temperatures as compared to labile components. The method seems applicable to define the ratio between fractions and their content in the OM and in its components. Thus, when assessing the changes in the carbon cycle of soils, it is feasible to take into account a diversity of the multi-component pattern of the soil OM. The method enables us to fractionate OM into three main groups: two relating to light (less than 2.O g/cm^3) and one to heavy (more than 2.O g/cm^3) fractions. They differ from each other in quality, velocity of the carbon cycle and the character of their interrelations with the clay matrix. The light fractions contain residues of plant, animal and microbic origin which are mainly concentrated in those with a density of less than 1.6 g/cm^3. The second group includes coagulates of complex-heteropolar salts of high-molecular humic acids with well expressed aromatized structure. They are rich in carbon and poor in nitrogen. They are not bound with clay matrix. In most cases these fractions have a bulk density of 1.6-1.8 g/cm^3. The heavy fractions include polymineral poly-dispersed stable adsorbed crystalline complexes of clay minerals and oxide-hydroxides incorporated by OM. Their nature is represented by low-molecular compounds enriched with nitrogen; the content of carbon is low. They do not exceed 1 mcm in diameter (clay fraction).

Two groups of OM containing light fractions in upper humus horizons are able to vary in different bioclimatic zones. For example, in soils of the subarctic zone the light fractions are greatly accumulated and make up 75% from the total soil OM amount. The share of detritus and remains of microbic biomass accounts for 8-7O% from organic carbon in light fractions. In sod-podzolic soils of southern taiga the carbon content in light fractions varies decreasing up to 2O-3O% from total carbon. In podzols of southern taiga hydrolyzable fraction comprises 55-60%. On the contrary, in the soils of forest-steppe and steppe zones, it increases reaching the maximum in thick typical chernozems (about 50%). In comparison to soils of northern zones, proper humus substances dominate and the share of detritus and microbic biomass remains make up only 1% and even less. In southern subtypes of chernozems the share of OM in light fractions decreases and reaches 35-40% of its total amount in soil. Such comparative characteristics show that changes in the carbon content of light fractions depend on changes in soil biopotential provided by climatic conditions. On the contrary, accumulation of OM connected with clay fractions occurs due to lithogenesis (the pattern and properties of soil forming rocks) and geochemical conditions.

5.4 Erosion of forest soils and organic carbon

Erosion itself does not destroy soil organic matter. It, so to speak, relocates organic matter incorporated in soil fine material in relief. However, almost no data is available for us to learn what happens with eroded material humus later. Losses of topsoil material enriched in humus decreases the soil C reserves, as well as modifies humus chemical composition due to exposure of lower soil horizons with likely different humus composition. Geological erosion ("natural" losses of fine soil material) is estimated to be 0.1–0.2 mm/year, but "human" erosion can reach significant numbers. It is accepted that erosion is not present in forest ecosystems. Also, if no data is available on fine material losses, all changes in humus content are attributed to accelerated decomposition, which is not quite true in many cases. However, disturbances in montane as well as in hilly-ridge regions might result in significant erosion. Superficial runoff from forested sites is 50% less than for the similar slope, but with grass vegetation. Soil without litter horizon is very susceptible to erosion. Erosion is marked for many regions, especially montane, however, very little data is available. Also, it is very difficult to evaluate the total amount of soil material lost. Very often it is just stated that erosion did occur. The following numbers are cited for post-fire erosion in tropical forest by Menaut *et al.*, 1993: up to 1 t/ha of soil is lost in savannas, 0.1 in protected areas and 100 t/ha on forested slopes. This amount is sufficient when compared with the total element losses in disturbed ecosystems. Post-fire erosion in montane conditions are described by Ivanov, Reymers and Malyshev, both cited by Furyayev and Kireyev, 1979). An increase of sandy fraction in topsoil due to erosion following the clearcut was indicated by many authors (Zonn and Karpachevsky, Lidov and Orlova, both cited by Stefin, 1981).

Intensive fires and clearcuts, especially when heavy machinery is applied, deteriorate soil physical and chemical properties and make soils more erodable. There are the following reasons for that: vegetation (trees and grasses) removal, litter and soddy layer destruction, soil mixing up, compaction and disaggregation. Also water channels are likely to form along skid rows, roads, natural depressions and so on. Weak multiple fires provide more favorable conditions for litter accumulation and tree growth and less erodability of soil. Dark-crown coniferous stands are more successful in the transformation of surface runoff into intrasoil percolation and protect lower located light conifer stands which are more sensitive to erosion.

Krasnoshchekov and Kuklin (1983) attribute anti-erosional functions of the forest litter to effective suspended load interception. Litter may accumulate up to 90% material in the cedar-taiga and larch-taiga forest and up to 65-35% in subtaiga-forest steppe communities. Thus, the amount of material eroded is not more than 20 t/km^2. Litter removal at slopes of 15-20° reduces soil infiltration 1.2-2.5 times, runoff increases 9-12 times. Therefore, total erosion losses reach 8000-9600 t/km^2/year. Baranov and Stefin (1978) studied a change of montane podzolic soils erodability due to litter layer loss.

Litter layer was 0–4 cm thick in the control stand. Weakly damaged stand had a litter layer of 0–2 cm thick (92% of the initial amount), medium damaged one (strong on-ground fire) had 0–1 cm (65% of the initial amount). Strong crown fire destroyed all vegetation and the remaining litter did not form any soil cover, therefore, the litter layer was reduced to 42% of the initial amount. Grass vegetation develops by the second year after fire. Erosion coefficient was 19 times higher than the standard value at the strongly damaged site (0.039) and it was 0.005 higher for a slightly disturbed one. By the third year after the fire, it became close to standard – 0.0021 for strongly disturbed site due to litter layer establishment. Fine material washing out from soddy taiga soils is marked due to surface runoff in strongly damaged pine stand (Stefin, 1981). This supports the data obtained by Stepanov and Burykin (both cited by Stefin, 1981) about silt material loss from pyrogenic soils. Soil erosion is common in soddy taiga soils that leads to more carbonate content in the upper horizon. Soils on coarse rocks formed in the Far East are easily exposed and are denuded afterwards (Sapozhnikov, 1984). Erosion processes after tree felling are most significant on roads, skid rows, exposed soil surface, and tree storing places. Soil compaction and linear character of disturbances results

Table 10. Losses of major elements during and following a land-clearing fire in Costa-Rican wet forest site (after Ewel *et al.*, cited by Menaut *et al.*, 1993). All values in g/m^2.

Chemical species	Amount in site (to 3 cm depth)	Amount volatilized in fire	Post-fire loss by deflation/erosion
Carbon	5000	1840	320
Nitrogen	219	50	33
Phosphorus	2.2	0[1]	1.1
Sulfur	15	7	1
Calcium	87	0	7

[1]Much of the post-fire P losses more than likely represent compounds transformed in forms inaccessible to the analytical methods used.

in significant channel erosion. Skid rows occupying 2–7% of cutover area are most effected by erosion with material loss into gullies and water streams. It is especially strong during the snow melting period. Winter logging is less dangerous for erosion development.

However, water erosion is not always found in montane regions. For example, Stefin (1981) considers ferruginous soils of the Baykal region to have high anti-erosional properties due to a high iron content in soil which provides better soil structure and also abiogenic aggregates formation. For soddy podzolic soils no surface erosion was found on clearcut plots but erosion was severe along roads. Mound-depression of the Far East relief divides surface flow and prevents strong losses and gullies formation on larch burnt-outs (Sheshukov *et al.*, 1992). Topsoil material is transported to the foot of slopes. Eroded area is usually greater than an area of deposition on burnt-outs. Soil erosion sometimes promotes tree regrowth. Weak fast on-ground fire, as well as medium-intensive fire at non-steep slopes (up to 20°), does not cause erosion.

5.5 Summary

The following compartmentation of soil organic matter (including forest floor) seems reasonable for an assessment of organic matter change:

(1) Forest floor may be divided into a forest litter layer and all other material.

- Forest litter includes leaves and needles, grass plant and animal residues, small twigs, coprolites and plant exudates;
- All others incorporate cones, twigs, branches, fallen boles, dead stumps.

(2) Peat of the bogs and bogged soils must be considered separately due to peculiarities of the peat chemical composition and also the specific water regime in bogged habitats.

(3) It seems quite reasonable to subdivide the soil profile, if it is not eroded, into two major parts:

- A part of the soil horizon up to the depth of 30–50 cm (topsoil, epipedon);
- A part of the soil horizon from the depth of 30–50 to 150 cm (subsoil, subsurface horizon). The reason for this is the quite different oxidability of OM at a different depth. Such a division also correlates with the OM chemical composition. The upper part of the profile is much more decomposable, contains more microorganisms and plant residues, and has better oxidation conditions. The lower part of the soil profile may be treated as a part of the soil OM pool, however, almost unchangeable through casual disturbances, some special depth coefficient may be used to reflect this change or it may be regarded as belonging to the slow turnover pool.

(4) Each part of the soil profile (only the upper one (?)) may be divided into:

- Fast turnover pool (light fraction, <1,6 g/cm^3):

(a) Easily decomposable material consisting of humus non-specific material such as ferments, some carbohydrates, aminoacids, fine roots, solved carbohydrates of calcareous soils (?) and other easily decomposable material;
(b) Medium-decomposable material composed by animal and microorganism remains, coarse roots, plant and animal residues rich in lignin, waxes.

- Medium turnover pool (medium fraction, fulvic and low-molecular clay-adsorbed humic acids (medium weight fraction mostly: 1.6-2.0 g/cm^3);
- Slow turnover pool (highly aromatized and condensated OM- humin, high-molecular humic compounds bound with heteropolar salts, charcoal, coal-like substances (mostly heavy fractions, >2.0 g/cm^3). Also the subsoil organic material can be included in this pool.

Soil erosion is present on cutovers, as well as on burnt-outs. Its severity and distribution depend very much on habitat, soil conditions, type, and intensity of impact. As a whole, clearcutting produces a more severe erosion hazard due to greater soil physical properties disturbances and peculiarities of this type of effect promoting to erosion development (skidding, road constructions and so on).

Usually erosion itself has a slight direct influence to soil carbon accumulation or decomposition rate. The indirect effect is due to differences in soil properties at different depths. More important is how much topsoil is lost because of erosion, and where it was moved. An assessment of humus decomposition (accumulation) and nutrient release rate changes does not include probobal material losses. Therefore that distorts all estimations and conclusions made. Especially those relating to the soil carbon cycling. Actually it is very complicated to make such evaluations and little data is available.

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