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Regeneration after Forest Fires in mixed Conifer Broad-leaved Forests of the Amur Region in Far Eastern Russia: the Relationship between Species Specific Traits Against Fire and Recent Fire Regimes

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Abstract

The number of forest fires has been increasing dramatically in the mixed conifer broad-leaved forests in the southern part of Far Eastern Russia. We should analyze the effect of this new fire regime on the vegetation and carbon budget in the forest ecosystem of this region. As each woody species develops specific traits to adapt to certain fire regimes, a change of fire regime affects each species differently. This can result in the alteration of the species composition of forest ecosystems. In the present study, we reviewed those adaptive traits exhibited by species in the region, and hypothesized a possible mechanism for the changes of species composition and amount of biomass stock that would result from the new fire regime. The new fire regimes described were an increased frequency of both intense canopy fires and low intensity surface fires. Both kinds of increased fire result in an increase of *Betula platyphylla* forests, but with different mechanisms. We proposed that an increase of *Betula platyphylla* forests due to either mechanism results in a decrease of biomass density.

Key words: Russian Far East, fire regime, specific traits against fire, vegetation recovery, biomass

Introduction

Russian boreal forest is commonly regarded as a huge carbon sink because of its large land coverage and slow rate of litter decomposition in the soil surface (Mellilo *et al*., 1993; Kasischke *et al*., 2000). Shvidenko *et al*. (1996) reported that 86,5Gt of carbon are stocked in Russian vegetation, and Shugalei *et al.* (1998) reported 74,0Gt of carbon in the forest soil. The carbon stock as forest biomass is once released by forest fire, because forest fire is a major disturbance factor in boreal forests. However, as it is re-stocked by the recovery of vegetation, the net carbon stock as biomass can be determined from the amount of carbon recovered by regeneration under a certain fire regime.

Throughout the Russian territory, with its various climates, there are many types of forest, which have varying regeneration patterns and coincidental sequestration rates of biomass after forest fires. The regeneration patterns and quantities of biomass recovered after fire have been well studied in various types of forests throughout Russia since the 1990s (e.g. West Siberia's scotch pine forest (Schulze *et al*., 1999; Wirth *et al*., 1999), Central Siberia (Kajimoto *et al*., 1999), larch forests in the Far East (Schulze *et al*., 1995) and mixed forest distributed in the southern part of Russia (Shvidenko *et al*., 1996)). Most of these studies are of forests under natural fire regimes, but in these decades, fire regimes have changed drastically. In particular, in the southern part of Far Eastern Russia, near China, the number of forest fires has increased significantly (Kakizawa and Yamane, 2003; Makoto, 2006). Frequently, multiple forest fires can be seen from satellite images of a broad area of the Russian Far East (using images from, for example, MODIS http://visibleearth.nasa.gov/search). This is due to the drastic recent increase of logging activity in the forest, and the resulting increase of man-caused origins of fire (e.g. through carelessness with cigarettes and campfires) (Kakizawa and Yamane, 2003).

The southern part of the Russian Far East is a transition zone between boreal and temperate forests, so woody species belonging to both forest ecosystems are present in the region's forests. According to the forest classification of Tatewaki (1955, 1958), the southern part of Far Eastern Russia belongs to the mixed conifer broad-leaved forests, and is characterized as having a high biodiversity of animals and plants, including endangered species such as the Amur tiger (Friends of the Earth Japan, 1996). The mix balance, or antagonism, between the two ecotopes is established as a result of

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the interaction of a variety of environmental factors, and so the vegetation in this region is sensitive to changes in environmental conditions, such as a change in fire regime, which could lead to replacement of the tree species.

Both factors, drastic change of fire regime and sensitivity of the forest, are thought to have a large impact on species composition. A change of fire regime might not only cause immediate vegetation change but also affect those animal and plant habitats which interact with the specific vegetation. Furthermore, changes of the regeneration pattern would also affect the amount and rate of biomass sequestration along with the vegetation recovery.

Although the relative land cover of the mixed forest in the southern part of the Russian Far East is small (Shvidenko *et al.*, 1996), its productivity is estimated to be relatively high (Alexeyev *et al*., 2000). Therefore, it is important to understand the effect of the recent fire regime on the regeneration pattern in this region in order to assess the impact on the biodiversity, the change of biomass stock, and the role of Russian Forest on the global carbon cycle.

Among the many regions possessing mixed forests, the southern part of the Amur region in the Russian Far East is one of the hot spots for biodiversity and frequent recent forest fires (Fig.1), and for this reason we began this study on the region’s forests focusing on the effects of changing fire regime on vegetation makeup (Makoto, 2006).

General description of mixed conifer-broad-leaf forest in the Amur region

In the Russian Far East, 249 million ha are covered by forest ecosystems (Kasischke *et al*., 2000). In the Amur region, forests cover 31.64 million ha which makes up 64% of this region’s total area (Yavorov, 2000) and 26.6% of the total Far Eastern forested area (Tagil’tsev *et al*., 2004)

The minimum temperature of the coldest month in this region is about -25, and annual precipitation is about 720mm. Snow covers the forest floor from October to April. As the periods between April to June and September to October are dry, these are the seasons of greatest risk of forest fire. The northern part is a transition zone between continuous and discontinuous permafrost, while the southern part is made up of areas of sporadic permafrost and seasonal frozen ground (Brown *et al*., 1997). The northern part of the forests is dominated by *Larix gmelinii*, while in the southern forest many species co-exist with the *Larix gmelinii*. The major species of the southern forests are *Larix gmelinii, Pinus sylvestris, Betula platyphylla, Quercus mongolica, Populus tremula*, and *Betula daurica*. The diversity index of trees is very high; sometimes most of these species co-exist even within a small 20m×20m plot (Fig.2).

Most of this region is on the flood plain of the Amur River, so soils under the forest are sandy (Fig.3). The composition of woody species in the forest is very similar to that of northern China, as reported by Goldammer and Xueying (1990). In China, both the varied mountain-like topographic features (e.g slope direction) and forest fire regime determine the vegetation distributions. In the southern part of the Amur region, most of the land is on a flat plain and topographically homogeneous, so the forest type is mainly affected by the fire regime.

After fire damage, the highly diverse and heterogeneous distribution of woody species is thought to be distributed in a mosaic like pattern of species, rather than a homogeneous pattern, as a consequence of the forest fire which damages forest heterogeneously and species-specific fire tolerance traits (Sannikov and Goldammer, 1996; Wirth *et al*., 1999). Wirth (2005) reviewed the five types of adaptation traits exhibited by tree species: 1) resister, 2) avoider, 3) invader, 4) endurer, 5) embracer. Each type of species developed a specific trait adapted to the local fire regimes in the evolutional stage (Wirth, 2005). The details of each adaptation trait are explained with the specific vegetation examples from this region in the next section. As different woody species have developed specific adaptation traits to a given fire regime, a change of fire regime would result in a change of woody species composition. Therefore in order to clarify how the vegetation of the forest ecosystem changes, we first review the adaptation traits of woody species in this region. Then, by relating them to the new fire regime, we suggest a hypothesis regarding the mechanism of vegetation change and the change of biomass stock in this region. As embracer species are not observed in this region, they are not further discussed.

Review of the species-specific fire tolerance traits of tree species in the Amur region

-Larix gmelinii- Gmelin Larch

Larix gmelinii is the most common species in this region; about 60% of the total forest area is made up of larch stands (Zyryanova *et al*. 2005). In the northern Amur region, the area of permafrost, *Larix gmelinii* dominance is very high. *Larix* species are able to inhabit permafrost soil because of the phenology of needle-fall, which avoids winter desiccation of the tree body (Berg and Chapin, 1994), and their high tolerance to the freezing stress of the winters in the area (Sakai and Larcher 1987). In the southern forests, the dominance of this species is lower. Although *Larix gmelinii* commonly prefers a xeric habitat, as the *Pinus sylvestris* more strongly prefers xeric areas, *Larix* tends to regenerate in relatively mesic areas in this region. Throughout the southern region *Larix gmelinii* frequently mixes with *Betula platyphylla, Pinus sylvestris, Betula davurica,* and *Quercus mongolica.* Although as a pioneer species *Larix gmelinii* has a high growth rate, the *Betula platyphylla* has a much higher growth rate. Therefore *Larix gmelinii* comes to dominance after the succession has gone on for some time, after *Betula platyphylla* has declined. On the forest floor, moss, fern, and Ericaceae species dominate, with seedlings of *Larix gmelinii* often observed on the moss species (Fig.4). *Larix gmelinii* is a so-called “resister species” to forest fire, as this species has thick bark near the bottom of the stem, which resists surface fire. As burning heat generated by surface fire can not damage the cambium and conducting tissues, this species is resistant to fire damage. After surface fires, this species disperses seeds near the surviving mother trees and produces patch-like habitats. However, as the thickness of the bark gradually decreases from the bottom upwards, canopy fires can easily result in the death of the matured trees (Wirth, 2005). To prevent surface fires transmitting to the canopy, this species tends to quickly shed dead branches from the lower part of the stem, as dead branches in the lower part act as a ladder for the fire to the canopy (Wirth, 2005). This self-pruning character results in fewer occurrences of canopy fires and more of surface fires in resister species communities.

-*Betula platyphylla*-White birch

Betula platyphylla is the most frequently occurring of the broad-leaved species. 21% of the total forest area is covered by this species (Zyryanova *et al*., 2005). After stand replacing fire (SRF), this species invades (Fig.5) and dominates to establish pure stands in the bare area. This regeneration characteristic is that of a so-called “invader species”. *Betula platyphylla* has a high growth rate and capacity to disperse seeds densely and widely. Usually, very high irradiance in bare areas inhibits seed germination, but the degree of inhibition is reported to be relatively low for *Betula platyphylla* (Katsuta *et al*., 1998). This species also regenerates by sprouting (Fig.6), which arises from the bottom of the stem (basal sprout), and replaces big unprofitable stems with new sprouting stems. Among the *Betula* species, *Betula platyphylla* has the greatest ability to sprout (Takahashi *et al*., 1984). This sprouting characteristic after fire is that of an “endurer species”, therefore, we should identify *Betula platyphylla* as not only an invader species, but also an endurer species. These double traits result in the early and dense establishment of large pure stands in areas bare after SRF. However, as *Betula platyphylla* has low resistance to even normal surface fires, after the first surface fire has occurred, *Betula platyphylla* forest gradually converts to *Larix gmenlinii* and *Pinus sylvestris*, which have high resistance to surface fire (Goldammer and Xueying, 1990). On the forest floor, Gramineae plants dominate.

- *Pinus sylvestris* –Scots pine

Pinus sylvestris mainly establishes pure stands, but is sometimes mixed with *Larix gmelinii* and other species. This species inhabits xeric sandy soils, such as are found on hills. On the forest floor, Gramineae plants dominate. This species is also a “resister species” to surface fires (Fig.7), and often co-exists with *Larix gmelinii* under the same fire regime due to their similar traits. *Pinus sylvestris* can dominate due to the absence of permafrost and their evergreen needle phenology (Berg and Chapin, 1994). The mean fire interval in *Larix* dominated forests is reported to be longer than that of *Pinus* species in a summary of global statistical data (Wirth, 2005). This difference is due to the habitat conditions. *Pinus* species prefer the higher risk xeric to mesic sites for their regeneration. Furthermore, as *Pinus sylvestris* provides good quality timber, there is significantly more human activity in *Pinus sylvestris* forests. These two factors would result in the greater incidence of forest fires in *Pinus sylvestris* forests.

- *Quercus mongolica* –Mongolian oak

Quercus mongolica is the second most frequently occurring broadleaf species, covering 2% of the total forest area. This species establishes stands on xeric soils. *Quercus mongolica* regenerates with heavy seeds (245 to 625 seed/kg) (Katsuta *et al*., 1998) and sprouting. *Quercus mongolica* has a higher fire tolerance than that of *Betula platyphylla*, but less than that of *Larix gmelinii* and *Pinus sylvestris*. We identify this species as having both the characteristics of endurer and resister species. Therefore under a moderate fire regime (moderate intensity and length of fire interval), this species tends to establish pure stands. Moreover this species has moderate tolerance to shade conditions compared to other hardwood species (Koike, 1991). Therefore, the sproutings of *Quercus mongolica* can grow well and were often observed on the forest floor of *Larix gmelinii* and *Betula platyphylla* (Fig.8). These sprouting individuals will eventually dominate after some decades under a moderate fire regime.

- *Populus tremula* –Trembling aspen

Populus tremula covers 0.7% of total forest area and is a typical pioneer species. *Populus tremula* is distributed from mesic to slightly xeric areas, but does not grow fully in xeric conditions (Katsuta *et al*., 1998). Although *Populus tremula* disperses seeds densely and widely, the seeds are unable to survive in strongly xeric conditions, limiting its habitat. *Populus tremula* particularly tends to dominate in post-fire stands near rivers. This species is a so-called “endurer species” whose suckers are not easily killed by surface fire and regenerate mainly through sprouting from survived root suckers. In aspen forests, crown fires rarely occur.

-*Betula davurica*- Dahurian Birch

Betula davurica covers less than 1% of total forest area. This species is another resister species. *Betula davurica* has thick and layered bark to prevent heat transmission to the internal cambium and conducting tissues. Therefore, in post-fire stands, while *Betula platyphylla* is easily killed by surface fire, *Betula davurica* frequently survives (Fig.9). *Betula davurica* is also an “endurer species”, as this species frequently sprouts from the bottom of the stem after forest fires. Although *Betula davurica* has dual fire adaptation traits, this species rarely dominates in forests, and instead is found mixed with other species at a low density.

It is important to note that the effectiveness of an adaptation trait is not determined by the absolute capacity potentially exhibited by a woody species, but by the relative degree of each characteristic (e.g. seed dispersal area, growth speed, light demanding) compared with other species present in the same stands under a certain fire regime. Moreover, woody species do not necessarily develop only one type of adaptation trait as Wirth (2005) reviewed; several species possess two.

Recent fire regimes and their impacts on vegetation

As mentioned above, the frequency of forest fires has been increasing in recent decades. The increase of fire frequency includes increases of both severe crown fires and low intensity surface fires. How do changes to the fire regime affect species composition, considering the adaptation traits to certain fire regimes that different species possess?

1) Increase in canopy fires

A recent increase in canopy fires in Far Eastern Russia is reported from a satellite investigation. Severe canopy fire frequently leads to severe SRF (Fig.5). After SRF, bare areas are established and invader species rapidly dominate. Therefore, an increase of SRF favors invader species. In this region, as *Betula platyphylla* is the main invader species, the increase of SRF results in more areas of young *Betula platyphylla* forests, as reported by Yavorov (2000).

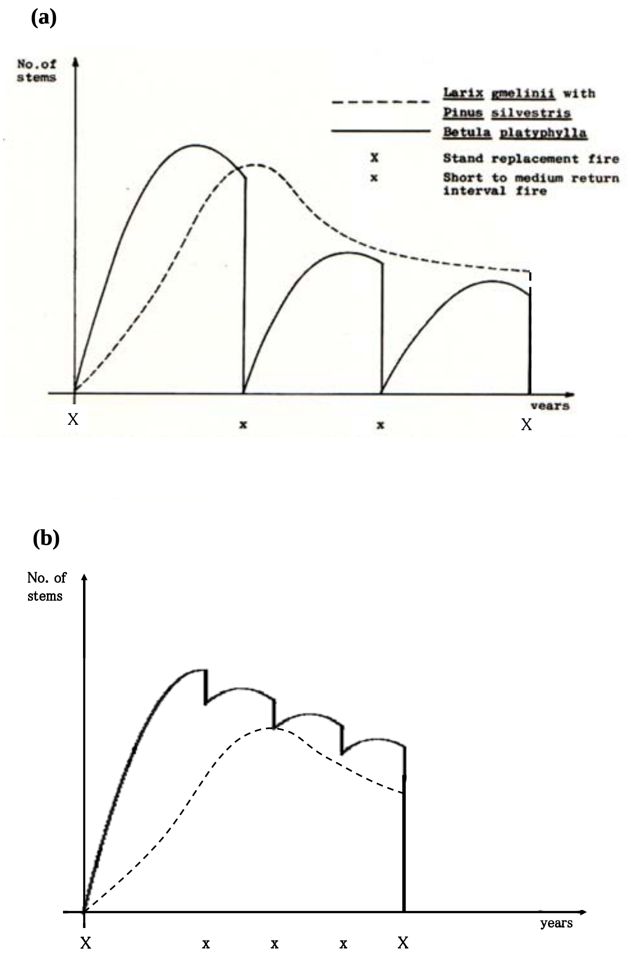

Fig.12. The generalized dynamic models of larch (pine)-birch stand development under the conventional (a) and recent (b) fire regime. These are the modified models of Goldammer and Xueying (1992).

2) Increase in surface fires

The increase in surface fires is rarely reported from satellite data, presumably due to the difficulties in detection from the sky. However in the field, the consequences of an increase in frequency of surface fire were observed. Shortly after surface fires, *Betula platyphylla* regenerates by sprouting from the bottom of stems. If a surface fire happens again soon after sprouting, as the aboveground part of tree is still small, the sprouting cohort is easily killed. However, this species regenerates again by sprouting. If this “regeneration-death cycle” is repeated, sprouting stumps are established which have sprouting cohorts of different ages (Fig.6). From such stumps and local field surveys by the inhabitant (Yavorov, 2000), the recurrence of surface fires was estimated at every 1-5 years. Surface fires generally kill fully matured *Betula platyphylla* because of their high sensitivity to forest fire (Goldammer and Xueying, 1990) (Fig. 10). However, in this region many scorched *Betula platyphylla* survive after surface fire for many years (Fig.11).

This indicates that the lower intensity surface fire of the new fire regime is not necessarily fatal for *Betula platyphylla*. It is possible that the recent frequent fires ensure that the potential fuel build-up on the forest floor remains low, leading to weaker fires which *Betula platyphylla* is able to resist, and hence comes to take on the regeneration characteristics of a resister species. If *Betula platyphylla* acquires the characteristics of a resister species by the shift in fire regime, other resister species (e.g *Larix gmelinii* and *Pinus sylvestris*) will be less able to regenerate in the forest because the space and nutrients are kept occupied for a longer period by the surviving *Betula platyphylla*. This would result in the increase of old *Betula platyphylla* forests. If we demonstrate the increase of surface forest fires and the coincidental increase of *Betula platyphylla* forests, we can establish the model in Figure 12.

In Russia, it is suggested that trees regenerate and forests develop according to a bimodal fire regime of a short cycle of frequent low intensity surface fires superimposed by a long cycle of SRF (Wirth, 2005). In a study of north-eastern Chinese forests, which have a similar tree composition and natural fire regime to those in the southern Amur region, Goldamer and Xuying (1990) suggested a model to show the relationship of a bimodal fire regime and vegetation succession (number of stems) (Fig.12a). If we apply the increase of SRF and light surface fire to the model of Fig. 12a, it would be as shown in Fig. 12b.

In Fig. 12b the mean interval of SRF becomes shorter than that of Fig. 12a. Consequently there is a shorter period of biomass recovery under this fire regime. Furthermore, in these two models, while each conventional surface fire with a moderate intensity eliminates all *Betula platyphylla* (Fig.12a), recent low intensity surface fires do not eliminate the *Betula platyphylla*, but only reduces the number slightly (Fig.12b). Then, while the *Larix gmelinii* stem density soon surpasses that of *Betula platyphylla* after its elimination in Fig. 12a, *Larix gmelinii* is unable to do so in Fig. 12b because *Betula platyphylla* still occupies the canopy layer. Although it is unclear whether the absolute number of stems of *Larix gmelinii* is greater than that of *Betula platyphylla* in Fig. 12b, the number of *Larix gmelinii* is clearly smaller than that in Fig. 12a. As low intensity surface fires do not affect *Larix gmelinii* survival, it decreases along with the growth of the tree component in the forest ecosystems with the same rate of Fig. 12a, assuming Goldammer and Xueying also do not posit an effect of surface fire on the *Larix gmelinii* survival in their model. As a result, in this limited time model, the number of stems of *Larix gmelinii* becomes smaller in Fig. 12b than that of Fig. 12a, while the opposite effect is obtained for *Betula platyphylla*.

These two types of change on the fire regime result in the accelerated increase of the *Betula platyphylla* forest area and decrease of those of *Larix gmelinii*, as reported by Yavorov (2000).

On the other hand, Makoto *et al.* (2007) suggested that changes in the intensity of surface fires would result in changes to seedbed types, which in turn would result in changes to seed germination in this region. After light surface fires, the scorched seedbeds of various litters are observed in mixed forest. Of the various types of litter, scorched larch litter showed a particularly high ability to germinate seed, but in general scorched litters were better able to germinate seed compared with litters remaining after severe surface fire (e.g. charcoal and ash) in our study. However, although the seed germination rate on the forest floor would have increased with the recent fire regime, and seed dispersal from the mother tree was indeed well observed, poor forest floors without growing seedlings were often established. This indicates that frequently repeated fires kill the seedlings directly, resulting in the establishment of poor forest floors.

Hypothesis of the change in biomass due to increased prevalence of *Betula platyphylla*

As vegetation changed, we saw increases of both young and old *Betula platyphylla* forests, rather than *Larix gmelinii* forests. How does the recent increase in the frequency of forest fires affect the carbon budget of the biomass in the Amur region through the increased abundance of *Betula platyphylla*? While it is clear that young *Betula* forest soon after SRF has a smaller biomass than that in matured *Larix gmelinii* stands, the difference between the old stands of *Betula platyphylla* and *Larix gmelinii* is complicated.

Although we do not have accurate data regarding changes to biomass stock, we can guess how biomass stock changes by comparing relative numbers of stems between the conventional situation (Fig.12a) and the recent one (Fig.12b), i.e. under each fire regime. In our previous study, we discovered that the potential maximum biomass stock in *Betula platyphylla* forests is attained at an early stage and the absolute value of the maximum biomass stock is smaller than that of *Larix gmelinii* in this region (Makoto *et al*., unpublished data). In sum, the long term dominance of *Betula platyphylla* in the forest canopy instead of the *Larix gmelinii* would result in the reduction of biomass density. In this section, we only referred the conversion from *Larix gmelinii* forests to *Betula platyphylla*. It could be said that recent fire regimes favor invader species to resister species such as *Pinus sylvestris*.

Further Perspective

In the future, we will validate the suggested hypothesis of vegetation and biomass change by observed data. For this purpose, we will analyze changes to the age distribution of forests and their areas, perhaps supported by aerial photographs or satellite images.

Furthermore, we will gain precise fire regime data (area burnt per year, fire distribution, and intensity) and biomass recovery rates using satellite image analysis and summation methods. Additionally, we need to accumulate data for the quantity of biomass released by fire, including not only aboveground biomass, but also belowground biomass and carbon stock in the soil. Although Kajimoto *et al*. (1999) reported that large amount of biomass is stocked as belowground biomass in the case of *Larix gmelinii* in the permafrost, the amount of data on belowground biomass is still limited. By analyzing belowground root biomass and soil carbon data with chronosequences after fire, we will be able to establish an appropriate model to estimate carbon stock in accordance with various types of fire regime. Moreover, to accurately evaluate the effect on the ecosystems in this region inclusively, we will also investigate the relationship between the establishment of *Betula platyphylla* forests and other organisms including micro-organisms and mammals, which have important roles in the conservation of forest ecosystems.

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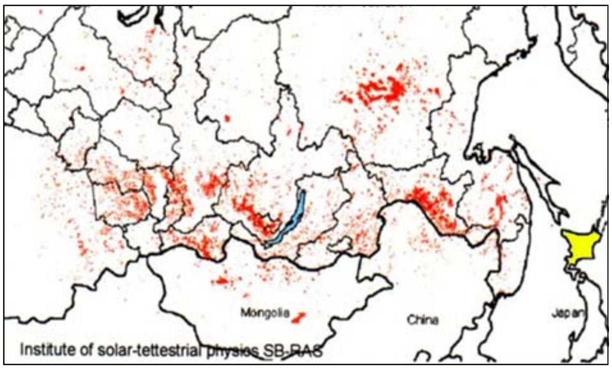

Fig.1. The distribution of the forest fires in Russian Federations in 2003. Each red point shows the fire location. The black arrow shows the location of our research site. (unpubrished data of Prof. Fukuda, M.)

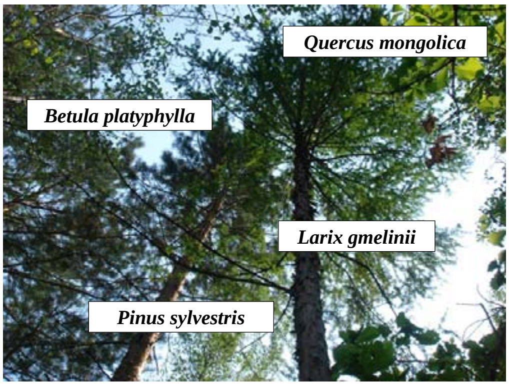

Fig.2. The canopy structure in the mixed forest with the *Larix gmenlinii, Pinus sylvestris, Quercus mongorica* and *Betula platyphylla* in this region.

Fig.3. A typical soil profile of sandy texture in the southern part of Amur region.

Fig.4. The regenerating *Larix gmelinii* seedlings on the moss in the forest floor.

Fig.5. The *Betula platyphylla* forest after the stand replacing fire. The regenerating seedlings are mainly those of *Betula platyphylla, Poplus tremula* and *Alnus hirsuta.*

Fig.6. The sprouting from the same root after the repeated surface fires. At least the three different cohorts are included.

Fig.7. The survived *Pinus sylvestris* after the intense surface fire.

Fig.8. The sprouting and regeneration of *Quercus mongorica* in the forest floor of *Betula platyphylla* dominated matured stand. The photograph is taken in the late September, 2006.

Fig.9. The survived *Betula davurica* after the intense fire in the mixed *Betula platyphylla* and *Betula davurica* forest. Black arrows show the survived *Betula davurica* and white ones show the dead *Betula platyphylla* respectively.

Fig.10. The scorched *Betula platyphylla* trees in the forest after the moderate intensity surface fire in May, 2006. The photograph is taken in June, 2006.

Fig.11. The scorched *Betula platyphylla* trees in the forest after the low intense surface fire in May, 2006. The photograph is taken in June, 2006. Even after the fire, they keep much fresh leaves.