Long-term silvicultural experiment with transformation of the mixed stand structure

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ABSTRACT: The paper summarizes the main characteristics of a mixed stand during 80-year transformation to the mixed stand with permanent selective structure. The initial main stand was mostly composed of conifers with group arrangement, broadleaves as the reserved trees created the upper storey. Partial opening by thinnings prepared the stand for regeneration. Heavy thinning in 1959 (22% of the growing stock) opened the main stand and released the advance growth of broadleaves. Subsequent stand development was negatively affected by air pollution. Mainly fir and spruce responded to air pollution by deteriorated health condition and increment reduction. Beech and other broadleaves gradually increased their proportion in the stand (64% of the growing stock in 2008). Initial diameter distribution was sinistral, reserved trees affected the frequency of thick trees. Final diameter distribution resembled the model curve for selective forests, the number of thin trees was below the model curve for broadleaved forests with selective structure in these types of localities. Mean increments of individual species changed according to their stand position. Low fecundity of trees, weed infestation and game damage limited natural regeneration, artificial regeneration dominated for the whole time. The complicated structure corresponding to selective forest occurred rarely during the monitored period, the stand was differentiated mainly by spatial arrangement.

Keywords: production; regeneration; species composition; stand transformation

Forest ecosystems are characterized by complicated internal relationships resulting from different ecological requirements of individual tree species. Mixed stands secure comparable wood production with coniferous monocultures, but mixed stands have higher stand stability against adverse abiotic and biotic factors. Fulfilling non-production functions, the volume and quality of produced biomass depend on the stand structure (Kantor 1997; Fritz 2006; Pretzsch 2009). The concept of close-to-nature management is receiving increased attention worldwide (e.g. Schütz 2001; O'Hara 2002). Close-to-nature management without clearcuttings plays an important role in Central European forestry (Schütz 2001; Saniga 2007).

The present experiences with alternative silvicultural techniques based on selective principles in mixed stands with a higher proportion of broadleaves are scarce (Schütz 2001). Conifers dominate in typical selective forests in Europe; broadleaves (mainly beech) are mainly presented in the lower storey while their proportion is limited. The main reasons for the low proportion of broadleaves are their different responses to individualization, different crown space occupancy and response to shade. Broadleaved species, free from lateral competition, expand their crowns laterally and tend to close the canopy, mainly by epicormic branches. The species with tendency of sympodial branching architecture under heavy canopy lose their ability to recover qualitatively and develop a plagiotropic branching form. These factors explain limited experiences and small area of selective forests with dominant proportion of broadleaves (Schütz 2001, 2006).

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An important problem of close-to-nature forest management at sites with high production potential is the maintenance of ecological stability and stability of production. The growing number of tree species in mature stand and young growth complicates the regeneration phytotechnique. The basic management conception in mixed stands at low altitudes should be a certain variant of shelterwood system. Regeneration under tree canopy creates suitable ecological conditions for mixed stands with high quality potential, continual stand rotation and suitable stand differentiation. The long-term application of shelterwood system limits the regeneration of species with higher demands on light. The occurrence of suitable conditions for their natural regeneration is limited in time and space.

The purpose of our investigation was to evaluate the development of a mixed stand which has been subjected to long-term transformation to a stand with selective (plenter) structure.

MATERIAL AND METHODS

The studied forest stand Křivina of an area 4.19 ha is situated in Eastern Bohemia (50°11'42.948"N, 16°6'12.45"E) on the western hillside at an altitude of 330 m a.s.l. The climate is mildly warm, average temperature is 7–8°C, precipitation totals are 650–700 mm per year (400–450 mm in the growing season) (Anonymous 1961). The bedrock is plaener overlaid by loess, Cambisols are a dominant soil type. The plant association *Querceto-Fagetum (acerosum) diluvium* represents the stand.

The initial goal of the stand management was the transformation of a mixed stand to a stand with rich species composition and selective structure. The main stand was two-storeyed at the time of the first stand inventory (1928). Spruce, fir and other species with group arrangement formed the main stand (low cohort, age 54 years). Oak and other broadleaves as individual reserved trees created the upper storey (154 years). Oaks (*Quercus robur, Quercus petraea*) dominated in the stand volume together with spruce, fir and larch, the proportion of other species did not exceed 10% of the stand volume. Rich species composition, mixed arrangement of species and reserved trees positively affected the stand differentiation (Konias 1950; Zakopal 1963).

The stand was analyzed by full callipering since 1928, realized cuttings were recorded by 1971. All trees with diameter over 8 cm at dbh were numbered in 1959, further measurements of numbered trees were realized in 1966 and 1971. Repeated measurements included also new ingrowth with diameter over 8 cm. The last measurement was done in 2008. The tree heights were measured by hypsometers to the nearest 0.5 m, heights were measured in all tree species across the entire area for the calculation of height curves for the particular species. Stand data were analyzed according to species and diameter classes, increments were calculated as the differences between individual measurements. Cores from dominant trees for increment analyses were taken in 2009. Regeneration groups were mapped in summer 1960 and 2010, groups were characterized by species composition and mean height.

RESULTS

The initial species composition and stand structure seemed favourable for the main goal, transformation to the stand with species, diameter and height differentiation (Konias 1950). Conifers and broadleaves had a comparable volume share at the beginning of stand observations (Table 1). Thinnings from above after 1928 released potential future trees in the main stand, gradual cuttings of reserved trees made suitable places for regeneration. The risk of weed infestation at released places influenced the initial low intensity of growing stock removal (7% in 1940, 13% in 1949, 6% in 1954). A reduction of reserved trees decreased the proportion of oak and admixed broadleaves while the proportion of conifers gradually increased. Heavy cutting in 1959 (22% of growing stock) opened the stand and encouraged advance growth. The next cutting in 1966 (16% of growing stock) already responded to worsened health conditions due to air pollution from local power plants. The first symptoms of defoliation occurred mainly in originally suppressed firs released by previous cuttings. The next sanitary cuttings (1976, 1982) further decreased the growing stock, a reduction of spruce and fir decreased their proportion. Repeated stand release without regeneration initiated weed infestation. The health condition of the stand improved after air pollution reduction in the 1990s. The last cutting carried out in 2003 released denser parts of stand, the final growing stock in 2008 was 289 $m^3 \cdot ha^{-1}$ (Table 1). An increase in the proportion of broadleaves in 2008 (mainly beech and mixed broadleaves) affected their positive response to previous stand opening and dominance in younger cohorts. The proportion of spruce and fir was decreased by previous sanitary cuttings. The proportions of Doug-

Table 1. Basic stand characteristics

Year	N (pcs·ha^{-1})	BA (m^2·ha^{-1})	V (m^3·ha^{-1})	Species share (%)							Regeneration (%)	
				spruce	fir	Douglas fir	larch	oak	beech	mixed broadleaves*	natural	artificial
1928	1,185	30.8	222	16	20	3	9	40	3	9		
1940	1,077	31.9	327	19	26	3	8	30	8	6		
1949	747	32.4	356	21	24	3	9	30	10	3	5	10
1954	607	30.6	349	17	25	3	9	30	12	4	8	17
1959	538	23.1	274	16	24	4	11	29	12	4	9	19
1966	463	23.6	296	21	28	5	14	15	14	4		
1971	344	24.4	318	22	26	5	15	14	14	4		
2008	341	20.9	289	14	2	5	15	15	23	26	1	16

*mixed broadleaves includes ash, maple, lime, hornbeam, birch, cherry and robinia; N – number of trees; BA – basal area; V – volume

las fir, larch and oak did not significantly change in the last 50 years (Table 1). The old cohort (trees marked in 1959) accounted for 22% of all trees, but for 74% of the growing stock in 2008.

Two stand cohorts influenced two peaks of diameter distribution at the beginning of experiment (1928), reserved trees formed thick trees. The number of trees gradually decreased and the curves of diameter distribution shifted to thicker dimensions (Fig. 1; Table 2). The inclusion of ingrowth (younger cohort) after 1966 only partly affected the diameter distribution due to heavy sanitary cuttings of thin trees at that time. The shape of diameter distribution in 2008 resembled the model curve for selective forests (Fig. 2), lower number of thin trees and stand texture differed from the present models of selective forests in a dominant proportion of broadleaves.

The initial mean stem diameter of larch and Douglas fir was influenced by their upper storey position, reserved trees increased the mean stem diameter of beech and oak. Further changes in mean stem diameters of the particular species depended on diameter distribution, tree vitality and system of cuttings. The inclusion of ingrowth trees partly reduced the mean diameter of spruce, oak, beech and mixed broadleaves in 2008. Silver fir and spruce dominated in thin and middle dimensions by 1971. The next sanitary cuttings reduced their proportion, diameter distribution and changes in mean stem diameters. Spruce in ingrowth accounted for 14% of the total spruce growing stock in 2008 (32% of the tree number). Larch and Douglas fir were individually mixed in the stand for the whole time without presence in ingrowth, their diameter distribution gradually shifted to thicker dimensions. The mean stem diameter of beech was partly influenced by reserved trees in 1959, its diameter gradually increased in the next periods. The inclusion of ingrowth trees reduced the beech mean stem diameter in 2008, beech in the original

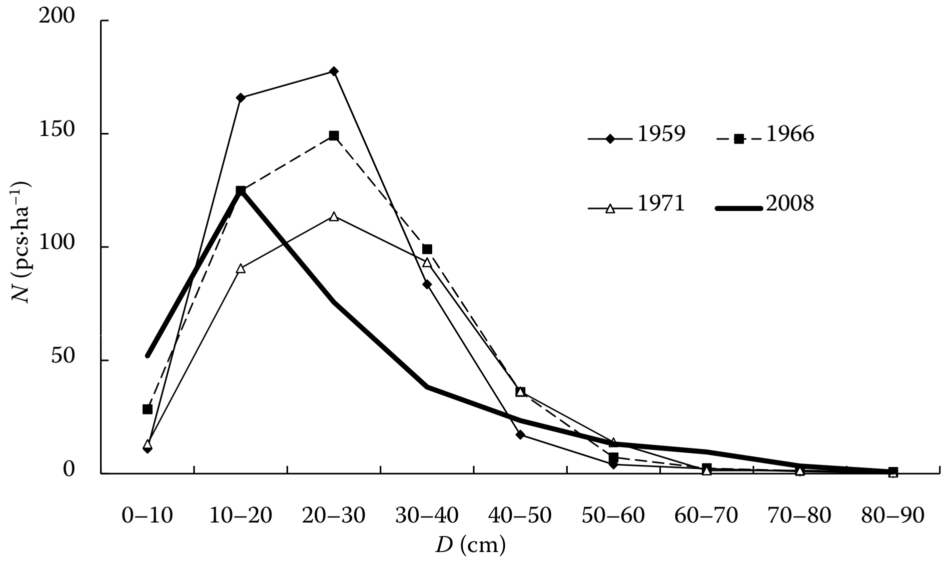

Fig. 1. Distribution of stem numbers

Table 2. Mean stem diameter (mean ± S_x), mean annual increment (mean ± S_x)

Species	Compound stand (cm)				Ingrowth (cm)	Diameter increment (mm)
	1959	1966	1971	2008	2008	1959–1971
Spruce	21.2 ± 8	23.6 ± 9	25.2 ± 10	36.6 ± 12	24.7 ± 6	2.3 ± 2
Fir	22.5 ± 8	24.3 ± 9	26.5 ± 9	28.1 ± 11	–	1.2 ± 1
Larch	33.6 ± 6	37.9 ± 7	40.3 ± 7	48.6 ± 10	–	6.0 ± 2
Douglas fir	49.3 ± 15	56.5 ± 11	59.4 ± 12	67.2 ± 12	–	5.1 ± 2
Beech	33.4 ± 13	39.7 ± 14	42.0 ± 12	22.7 ± 20	14.4 ± 6	7.5 ± 3
Oak	25.9 ± 10	29.3 ± 10	31.2 ± 10	37.4 ± 16	16.2 ± 6	4.2 ± 2
Mixed broadleaves*	18.7 ± 8	21.7 ± 8	23.8 ± 9	18.3 ± 9	17.5 ± 8	3.5 ± 2

*mixed broadleaves includes ash, maple, lime, hornbeam, birch, cherry and robinia

stand had the mean stem diameter of 61 cm. The young beech cohort had sinistral diameter distribution with culmination at 14 cm (Table 2). Beech ingrowth accounted for 82% of the beech tree number (23% of the growing stock). The initial distribution of oak was regular with culmination at 26 cm, reserved trees had a diameter over 45 cm. Oak diameter distribution had two peaks in 2008, the mean diameter of original stand was 45 cm, 16 cm in ingrowth. A group of mixed broadleaves occurred mainly in understory at the beginning of experiment, their number gradually increased by ingrowth (96% of the tree number in 2008, 84% of the growing stock). Broadleaves growing in groups had straight stems, the size and length of their crowns depended on previous thinnings. Stem quality of individually growing broadleaves trees was often low, most of them had long crowns with thick branches.

The low mean annual increment of fir determined by repeated measurements was influenced by a high number of suppressed trees; the mean annual increment of dominant firs with appropriate crown dimensions was over 3 mm. Fir responded to deteriorated conditions due to air pollution the most noticeably. The mean diameter increment of fir determined from bores did not exceed 1 mm at that time. The health condition of fir significantly improved after air pollution reduction at the beginning of the 1990s, the growth rate of fir increased and it started to regenerate. Spruce had a higher mean diameter increment than fir by the comparable dimensions. Annual increment of dominant trees was over 5 mm. The growth response of spruce in the 1990s was lower compared with fir. Larch and Douglas fir had high diameter increments determined by repeated measurements due to their position in the stand (Table 2). Increments of sample trees of both species were lower with great oscillations, mainly larch showed a significant decrease in increment in the 1990s. Broadleaves showed higher diameter increments than conifers (Table 2), diameter increment of released beeches in the upper storey was over 10 mm. Annual increment broadly oscillated in the particular periods and growth depression due to air pollution was not so significant. Oak had a lower mean diameter in-

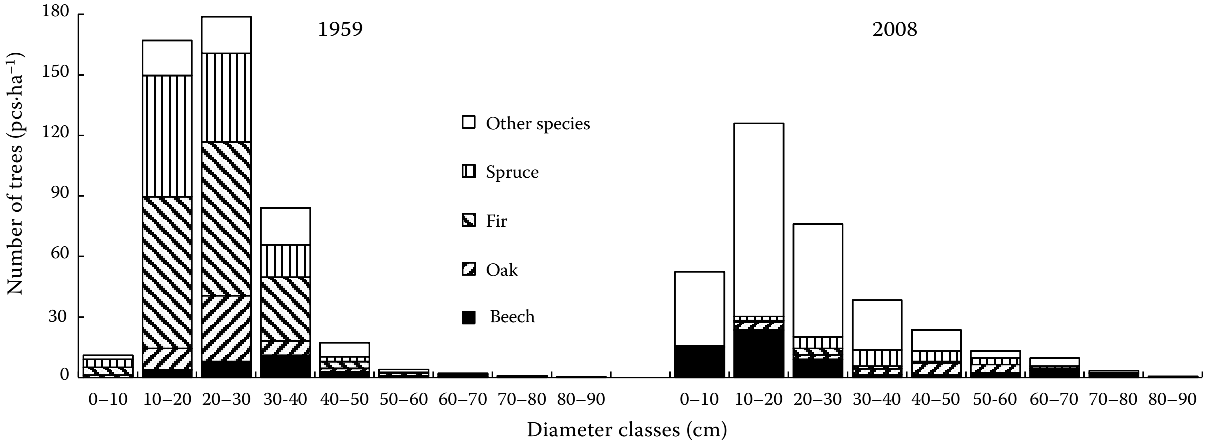

Fig. 2. Diameter distribution of species in years 1959 and 2008

crement, some of the thick trees did not respond to previous release. The lower increment of mixed broadleaves was affected by their initial position in understory, the mean increment of dominant trees was comparable with other species.

Gradual stand opening improved conditions for regeneration, 15% of the stand area was covered by advance growth in 1949. The area of regeneration slowly increased and culminated in the 1960s (Table 1). Natural regeneration accounted for one third of the total regeneration area, mainly ash, lime, maple and mixed broadleaves regenerated naturally. Artificial regeneration with plantations dominated for the whole time. Released gaps were underplanted by lime at first, later conifers (spruce, fir, Douglas fir) and beech were used. Most regeneration groups were situated near forest roads or on the stand borders (Fig. 3), broadleaves dominated in the species composition. Oak occurred in groups with beech and hornbeam in the most released stand parts. Groups composed of ash, lime and maple took up the largest area, some groups started to differentiate in height. Fir and spruce from natural regeneration individually occurred in mixtures with broadleaves, plantations formed small groups.

A problem with regeneration in the last years is illustrated in Fig. 4. Natural regeneration in previous years was limited by low fecundity of trees, dense weed cover and repeated game browsing. Small groups of natural regeneration of broadleaves (beech, lime and hornbeam) occur mainly on borders of stand openings, areas of three compact groups in the central part are below 0.01 ha. New fir underplantings are distributed into 3 fenced plots of irregular shape (total area 0.26 ha). Advance growths formed by spruce originating from previous underplantings are fully stocked at a height of 4–8 m (area 0.38 ha).

The complicated stand structure composed of more than two storeys does not occur at the present time. Beech, larch and Douglas fir in overstory (reserved trees) are dispersed individually or in small groups. Their positions near the stand border or roads allow their cutting without significant damage to the lower stand. A compact part of mixed stand with understory (1.36 ha) is situated in the central part of the stand. Spruce and fir in the lower storey were removed by sanitary cuttings in the past, the present individual understory is composed of broadleaves. Stem and crown quality of broadleaves growing individually in understory is low, but trees shelter the soil and partly limit weeds. Groups of regeneration drawn in 1960 form compact parts of the maturing stand of broadleaves with heights about 30 m. Their sufficient area and past management promise a high future quality potential.

DISCUSSION

The permanent occurrence of selective structure in stands where broadleaves dominate is complicated.

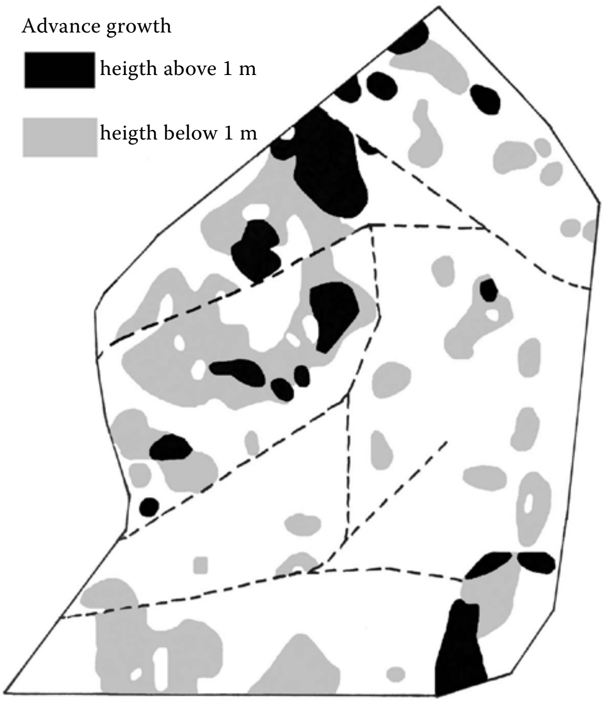

Fig. 3. Map of regeneration (1960)

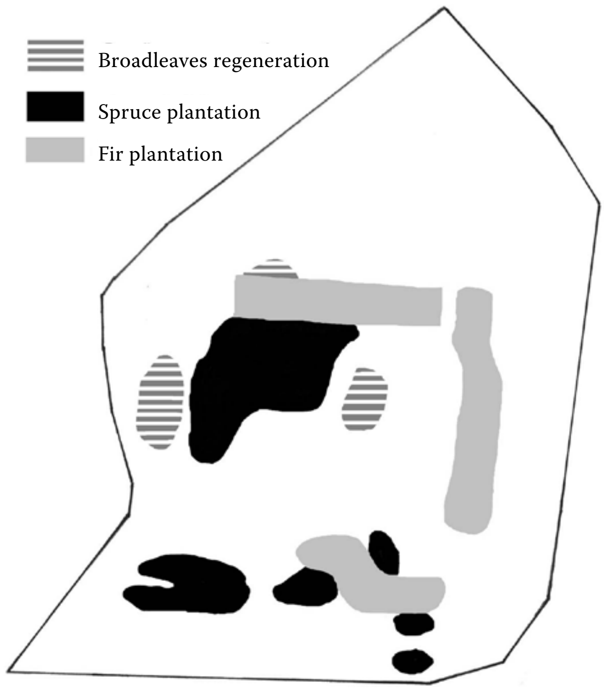

Fig. 4. Map of regeneration (2010)

For beech forests with selective structure most authors recommend an irregular shelterwood system rather than a selection cutting system. Stand parameters of selective forests with dominance of broadleaved tree species are generally lower compared with selective forests composed of conifers. The optimal growing stock for beech selective forests in Germany does not exceed ca. 250 $m^3 \cdot ha^{-1}$ in order to keep the rule of the biological automation of production, permanent dynamic regeneration and transfer of trees in diameter and height classes. Basal area of these stands is 22 m^2 and minimal number of thin trees (*N*10) should not drop below 100 individuals per ha. Stand parameters for coppice with standards as a variant of selective forests should not exceed 160 $m^3 \cdot ha^{-1}$ for the rotation period of 25–30 years (Schütz 2006). Beech forests with selective structure from eastern Slovakia and Poland were described mainly by Saniga and Jaworski, when both authors described stands situated at a higher altitude with higher growing stock. Saniga (1996) analyzed the structure of mixed oak-beech stands with fir and hornbeam. Occurrence and growth of natural regeneration were sufficient under conditions of this stand. A future decrease in the oak proportion in the stand should be supposed due to high stand canopy (Saniga 1996). The optimal growing stock of beech selective forests in eastern Slovakia is about 300 $m^3 \cdot ha^{-1}$ with 160 ingrowth trees (*N*10), real numbers of ingrowth trees on research plots were half (Saniga 1998). The model growing stock for fir and beech mixed stands was counted on 460–500 $m^3 \cdot ha^{-1}$ by target diameter 70 cm. Repeated cuttings with 10% intensity twice per decennium are recommended for permanent preservation of stand conditions (Saniga 1998; Saniga, Szanyi 1998). Beech dominated forests with selective structure in the Bieszczady Mts. (Poland) were studied by Jaworski and Kołodziej (2002, 2004). The studied managed forests or beech forests of primeval character had suitable diameter distribution while the number of thin trees on plots varied. Despite the suitable division of trees into diameter classes the other stand characteristics did not correspond to the model of beech selective stands. Tree number decreased with increasing stand basal area. The investigated stands represented the growing-up stage and the phases indicating a complex storeyed structure.

The values of basal area and growing stock of the studied stand corresponded to modelled values for this type of forests, whereas the number of trees in advance growth was lower than the model value. Shortage of thin trees affected weed occurrence and repeated game damage. Middle and low storey are composed only of broadleaves, groups of spruce and fir from artificial regeneration are below the registration limit.

CONCLUSIONS

The paper summarizes the development of a mixed stand with long-term management aimed at stand transformation to selective forest. The initial mixed stand with some reserved trees had suitable stand structure and characteristics. Oak, beech and larch dominated among reserved trees, the lower cohort was composed of the group arrangement of spruce, fir, beech and other broadleaves. Thinnings improved stand conditions and released places for regeneration. Heavy thinnings in the 1960s and subsequent air pollution negatively affected the stand development. The next sanitary cuttings, absence of regeneration due to weed infestation and game damage interrupted the continuity of appropriate stand development. A suitable tree species mixture overcame the deteriorated situation of spruce and fir in the stand. Vital trees in the main stand released by cuttings substituted increment losses by air pollution. The present stand is composed of a rich mixture of tree species, while stand volume production and wood quality potential are high. High biodiversity of the stand ensures the maintenance of stand stability and production in the future. The target species composition (oak, beech, Douglas fir, larch and fir) can ensure above-average wood production at these types of sites.

The maintenance of ecological and economic stability of stands is a cardinal problem of sustainable stand management at highly productive sites. The initial idea of stand transformation to the mixed one with selective structure was incorrect for this type of forest. Realized management preserved suitable stand conditions for a long time. The stand was differentiated mainly by spatial arrangement, the occurrence of a more complicated stand structure was limited and only temporary. Permanent height differentiation was not reached on the plot concerned. The occurrence of suitable conditions for natural regeneration is limited at these sites, artificial regeneration requires vast expenses on plantation protection against weed infestation. Absence of regeneration, its repeated damage by deer and interruption of management are the main reasons for a failure.

Long-term management without clearcuttings increases the risk of stand structure homogenization, species composition changes and loss of light-demanding species. Larch and Douglas fir are absent in the young stand, most of individual oaks in the lower canopy had irregular crowns and stems with low quality potential. The Swiss irregular shelterwood system of regeneration combined with strip cuttings provides more suitable conditions for regeneration and growth of species with different light demands. Desirable species with high demands on light should be artificially planted in gaps, but possibilities of their natural regeneration are limited.

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