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Comparison of different forest regeneration methods after windthrow

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ABSTRACT: The prosperity of various forest regeneration methods was evaluated on the prepared windthrow area established in 2010 in a previously allochthonous coniferous stand growing in mid-elevations of the Czech Republic. The forest regeneration variants were as follows: (1) "planting" of target species (*Picea abies* [L.] Karst.) and *Fagus sylvatica* (L.), (2) "seeding" of pioneer (non target) species (*Betula pendula* Roth) and (3) spontaneous "succession". Two years after windthrow the "planting" was evaluated in accordance with the Czech forestry law as regeneration method with sufficient attributes, density (6,000–9,000 indd·ha^{-1}) and regular spatial distribution of target tree species. The "seeding" and "succession" variants showed a insufficient attributes of target tree species – total density ca 3,000 indd·ha^{-1} (being ca 1,000 indd·ha^{-1} higher than 20 cm) and irregular distribution across the plot. The non-target species birch on the "seeding" variant showed a high density of plants (131,000 indd·ha^{-1}) being eight times higher than the succession variant. The cost of the regeneration treatment was different between the variants – planting: 5,000–6,000 EUR·ha^{-1}, 1,300 EUR·ha^{-1}, succession: 1,000 EUR·ha^{-1}. Comparing to "planting" the higher diversity of tree species and higher density of non-target species (20,000–134,000 EUR·ha^{-1}) in the "seeding" and "succession" variants promise success for the future, however the real potential of regeneration methods that were used will be clear after long-term observations.

Keywords: target tree species; pioneer tree species; planting; seeding; succession

While natural disturbances play a considerable role in natural forests left to spontaneous succession (Willing 2002), in commercial forests they cause great economic losses (Heger 1957; Tesař, Tichý 1990, 2001; Saniga, Kmeť 1994; Kantor et al. 2000; Tesař, Klimo 2004; Souček, Tesař 2008; Jonášová et al. 2010; Albrecht et al. 2012). As to the extent and impact of damage, wind disturbances stand at the top (Liška, Tuma 2008; MZE 2011). Gale disturbances often result in extensive wind-thrown areas with conditions entirely different from intentional regeneration elements (Pěnčík et al. 1958; Bücking et al. 2001, 2006; Gregor, Tužinský 2011).

Artificial regeneration is a prevailing method of regenerating forests in the Czech Republic (MZE 2009), which is used most often also in the regeneration of wind-thrown areas. In addition to high costs, artificial regeneration entails also high biological risks (Poleno, Vacek 2009). These primarily include severe root malformations that can be eliminated by the high-quality planting stock and by proper planting (Mauer et al. 2004). Artificial regeneration is often connected with the introduction of climax type species into the environment of wind-thrown areas, which may have considerable negative consequences for tree growth, forest stability and wood quality (Kaňák 1988; Košulič 2010).

Especially in connection with the regeneration of large wind-thrown areas, the papers discussed also the issue of using alternative methods of artificial regeneration, i.e. seeding or partial-area regeneration (Anderson 1930, 1951; Gaul, Stüber 1996; Gockel et al. 2001; Ehring, Keller 2006; Bolte et al. 2009; Somidh et al. 2013). We can call this combined forest regeneration – the process of using both natural and artificial regeneration

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(Gockel 1995; Burschel, Huss 2003; Kulla, Sitková 2012). Important aspects of successful natural regeneration on a wind-thrown area include the promptness of the invasion of weeds and their type, presence and proportion of mother tree species (seed banks) (Saniga 2010) and their distance from the regenerated site (spread of seeds), incidence of mast years, possibly also predation on seeds and fruits, climatic conditions etc. (Wagner et al. 2004; Övergaard et al. 2006).

From the biological point of view, pioneer tree species play an indispensable role on wind-thrown areas (Míchal 1994; Košulič 2010). However, their wider use is currently limited in the Czech Republic by the valid legislation (Attachment No. 4, Decree No. 83/1996 of the Statute Book). Forest regeneration is usually connected with the evaluation of its success (Decree No. 139/2004 of the Statute Book). Pursuant to Forest Act, a wind-thrown area is to be reforested within two years from its coming into existence (§ 31 of the Forest Act). Further to the regenerated stand, forest establishment parameters are also defined (Decree No. 139/2004 of the Statute Book), which the forest stand should exhibit in five years from the successful regeneration, and/or seven years from the origination of the wind-thrown area.

The paper aims to compare various forest regeneration methods on the wind-thrown area after two years from its occurrence. Planting, seeding of pioneer tree species and succession are compared in terms of biological and economic parameters.

MATERIAL AND METHODS

Study area. The investigations were conducted on the "Tipeček" experimental plot (EP) situated in the territory of the "Masarykův les" Training Forest Enterprise of Mendel University in Křtiny. "Tipeček" EP (49°19'N, 16°44'E) is located in the Drahanská vrchovina Uplands at an altitude of about 500–520 m a.s.l. and with annual precipitation of about 620 mm. The wind-thrown area came to existence in June 2010 after the Antonín gale disaster (Dobrovolný et al. 2010). The original forest was a stand of about 100 years of age with the fully closed canopy, consisting mainly of spruce. The new wind-thrown area of about 1.5 ha links up immediately with young forest stands and forms a complex of non-established stands stretching over the area of 6 hectares. The predominating potential natural vegetation is acidophilous beech and silver fir woodland (Neuhäuslová et al. 1998) on the plain with slope gradient up to 5°. In the NE part, the wind-thrown area passes into stony oak-beech growths with lime on the slope with the western aspect up to 20°.

Experiment design. Three forest regeneration variants were compared on the site after removing wood and slash and after soil preparation:

– artificial regeneration by planting target species – "planting"
– establishment of pioneer stand by seeding birch – "seeding"
– variant left without subsequent human interventions – "succession".

Each of the variants was established in two replications: 900 m^2 (30 × 30 m) and 625 m^2 (25 × 25 m). The total number of permanent research plots established on the site was six (Fig. 1 and Table 1).

In the "succession" and "seeding" variants, the regeneration was monitored on inventory patches sized 1 m^2. These were stabilized on plots in the middle of compartments sized 5 × 5 m (Fig. 1). In the variants 30 × 30 and 25 × 25, 36 and 25 patches were laid out, respectively, i.e. sampling intensity of 4%.

Data processing and analysis. Recruits were quantified on the patches and classified according to categories and aboveground part height. The condition of recruits corresponded with inventory measurements taken towards the end of the growing season in 2012. Since the beginning of the experiment, the planted plots were monitored for the actual mortality of regeneration and possible improvement. Two years from the establishment of the experiment, we measured the aboveground part height in the planted trees.

Differences in the aboveground part height of individual species between Permanent Research Plot (PRP) 2 and PRP 5 were compared by *t*-test. From

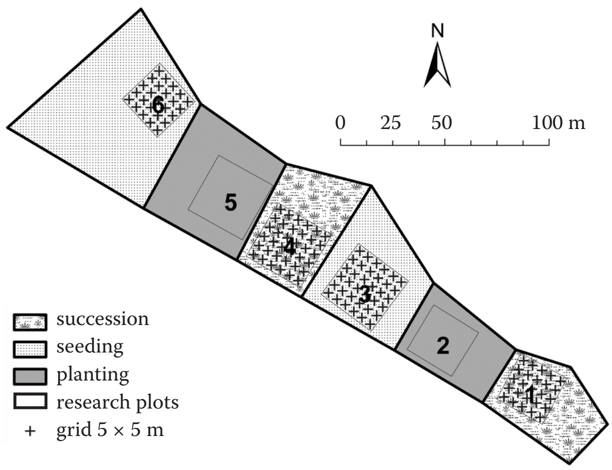

Fig. 1. Scheme of experimental site establishment (Dobrovolný et al. 2010)

Table 1. Basic characteristics of regeneration variants and permanent research plots on the experimental site

Permanent plots	Variants of regeneration	Plot area (m)	Specifics of regeneration
PRP 1	succession	25 × 25	without human interventions
PRP 2	artificial regeneration – planting	25 × 25	autumn 2010, row spacing – 2 rows of beech and 2 rows of spruce: spruce 110 plants, 47% of plot area (1.5 × 2.0 m); beech 353 plants, 53% of plot area (2.0 × 0.5 m)
PRP 3	seeding	30 × 30	birch seeding: autumn 2010: 1 g·m^{-2}; spring 2011: 1 g·m^{-2}
PRP 4	succession	30 × 30	without human interventions
PRP 5	artificial regeneration – planting	30 × 30	autumn 2010, row spacing – 2 rows of beech and 2 rows of spruce: spruce 141 plants (1.5 × 2.0 m); beech 561 plants (2.0 × 0.5 m); spring 2011 (between rows): lime 66 plants; oak 109 plants; larch 15 plants; beech 72 plants
PRP 6	seeding	25 × 25	birch seeding: autumn 2010: 1 g·m^{-2}; spring 2011: 1 g·m^{-2}

spruce – *Picea abies* [L.] Karst.: 2 years old container planting; beech – *Fagus sylvatica* L.: 1 year old planting; lime – *Tilia cordata* Mill.: 2 years old planting; oak – *Quercus petraea* (Matt.) Liebl.: 2 years old planting; larch – *Larix decidua* Mill.: 2 years old planting; birch – *Betula pendula* Roth: seed

the very beginning of the experiment, cost effectiveness of the respective variants was recorded as a sum of all cost items of the particular plot and converted per hectare.

RESULTS

State of regeneration – planting (PRP 2, 5)

Actual mortality on PRP 2 in the two years of monitoring was 2% in spruce and 17% in beech. PRP 5 exhibited similar mortality of the two main species: spruce up to 1% and beech 18%. Of the other planted species, the highest mortality (100%) was recorded in larch, the reason being the poor quality of planting stock. Mortality of lime and oak was 17% and 10%, respectively.

On PRP 2, spruce occurred on 47% of the area at 3,700 indd·ha^{-1}. Per-hectare numbers for beech occurring on the remaining part of the area reached 9,300 indd·ha^{-1} after two years. Thus, both species exceeded the stipulated 90% of minimum number, i.e. 3,600 and 8,100 indd·ha^{-1}, respectively. On PRP 5, spruce occurred on 35% of the area at actual per-hectare numbers of 4,500 indd·ha^{-1}; beech occurred as the main species on the remaining area at 9,300 indd·ha^{-1}. Apart from these, species occurring on the same part of the plot were oak and lime. There, the planted trees also met the criterion of minimum per-hectare numbers.

After two years the average height of spruce on PRP 1 reached 61 cm and was statistically significantly greater than that on PRP 5, where it reached only 49 cm. Significant differences in the height of the aboveground part between the plots were found also in beech (Table 2). The average height of beech was 32 cm, and 29 cm on PRP 5.

State of regeneration – seeding (PRP 3, 6)

Birch regeneration on PRP 6 was found unsatisfactory already during the first inventory in the spring of 2011. Recruits occurred only on two patches – with only a single seedling recorded in the first case and four seedlings in the second case. This is why we gave up further monitoring and the plot was regenerated by group planting in the spring of 2011.

On PRP 3, the regeneration of both target and pioneer species was found on 25 patches out of the total 36, i.e. 31% of the area remained unoccupied as shown in the scheme – see Fig. 2. The density of target species reached nearly 4 thousand per hectare (plants with a height over 20 cm only 1.4 thousand per hectare) and the density of pioneer species was about 131 thousand plants per hectare (Table 3). Birch regeneration was detected on 23 patches. The number of birch plants amounted up to 131,000 indd·ha^{-1} and was ca 8 × higher than on the neighbouring plot left to natural succession

Table 2. Comparison of aboveground part heights in spruce and beech plantations (in cm) on PRP 2 and PRP 4 – ascertained by the statistical method of *t*-test

Tree species	PRP 2 (25 × 25 m)			PRP 4 (30 × 30 m)			*P*-value
	number of trees per plot/per ha	average height (cm)	SD	number of trees per plot/per ha	average height (cm)	SD	
Spruce	109/3,710	60.93	10.77352	141/4,480	48.65	11.40300	0.537702
Beech	307/9,270	31.59	10.87936	544/9,300	29.01	10.88589	0.998039

SD – standard deviation, spruce – *Picea abies* (L.) Karst.; beech – *Fagus sylvatica* L.

(Table 3). Some 68% of the total birch regeneration consisted of plants in the height category over 20 cm. Birch seedlings over 50 cm occurred at ca 35,000 indd·ha^{-1}. Average cover of the herbaceous vegetation component on PRP 3 was ca 76%.

State of regeneration – natural succession (PRP 1, 4)

On PRP 1, the regeneration of both target and pioneer species was detected on 23 patches out of the total 25; the area unoccupied by recruits was only 8% while the number of unoccupied patches on PRP 4 amounted to 10, i.e. 28% of the total area, with the patches being concentrated as shown in the scheme – see Fig. 2. The density of target species on PRP 1 reached about 18,500 indd·ha^{-1} (plants with a height over 20 cm only 4 thousand per hectare) while the values on PRP 4 were 3,500 indd per ha (plants with a height over 20 cm only 1.1 thousand per hectare) (Table 3). On both PRPs, the target species over 20 cm occurred only on 4 patches. The numbers of pioneer species recorded on PRP 1 and PRP 4 were ca 100 thousand per hectare and only 19 thousand per hectare, respectively (Table 3). In both cases, the most important group in this height class consisted of the broadleaves of pioneer character (birch, rowan, goat willow, aspen). On PRP 1, these species occurred on 72% of the patches while on PRP 4 it was only on 44%. Average cover of the herbaceous vegetation component on PRP 1 and PRP 4 was ca 85% and 63%, respectively.

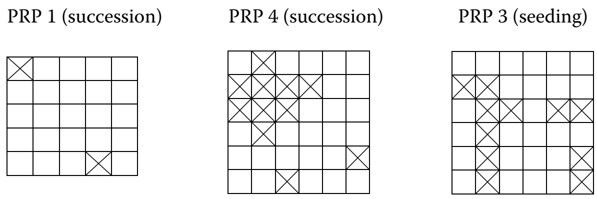

Fig. 2. Scheme of the occupation of patches by natural regeneration and/or in combination with seeding on PRP 3 (dagger – without regeneration)

Economics of regeneration

The highest total per-hectare costs were incurred in the planting variant, reaching 5,000–6,000 EUR·ha^{-1} (Table 4). Cost differences of about 15% between the “big” and the “small” variant were given by the higher per-hectare numbers and by the greater diversity of species composition chosen for PRP 5 in establishing the experiment. The highest share of the costs (48% and 43%) fell to regeneration, i.e. the purchase of transplants and planting itself. The following cost item was protection with 36% and 38%. Site preparation costs amounted to 17% and 20% of the total costs.

Costs of regeneration by seeding (1,300 EUR·ha^{-1}) reached 21% and 25% of the total costs for planting. Of the total per-hectare costs the greatest proportion (ca 4/5) went for site preparation with the remaining part being costs of regeneration alone (seeds and sowing) (Table 4).

The only cost item in the variant of natural succession was site preparation. The costs of natural succession reached 17% and 20% of the costs for regeneration by planting (Table 4).

DISCUSSION

Pursuant to the national legislation of the Czech Republic currently in force (Forest Act No. 289/1995 of the Statute Book, Decree No. 139/2004 of the Statute Book), the wind-thrown area has to be regenerated and/or reforested within two years from its coming into existence regardless of the regeneration method and wind-thrown area size. Parameters of successful regeneration include adequate species composition, sufficient density of trees and their regular spatial distribution. The “Tipeček” experimental site was established in or-

Table 3. Density (1,000 indd·ha^{-1}) and height category of regenerated tree species on the research plots

Tree species according to height category	Natural succession		Seeding of birch	Planting	
	PRP 1	PRP 4	PRP 3	PRP 2	PRP 5
Pinaceae 1st year	3.60				
Spruce[1] < 20 cm	1.20	0.28	0.28		
Spruce 20–50 cm	1.60		0.83		
Spruce 0–130 (80 high)				1.74	1.57
Beech[2] 0–80 cm (0–20; + 20 cm)				4.91 (4.56+0.35)	6.04 (4.33+1.11)
Pine[3] < 20 cm	3.20	1.67	1.11		
Pine 20–50 cm		0.28			
Larch[4] 1st year	2.00		0.28		
Larch < 20 cm	4.40	0.56	0.83		
Larch 20–50 cm	0.40	0.56	0.28		
Larch 50–130 cm		0.28			
Oak[5] 0–90 cm	0.40		0.28		1.10
Hornbeam[6] 50–130	1.60				
Lime[7] 0–60 cm					0.74
Σ Target species[8] > 20 cm	**4.00**	**1.11**	**1.39**	**6.35**	**8.23**
Σ Target species	**18.40**	**3.61**	**3.89**	**6.66**	**9.47**
Birch 1st year	12.80	0.83	4.72		
Birch[9] < 20 cm	2	1.39	36.39		
Birch 20–50 cm	32.40	5.28	55.28		
Birch 50–130 cm	23.60	8.61	34.44		
Birch > 130			0.28		
Rowan[10] < 20 cm	0.40	0.28	0.56		
Rowan 20–50 cm	4.00	0.56	0.28		
Rowan 50–130 cm	0.80	0.83	0.28		
Willow[11] < 20 cm	0.40	0.28	0.56		
Willow 20–50 cm	4.00	0.56	0.28		
Willow 50–130 cm	0.80	0.83	0.28		
Aspen[12] < 20 cm		0.28			
Aspen 20–50 cm			0.56		
Aspen 50–130 cm			0.28		
Aspen > 130 cm	0.400				
Σ Pioneer species	**99.60**	**19.44**	**134.17**		
Σ Target + pioneer species[13]	**118.00**	**23.06**	**138.06**		

spruce[1] – *Picea abies* [L.] Karst., beech[2] – *Fagus sylvatica* L., pine[3] – *Pinus sylvestris* L., larch[4] – *Larix decidua* Mill., oak[5] – *Quercus petraea* (Matt.) Liebl., hornbeam[6] – *Carpinus betulus* L., lime[7] – *Tilia cordata* Mill., target species[8] – see index [1–7], birch[9] – *Betula pendula* Roth, rowan[10] – *Sorbus aucuparia* L., willow[11] – *Salix caprea* L., aspen[12] – *Populus tremula* L., target + pioneer species[13] – see index [8–12]

der to compare some non-traditional methods of forest regeneration (Dobrovolný et al. 2011).

The legislative requirements of "successful regeneration" were met by the two variants of artificial regeneration by planting the target species. Spruce and beech are target and/or basic species for these sites. Their regular distribution and density on the plots corresponded to current legislation (Decree No. 139/2004 of the Statute Book). During the experiment, some plants died; nevertheless, the missing plants were replenished continually. The exception was larch whose mortality of up to 100% caused probably by unskilled handling of the planting stock did not affect the success of regeneration. Larch regenerated from the natural seeding of the surrounding parent trees. Particularly on PRP 5, the per-hectare numbers were over-dimensioned by the enrichment with other planted species.

Table 4. Costs of regeneration variants during the two-year period

Item	Succession –PRP 1 and 4		Seeding – PRP 3		Planting – PRP 2		Planting – PRP 5	
	(EUR)	(%)	(EUR)	(%)	(EUR)	(%)	(EUR)	(%)
Site preparation	1,006	100	1,006	79	1,006	19.5	1,006	16.5
Regeneration	0	0	270	21	2,209	43	2,900	48
Protection	0	0	0	0	1,938	37.5	2,158	35.5
Total	1,006	100	1,276	100	5,153	100	6,064	100

Although the legislative criteria of successful regeneration do not include the aboveground part height, the experimental results suggested that this parameter may also be of significance. While the recorded aboveground part height in spruce indicated that the species would not have any problem to grow in the given conditions of the wind-thrown area, the situation of beech was opposite. Shoot height of the beech planting stock ranged from 36 to 50 cm and was distinctly greater than the aboveground part height recorded in the plants two years later – 29 and 32 cm, respectively. Not even could the costly measures protect the plants from the repeated damage by wildlife or from drying of terminal parts. The other broadleaved species, i.e. lime and oak, did better than beech. Thus, the results of our experiment corroborated the inappropriateness of beech cultivation in the environment of wind-thrown areas (e.g. Gemmel et al. 1996; Košulič 2010). The negative influence of the regeneration element size on the growth of trees was confirmed also by the comparison of aboveground part heights on PRP 2, which is sheltered on two sides by the existing stand, and on PRP 5 with the character of large-scale wind-thrown area. The adverse effect of the wind-thrown area size on the growth of young plantations was observed in spruce as well. Problematic here was the choice of spruce itself as a target species for these sites (Spiecker 2004; Kulla, Sitková 2012).

Limiting factors for the successful regeneration on plots with natural succession include namely the low number of target species and their irregular distribution. Target species occurred at densities not corresponding to current legislation with the exception of larch on PRP 1. However, for the site in question, this species is mentioned only as admixed or interspersed – not basic (Attachment No. 4, Decree No. 83/96 of the Statute Book). It is to note that the regular distribution of recruits as well as their corresponding density, namely in mixtures, can be established for the needs of existing legislation only with considerable difficulties. The occurrence of natural regeneration on the plot with spontaneous succession was limited to a considerable extent by the occurrence of weeds, which after two years formed a continuous stand of mainly reed grass and bramble reaching a height over 1 m.

At the same time, the two plots with natural succession exhibited the occurrence of pioneer species, the abundance of which exceeded the abundance of target species several times. The spontaneous occurrence of these species on the wind-thrown area corresponds with their natural strategy (Míchal 1994).

In addition to self-sowing, the regeneration of pioneer species is recommended to be carried out mainly by seeding (Poleno, Vacek 2009). The species used in our experiment was birch. Artificial regeneration by seeding resulted in the increased occurrence of the species in the regeneration. Similarly like in most other tree species of pioneer character, the occurrence of birch is very limited by the current legislation. A great majority of these species belong to the category of so-called auxiliary forest tree species, the attendance of which in regeneration is limited to 15% out of the 90% of minimum per-hectare numbers for the particular target species (Decree No. 139/2004 of the Statute Book). Nevertheless, the results of our experiment, i.e. both the detected abundance and the aboveground part height, confirmed the biological justification of their use. Birch is a typical pioneer tree species which occupies voids easily and grows well in conditions after disturbances (Kaňák 1988; Košulič 2010).

Similarly like in the artificial regeneration, in the case of spontaneous succession and seeding some distinct differences were found between the plots situated in the middle of the wind-thrown area (PRP 3 and 4) and the plots situated on the perimeter (PRP 1 and 6). The lower success of regeneration on PRP 5 was likely due to a greater flying range from the surrounding trees and hence the potential import of seeds on the plot with more extreme climatic conditions. The failure of seeding on PRP 6 is attributed to site conditions (lower soil depth), which were completely different from those in the other parts of the area (Martiník unpublished).

As expected, the highest costs were incurred in the regeneration by planting, i.e. in the variant which meets the requirements of the current legislation. However, the future development of this variant can be predicted only with difficulties, similarly like that of the other variants – not only from the viewpoint of established stand but also from the perspective of a stand that would fulfil all required functions. Our experimental results suggest that a considerable potential exists for using natural processes combined with rational procedures in the artificial regeneration (combined or multiple-phase regeneration) as a way to reduce forest regeneration costs and to create stable commercial forests (Kulla, Sitková 2012). That means using target species only in gaps of pioneer species recruits. Pioneer tree species could play an important role like nurse or filler species (Košulič 2010). The number of target species should also decrease because the occurrence of target species by succession process (Jelínek, Kantor 2006; Kulla, Sitková 2012).

CONCLUSION

Results obtained by the evaluation of regeneration success in two years after establishing the experiment are sufficient for forest regeneration in terms of cumulative data assessed. They are also in accordance with the current legislation in force; nevertheless, the future development of the stand and its individual variants can hardly be predicted in this initial phase of research. It is however possible to state that the regeneration variant meeting the legislative requirements, i.e. planting of target species, brings not only high costs but also numerous biological disadvantages. By contrast, variants closer to nature, i.e. wider use of pioneer tree species, are economically much less intensive in the regeneration of clear-felled areas; they are however outside the framework of valid legislation. Thus, a legislation amendment can be recommended based on our research in order to permit a wider use of the tree species of pioneer character in regenerating forests on clear-felled areas.

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