Structure and regeneration of spruce forests as affected by forest management practices in the Moscow Region

V Kiseleva¹, S Korotkov¹, L Stonozhenko², E Naidenova¹

¹Mytishchi Branch, Bauman Moscow State Technological University, 1 Insitutuskaya Street, Mytishchi 141500, Moscow Region, Russian Federation
²All-Russia Institute of Improvement of Professional Skill of Executives and Specialists of Forestry, 17 Insitutskaya Street, Pushkino 141200, Moscow Region, Russian Federation

¹E-mail: vvkisel@mail.ru

Abstract. Spruce (Picea abies (L) Karst) is referred to as late-succession species of the Moscow region. However, its large areas have been and continue to be maintained by cultures initially planted to timber harvesting but remained unlogged as all the forests of the Moscow region were referred to as protective ones. During the last years, approximately 20% of spruce forests dead, mainly monodominant cultures with reduced tolerance to pests and extreme weather factors. The forests with the predomination of spruce in the canopy and subcanopy were studied on permanent observation plots in the northeastern part of the Moscow region. Twenty of 25 spruce stands have the diameter structure homogenized by previous treatments. The traditional practice of forming high-density close-canopy stands led to the suppression of spruce second layer and understory and its substitution by linden (Tilia cordata L) and maple (Acer platanoides L). Both natural species composition shift and ecological and recreational functions of forests in the Moscow region demand to reject the outdated practice of creation and artificial sustention of monodominant spruce forests. A complex management strategy should be elaborated for the protective forests of the Moscow Region, turning from passive following of forest decline to active formation of complex polydominant stands.

1. Introduction

The interest to the Norway spruce (Picea abies (L) Karst) in the Moscow Region is quite natural. For the majority of sites of the Moscow region, spruce is the climax (late succession) species. It has been present in the region during the whole Holocene period, which is supported by numerous palinological studies of local peat bogs. M I Neuschtadt [1] distinguished two spruce maxima: in the preboreal period, 10-12 thousand years ago, and in the subatlantic period, 2 thousand years ago. Since that time, the proportion of spruce in vegetation composition has remained noticeable.

Commercial value of spruce forms another aspect of the problem. It is recognised as commercially valuable species, its cultivation giving large volumes of high-quality timber. In the Moscow region, spruce is a rapidly growing species, unlike northern regions of Russia. Local spruce forests of top site index classes are characterized by high growth rate and high stock volume already in middle-aged stands but relatively early stand decline.

At the same time, spruce state is far from being optimal in many aspects. Spruce forests, especially monodominant ones, are weakened by root fungi (Heterobasidion annosum (Fr) Bref), suffer from
windfalls and pest attacks. Bark beetle (*Ips typographus* L) plague in 2000-2002 and 2010-2013 became the indicator of reduced spruce forests’ stability. Our own studies indicated that only the stands younger than 60 years remained intact after bark beetle outbreak. Mass spruce mortality points out to its low adaptation to climate changes (increased frequency and intensity of droughts) [2]. From the viewpoint of dynamics, spruce positions cannot be called stable because of poor regeneration under spruce parent canopy [3, 4].

Nevertheless, the presence of spruce in subcanopy puts the question about its future in the studied region and optimal structure of stands with the predominance or significant proportion of spruce. The forests of the Moscow region have lost their initial shape several centuries ago, their composition and structure having been crucially modified. The succession dynamics of forest communities should be interpreted accurately considering the whole range of factors including possible effect of the historical factor [5].

In the last century, high percentage of spruce forests in the Moscow region has been maintained by silvicultural measures. At the edge of 19th and 20th centuries, spruce stands occupied approximately 30% of forested lands of the region. Their proportion has decreased down to 24% by the beginning of the 21st century and to 19.3%, by 2015, after recent droughts and pest attacks.

Commercial monodominant stands aimed at timber harvesting appeared in the early 20th century. Later on, the destination of forests shifted radically: the forest-park protective belt was established around Moscow in 1931, the forests of the whole region got the protective status, with total prohibition of clearcuts. In the last decades, the scales of sanitation fellings became insufficient, other treatments (including thinnings or landscape-formation cuttings) were absent. As a result, by the end of the 20th century, large massifs of mature and overmature spruce forests disagreeing with their new protective destination have been formed in the region.

Already in 1930-s, prof. M M Orlov stressed: “The most desirable form of stands in protective and water-conservation forests should be that of multi-aged mixed stands completely using the area and possessing a vertically close canopy. But these stands still are to be created, as at present, our forests are predominated by simple stands with a horizontal canopy; their structure prevents us from successful application of not only selective, but gradual cuttings” [6].

Decreasing tolerance of spruce forests of the Moscow region and their inability to fulfill protective and recreational functions at the age of maturity became one of the most acute problems of regional forestry and forest management.

These statements are supported by the results of our long-term observations in the Moscow region represented below.

### 2. Experimental part

Spruce status and regeneration was studied on permanent observation plots (POP) set in 1990s – 2000s in the eastern sector of the Moscow region: National Park *Losiny Ostrov* (55°51’ N, 37°49’ E) (54 plots) and Shchelkovo Experimental Forestry (55°56’ N, 38°07’ E) (28 plots). We examined both the plots with the predominance of spruce in the overstore and those of other species having spruce in the undergrowth.

All spruceries examined are pre-mature and mature (elder than 80 years). The POP represent the forests of natural or indefinite origin and spruce cultures. The latter were subjected to serial thinnings with the removal of all suppressed trees. Natural forests also were treated, at least, until the age of 40 years, the main trend of cuts being the removal of accompanying deciduous species.

Each permanent observation plot included as least 150 trees with the diameter over 7 cm, of which minimum 100 trees of main species. Depending on stand age and density, plot size varied from 0.2 to 0.6 ha. In the process of each following revision, new trees having reached the diameter of 7 cm were included into the database. Thinner specimens were referred to as undergrowth; the latter was described on test plots with the area of 25 m², 5 test plots on each POP, situated in the center and the corners of the POP. The undergrowth quantity was recalculated per unit area (hectare).
Each tree was characterized by the diameter at breast height (DBH) and grade of sanitary state according to national Rules of sanitary security in the forests (2017): 1 – healthy, 2 – weakened, 3 – strongly weakened, 4 – declining, 5 – least season deadwood, 6 – old deadwood. Height of model trees (up to 20-25 per permanent plot) was measured. The heights of all other trees were calculated from the diameter-height graphs.

Analytical graphs were compiled: (a) the vertical stand structure representing tree distribution by layers and (b) the histograms of tree distribution by 2 and 4 cm diameter grades. In each stand, trees were divided into 10 diameter classes.

To determine the absolute age, cores were taken at the height of 0.3 m from 25-30 spruce trees (3 specimens in each diameter class).

Data ranges were subjected to standard statistical procedures including Student-test.

3. Results

3.1. Stand structure as indicating previous management

In order to separate the types of diameter structures of spruce coenopopulations, the ranges of spruce trees distribution by diameter grades were subjected to Student-test, returning the probability of attribution of samplings to the same general totality. Several groups were revealed with the probability exceeding 0.95 and 0.90: spruce cultures and the stands after thinnings; spruce coenopopulations of mature mixed forests with the right or left maximum; subcanopy spruce trees. Some diameter structures could not be definitely attributed to any group as the probability of their similarity to any other diameter range was below 0.7.

As a result, the diversity of diameter structures of spruce coenopopulations was divided into four groups represented on Figure 1 by averaged curves.

1) The coenopopulations with quasi-normal distribution of trees by diameter grades (Figure 1, curve 1) are typical for forest cultures subjected to thinnings and to some monodominant spruce forests of indefinite origin where spruce forms one cohort. The analysis of cores indicated the absolute predomination of one tree generation, with single presence of two neighbouring ones. Hence, we regard this group as even-aged.

2) Stands characterised by the curves with smoothed peaks or very expanded maximum (Figure 1, curve 2). This diameter structure is typical for the stands of natural origin where spruce grows together with pine (*Pinus silvestris* L.), birch (*Betula pendula* Roth), linden (*Tilia cordata* L.), or oak (*Quercus robur* L.), and often participates in the composition of the second layer.

The analysis of cores allowed us to refer these stands to as conditionally uneven-aged (3-4 adjacent age classes) but revealed a very low proportion of trees of the first three age classes (below 60 years); the thinnest trees proved to be one age with the canopy trees but strongly suppressed. The latter fact makes us to interpret these coenopopulations as degrading.

3) Uneven-aged forests with the highest peak in the left part of the spectrum resembling the lognormal distribution (Figure 1, curve 3). The trees can belong to 4-5 age classes, however, the specimens younger than 40 years are single.

The types 2 and 3 are the most typical in mature stands of the national park.

4) The fourth group unites the plots where spruce predominates or participates in the second layer composition under the canopy of pine, birch, or mixed deciduous (linden, aspen, and birch) of natural and cultural origin. In most cases, one cohort is seen on the graphs (Figure 1, curve 4). Even the populations with the average diameter of 18-20 cm, which corresponds to the age of 40-50 years, show the absence of ingrowing younger (thinner) trees. Hence, no basis for the formation of really uneven-aged stands in future is observed at present. We suggest that spruce appeared after thinning and canopy opening, but as no treatments have been undertaken in these stands during the last 25-30 years, the canopy relative density recovered up to 0.8, which is unfavourable for spruce undergrowth.
Figure 1. Types of diameter structures of spruce coenopopulations on permanent observation plots in the Moscow Region: (1) cultures and even-aged stands, (2) conditionally uneven-aged declining stands, (3) uneven-aged stands, and (4) spruce in subcanopy.

3.2. Spruce undergrowth and potential of spruce stands development

It seems evident that in secondary forests with low management intensity, the trend towards the restoration of late-succession forest communities should be observed. A complex multilayered stand structure is to be formed. Thus, we can expect the predomination of spruce, linden and oak in the subcanopy vegetation in nutrient-rich sites and that of spruce alone on relatively poor soils.

However, real proportions of undergrowth species prove to be quite different from this pattern.

At present, the quantity of spruce undergrowth under spruce canopy cannot be called satisfactory. Among the 25 observation plots with the predomination of spruce, its undergrowth is present on a half, the quantity of young trees (100-400 pc.ha⁻¹) being insufficient to provide a significant role of spruce in the future forest (Table 1). In most cases, the undergrowth is represented by oak-accompanying trees, first of all, by linden.

More or less successful spruce regeneration is observed under birch or pine parent canopy in oxalis forest types with favourable light conditions and litter composition, sometimes – in composite pine forests and polydominant deciduous (in Shchelkovo Forestry only). However, in these forest types the number of undergrowth does not exceed 2 thousand specimens per hectare, with two exceptions observed in the birch forest in Losiny Ostrov and polydominant deciduous in Shchelkovo (Table 1).

Within one forest type, the abundance of forest undergrowth does not show a definite dependence on canopy density because all relative density values exceeding 0.7 are unfavourable for spruce undergrowth [7].

A specific case is the regeneration after spruce forests death as a result of drought and pests in 2010-2011. This is the most evident example of species composition shift in new generations, when it is possible to state that spruce has totally lost its positions in all layers (Table 2). To represent the species composition, stand formulas are used expressing the proportion of stock volume of each species of 10 units total, in decreasing order.
Table 1. Number of undergrowth in different forest types.

| Forest type                      | Site            | Age   | Relative density | Number of undergrowth, average (min.-max.), pc.ha⁻¹ |
|----------------------------------|-----------------|-------|------------------|-----------------------------------------------------|
|                                  |                 |       |                  | All species  | Spruce       |
| Oxalis spruce forests            | Losinyi Ostrov | 90-110| 0.8              | 210 (0-480) | 125 (0-400) |
|                                  | Shchelkovo      | 55-130| 0.9 (0.8-1.0)    | 1100 (120-2700) | 130 (0-550) |
| Composite spruce forests         | Losinyi Ostrov | 80-100| 0.6-0.8          | 10150 (2200-16700) | 0 or single |
|                                  | Shchelkovo      | 45-105| 0.7 (0.6-0.9)    | 3100 (1600-4300) | 180 (0-360) |
| Oxalis pine forests              | Losinyi Ostrov | 60-80 | 0.7-0.9          | 2520 (210-7060) | 460 (60-1840) |
| Composite pine forests           | Losinyi Ostrov | 60-80; 210 | 0.6-1.0 | 6650 (500-11140) | single (0-240) |
|                                  | Shchelkovo      | 60-65 | 0.9-1.0          | 8000 (2300-19000) | 800 (200-1400) |
| Oxalis birch forests             | Losinyi Ostrov | 60   | >1.0             | 4200 | 4000 |
| Composite birch and aspen forests| Losinyi Ostrov | 60(100) | 0.8 | 6620 (950-27300) | 0 or single (0-200) |
|                                  | Shchelkovo      | 60-75 | 0.8              | 5700 (4100-7300) | 400 (80-750) |
| Mixed forests with spruce and oak| Losinyi Ostrov | 100-120 | 0.7  | 4525 (1020-14650) | 100 (80-160) |
| Deciduous linden-predominated forests | Losinyi Ostrov | 80-110 | 0.7-0.9 | 6912 (1800-20600) | 0 or single dead |
|                                  | Shchelkovo      | 45-90 | 0.9-1.0          | 5100 (3500-7100) | 1300 (300-4000) |

Table 2. Species composition changes in spruce forests after drought and pest invasion.

| Obs. plot No. | Status before spruce death (2008) | Status after spruce death (2013) | Undergrowth |
|---------------|-----------------------------------|---------------------------------|-------------|
|               | Species composition⁴               | age                             | density     | Species composition⁴ | age | density |
| 16            | 7S1As1Li1Ma, single O, B           | 85                              | 0.8         | 5S3Li1O1Ma, single As, B | 90  | 0.5 |
|               |                                   |                                 |             |                         |     | 8Ma1Li1As | 11800 |
| 17            | 8S1B1Li, single Ma, P, As, O       | 90                              | 0.8         | 7Li1B1Ma1P              | 60-90 | 0.3 | 8Ma2Li | 5300 |
| 115           | 9S1Li, single P, B, O              | 88                              | 1.0         | 6Li2B1O1P               | 75-90 | 0.2 | 10Li | 2800 |
| 118           | 7S3Li, single B, O                 | 99                              | 1.0         | 9Li1S+O                 | 50-65 | 0.5 | 7Li1As1Ma1S | 3500 |

⁴ Abbreviations used: As – aspen, B – birch, Li – linden, Ma – maple, O – oak, P – pine, S – spruce.
Hence, spruce forests are not provided with a stable flux of generations of the main species and we have to agree with A.V. Abaturov who states that monodominant even-aged stands (in our case, mixed stands, as well) will not reproduce themselves in future generations under natural development [3].

3.3. Weakening of subcanopy trees
Even in the forests where spruce is present in subcanopy, the formation of future spruce stands is limited by its suppressed status. Table 3 represents the distribution of subcanopy trees by the categories of sanitary status in different forest types.

The table shows that strongly weakened specimens predominate on the majority of observation plots. Healthy trees are either absent or constitute less than 20% of total number of subcanopy spruce trees.

A lower percent of declining and dead trees is typical (with one exception) for the forest with mixed overstorey, first of all, with the predomination of light-demanding species – pine and birch. The highest percent of declining and dead trees was recorded under spruce (plots No. 120 and 134) and oak (plots No. 51 and 52) canopy.

Table 3. The distribution of subcanopy spruce trees by the categories of sanitary status on permanent observation plots, %.

| Overstorey                  | Observ. plot No | Category of sanitary status |       |       |       |       |
|-----------------------------|-----------------|------------------------------|-------|-------|-------|-------|
|                             |                 | healthy                      | weakened | strongly weakened | declining | dead |
| Spruce forest               | 120             | 2.5                          | 19.7    | 26.2    | 9.8    | 41.8  |
|                             | 134             | 0.0                          | 12.9    | 27.4    | 29.0    | 30.6  |
| Mixed spruce-deciduous forest | 46             | 1.1                          | 21.6    | 60.2    | 11.4    | 5.7   |
|                             | 125             | 20.5                         | 31.5    | 43.8    | 2.7     | 1.4   |
| Pine-spruce forest          | 32              | 2.0                          | 33.3    | 31.4    | 19.6    | 13.7  |
|                             | 38              | 16.3                         | 34.9    | 30.2    | 7.0     | 11.6  |
| Pine-birch forest with spruce | 22             | 7.3                          | 43.9    | 26.8    | 14.6    | 7.3   |
|                             | 131             | 0.0                          | 16.9    | 83.1    | 0.0     | 0.0   |
| Birch-spruce forest         | 36              | 0.0                          | 45.5    | 39.4    | 3.0     | 12.1  |
| Birch with spruce and exotic species | 40        | 0.8                          | 19.2    | 71.7    | 6.7     | 1.7   |
| Oak                         | 51              | 0.0                          | 5.1     | 40.7    | 39.0    | 15.3  |
| Oak-lime forest             | 52              | 0.0                          | 6.7     | 16.7    | 10.0    | 66.7  |
| Mixed deciduous             | 126             | 1.1                          | 22.7    | 72.7    | 3.4     | 0.0   |

3.4. How a management practice can alter the destiny of undergrowth
The next experiment illustrates how a management practice can alter the destiny of undergrowth under spruce canopy.

Two observation plots were set in neighbouring sites, one representing the sprucery formed from undergrowth preserved during harvesting in 1975; another one, the same unharvested stand where the undergrowth has formed the second layer. The characteristics of the 50-year-old stand and the second layer of the same age differ significantly, reflecting the difference in growth rate (Table 4). The fact that the stand formed from undergrowth after harvesting possesses much better quality as compared to the contemporary second layer seems to be quite natural.
Table 4. Characteristics of stands developed from undergrowth in case of removal and preservation of overstorey.

| Stand                                      | Species composition*, by layers | Age | Sum of cross-sectional areas, m² ha⁻¹ | Dₘ, cm | Hₘ, m | Stock volume, m³ ha⁻¹ | Relative density |
|--------------------------------------------|---------------------------------|-----|---------------------------------------|--------|-------|-----------------------|-----------------|
| Formed from preserved undergrowth          | 9S1B, single O, Li              | 50  | 39.6                                  | 20.1   | 21.0  | 380.0                 | 0.9             |
| Unharvested two-layered                    | I: 10S, single O                | 90  | 25.4                                  | 32.5   | 25.5  | 289.6                 | 0.5             |
|                                            | II: 7S3B, single O              | 50  | 11.3                                  | 14.5   | 15.6  | 84.2                  | 0.3             |

*For species abbreviation, see Table 3.

4. Discussion

A large amplitude of diameters and variability of structure types in general in intrinsic to unmanaged forests. Natural forests possess an expanded descending range of diameters, while managed forests possess either bimodal or even quasi-normal distribution along diameter range [8, 9]. Increasing forest management intensity homogenises the diameter structure [10].

The majority of pre-mature and mature stands of the Moscow region, studied at the permanent observation plots, are characterized either by quasi-normal or expanded distribution of diameters, the latter demonstrating the lack of thin trees. This indicates two important facts:

1. All studied forests were managed more or less actively, even in the national park.
2. Despite the protective functions of the forests, the management traditionally has been aimed at the formation of homogeneous canopy and maximum stock volume. This led to the formation of close-canopy stands with very limited natural regeneration of spruce. Being shade-tolerant, spruce undergrowth, nevertheless, loses the competition to even more shade-tolerant linden and maple.

An active spruce regeneration could take place 35-50 years ago when thinnings and other treatments were practiced. As a result, at present we meet the spruce-predominated second layer under the parent canopy of both spruce and other species. Its development is more successful under light-demanding pine and birch, in oxalidosa types of forests.

The experiment demonstrated that timely canopy opening could provide proper conditions for spruce undergrowth. However, this is the one-time effect, and one-cohort spruce population is thus formed. Similar processes were observed in old-growth naturally developing forest where, in case of moderate large-scale disturbances leading to canopy opening, spruce is able to form even-aged patches with the area from 0.05 to 0.25 ha [11, 12].

The studies of permanent observation plots demonstrated that only in single cases the natural development of forest biocoenoses gave the composition of newly forming forest generations which was similar to that of the parent canopy. Shifts in the species composition were observed almost everywhere. From the viewpoint of ecology, species shift can be regarded as a positive phenomenon as it leads to the extinction of centers of root fungi concentration, especially in spruce cultures.

The gradual development of the forests of the Moscow Region appears to be the following: deciduous or pine forests are replaced by late succession species – spruce, linden, maple. Pure spruceries, even if being formed, would not be provided with sufficient amount of spruce undergrowth and will be replaced by broadleaved species, first of all, linden (Figure 2).
However, forest management in the Moscow Region has always been aimed at the cultivation of monodominant coniferous stands; after harvesting, they were replaced either by the cultures of the same species or by secondary deciduous forest with the following development of late-succession species under their canopy (Figure 2). New harvesting returned the process to the starting point – mono-cultures or secondary deciduous stands. Thus, forest development was retained artificially at the stage of short-derivative communities or forest cultures.

At present, there is no strategy of forest management in the protective forests of the Moscow region. Modern forest legislation offers nothing but the system of restrictions, which leads to the passive management following forest mortality. Statistical data demonstrate that 3202 of 3285 thousand m$^3$ logged in 2014 in the region were provided by cross-cut sanitary felling [13]. The programme of reforestation envisages the creation of mono-cultures of coniferous species.

This practice arises from the fact that forest managers have no concrete idea of the shape (species composition and spatial structure) of the forests carrying out ecological and social functions.

The same items are discussed in Europe where commercial spruce cultures are also widespread. At present, after the understanding of forest functions had changed, the question of reconstruction of pure spruce forests arose. It is recognised that monodominant spruce cultures are convenient for forest management but they do not correspond to revised forest destination, including forest ecological functions [14]. The fact that mixed coniferous-deciduous forests demonstrate higher resistance to blowdowns became widely known [15, 16], as well as their higher tolerance to pests. The admixture of deciduous species affects the growth of spruce itself: changes in litter composition and enhanced element cycling can increase stand productivity [14, 17].

Considering spruce as climax species of the region and traditionally referred to as valuable species, we should stress that large areas of pure spruce forests fit neither protective, nor recreational functions of peri-urban forests. E.g., to carry out water-conservation functions, it is recommended to have the share of spruce between 5 and 7 units of 10 [6]. Pure spruce is not desirable in recreational forest as well as it produces unfavorable microclimate and suppressing emotional effect.

**Conclusion**

All studies sites represent the results of traditional forest management practice in Russia, directed towards the increase in the percentage of coniferous species in young forests and the increase in the growing stock of coniferous in middle-aged and pre-mature stands. All attention was given to the parent canopy, the close-canopy stands were formed with rather unfavourable conditions for natural regeneration of the majority of tree species, with the exception of the most shade-tolerant ones – linden and maple.
The diameter structure of stands is homogenised; spruce populations either are created artificially or represent the first generation of late-succession species. Cross-cuts (formerly timber harvesting, at present, sanitation ones) retain forest communities at the stage of short-derivative forest types.

Subcanopy spruce trees are suppressed and weakened; the amount of natural regeneration is insufficient. No stable generation flux of spruce is provided; no potential exists for the formation of multi-aged forests, which correspond to the goals of biodiversity conservation and dynamic stability.

The forest of the Moscow region, especially those bordering with the megacity, represent a complex mosaic of sites dominated by different species, corresponding to various succession stages and having different development trends. Recent natural processes are directed towards the reduction of spruce participation in forest composition, with simultaneous increase of the importance of broadleaved species, first of all, linden. These natural trends should be taken into consideration when setting the target composition of the forest of the Moscow Region fulfilling recreational and protective functions. The goal of forest management in spruce forests is the formation of mixed stands with the share of spruce 30-50%. Higher proportion of spruce can be acceptable at small sites (1-2 ha). The doubtful practice of mass creation of monodominant spruce cultures should be avoided.

In general, a complex strategy of forest management in protective forests should be elaborated for the Moscow Region, turning from passive following of forest decline to preventive measures aimed at the formation of forests with the composition and structure corresponding to their conservational and social functions. This will demand the revision of modern practices of forest use and legislative regulations of logging in protective forests.

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