Occurrence of frost episodes and their dynamics in height gradient above the ground in the Jizerské hory Mts.

J. Gallo[1], I. Kuneš[1], M. Baláš[1], O. Nováková[1], M.L. Drury[2]

[1]*Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic*

[2]*National School of Forestry, University of Cumbria, Newton Rigg, United Kingdom*

ABSTRACT: We have verified whether the temperatures in the zone of terminal leaders of saplings (+100 cm) were less extreme than the temperatures in the zone of terminal leaders of common-sized planting stock (+30 cm). In May and June of 2011 and 2012 we investigated the occurrence of late frosts at different levels above the ground. The number of days and amount of hourly frost records were counted and the sum of sub-zero temperatures was calculated. Our study confirmed that sub-zero temperatures mostly occur at levels near the ground. Therefore, on the sites exposed to late frosts, such as mountain frost hollows, in addition to common-sized planting stock we recommend to consider also the use of large-sized transplants (saplings), since their terminal buds are mostly above the zone near the ground most endangered by frost.

Keywords: frost hollow; late frost; temperature data loggers; forest tree prosperity; mountain sites

Sub-zero temperatures occurring during the growing season can cause serious damage to forests (Hawe, Short 2012). The negative impact of low temperatures is noticeable especially in spring (in May and at higher altitudes also in June) when the young leaves and needles have not fully matured yet.

Some mountain sites in Central Europe are often predisposed to frost events during the whole vegetation periods (Jůza 2011). Rapid declines in temperature in the growing season are mostly connected with nocturnal radiation inversions in shallow valleys, so called frost hollows. Cold air accumulates in basin-shaped valleys with shallow slopes and forms pools of cold air (Vysoudil 1997). The energy balance of frost hollows is particularly influenced by limited mixing and movement (Greene, Nelson 1982).

Due to the flat relief with the shallow valleys, the ridge areas of the Jizerské hory Mts. are ideal for frequent occurrence of frost hollows. One of the most noticeable areas of frost hollow is situated in the Jizerka valley. It is especially in spring and in autumn (less often during the summer months too) that temperature inversions close to the ground surface can cause near ground frosts (Balcar, Špulák 2006).

A forest stand alleviates climatic extremes in comparison with open land (Bäucker, Eisenhauher 2001). Extreme damage by low temperatures to flushing buds and freshly sprouted shoots of forest plantations was recorded previously on former salvage plots without forest shelter (e.g. Jordan, Smith 1995). Thus, on mountain clear-cut tracts, rapid height growth in the initial years acts against mortality, because it quickly gets the terminal leaders of trees above the zone of ground frosts and competing weeds (Kuneš et al. 2012).

The climate of the Jizerské hory Mts. is typical of an area with high precipitation in the Czech Republic; the annual mean fluctuates between 800 mm at lower elevations and 1,700 mm at high mountain elevations. The whole forest region of the mountains

Supported by the Czech University of Life Sciences Prague, Projects IGA FLD ČZU No. 20124343 and CIGA ČZU No. 20114314, CIGA ČZU No. 20124304, and by the Ministry of Agriculture of the Czech Republic, Project No. QJ1220331.

was formerly exposed to pollution and damaged by bark beetle (Slodičák et al. 2009). North-western winds prevail; this transported airborne pollution from German and Polish sulphur emission-sources. Besides browsing and poor soils, high snow levels and strong wind, trees are exposed to extreme early and late frosts. The growing season on the plateau lasts less than 100 days per year and night frost is often recorded in the course of this short period. The severity of early and late frosts can vary between different air and ground layers (Balcar et al. 2011).

It is known that the variation in temperatures is lower under the canopy of forest stand and also that frost episodes occur less frequently on sites sheltered by canopy (Blennow 1998; Langvall, Ottosson-Löfvenius 2002; Špulák 2009a etc.). The microclimate of woodland is generally more conducive to tree establishment than an open-field situation (Hawe, Short 2012). Temperature decrease during clear and calm nights depends on air and soil humidity and the effect is pronounced when the soil moisture is low (Langvall, Ottosson-Löfvenius 2002).

Only late frosts in the near-ground zone are common in Central Europe. Very severe frosts at several meters or even several tens of meters above the ground, as described by Strasser (2011), are exceptional: on 3rd and 4th May 2011 temperatures dropped down to –5°C. Damage occurred even on adult trees, but also on younger trees protected by being under a forest canopy. Besides dieback, the stem form of trees planted in open fields may deteriorate due to late spring frost, exposure to cold and wind (Hawe, Short 2012).

It is clear that microclimate plays a significant role in determining the vitality of forest plantation. The occurrence of late and early frosts might justify the use of large-sized planting stock on the specific sites as mountain frost hollows. The aim of this article is to compare the occurrence of sub-zero temperatures during the growing season, at different heights above the ground under the conditions of mountain frost-hollows and on the nearby slopes. An understanding of the frequency of nocturnal frosts could help in choosing the right reforestation methods and silvicultural measures.

MATERIAL AND METHODS

The study area is situated in the Jizerské hory Mts., the northernmost mountain range in the Czech Republic. The mean annual air temperatures (1997–2010) in the Jizerka research plot, which is located close to the monitored localities, were 5.0°C at 200 cm and 5.6°C at 30 cm above the ground. The higher mean annual temperature near the ground (+30 cm) was caused by insulation from snow, since the temperature of snow does not drop much below 0°C (Balcar et al. 2012).

To obtain relevant temperature data, automatic temperature loggers Comet S0141 with Pt1000TGL40 sensors were used (Comet Systems Ltd., Rožnov pod Radhoštěm, Czech Republic). The first two loggers were installed in autumn 2009; the next three loggers were installed in May 2010. In spring 2012 the period of the study was extended and further eight data loggers were installed – 4 under slope conditions and 4 under shallow valley conditions. An overview of locations is shown in Table 1. Detailed data regarding two early vegetation periods (May and June, 2011 and 2012) for four data loggers (that were already in operation in spring 2011) are presented. Summary data

Table 1. List of locations of data loggers

Locality	Latitude [N]	Longitude [E]	Installed	Location
Panelka	50°49.162'	15°21.096'	2009-08-21	valley
Jelenka	50°50.933'	15°19.596'	2009-09-10	
Jelení stráň	50°49.968'	15°20.474'	2010-05-21	
Promenádní cesta	50°48.947'	15°20.133'	2010-05-21	
Smědavská silnice	50°50.241'	15°19.005'	2010-05-22	
Celní cesta	50°49.144'	15°21.201'	2012-05-29	
Kosodřevina	50°49.091'	15°21.182'	2012-05-29	
Lánský	50°49.460'	15°20.556'	2012-05-29	
Střední hřeben	50°49.569'	15°21.380'	2012-05-30	slope
Jizerka	50°49.714'	15°21.344'	2012-05-31	
Hlídková	50°49.746'	15°21.207'	2012-05-31	
Pytlácké kameny	50°50.608'	15°19.839'	2012-05-31	
Český vrch	50°50.781'	15°19.393'	2012-05-31	

from the 2012 growing season (excluding May) is presented for all data loggers installed later. The temperature was monitored at three different heights: 200 cm, 100 cm and 30 cm above the ground. Temperature was recorded at hourly intervals, to the nearest ± 0.1°C.

The data were collected throughout the years 2010–2012, so together the temperature extremes were recorded over three successive springs. Our attention was given to the periods from May 1 to June 30, because the temperature extremes in those periods affect the sprouting trees most intensively. The snow often covers the temperature sensor at + 30 cm even during April. Furthermore, trees do not usually sprout (and therefore do not become more susceptible to frost damage) in the area until the beginning of May. Therefore the temperatures were evaluated only from the beginning of May.

The comparison of temperature characteristics at the different heights above the ground was assessed using two criteria:

– number of nights when the minimum temperature dropped below 0°C to a certain temperature interval (see the text below),
– number of hourly frost records in particular temperature intervals.

The set of temperature intervals was as follows: –0.1 to –2°C; –2.1 to –4°C; –4.1 to –6°C and less than –6°C. The numbers of freezing nights in particular intervals (see Tables 3 and 4) represent the number of the nights when the lowest temperature (recorded during the freezing night) reached the corresponding interval. For example: a night with the lowest temperature equal –5°C was included in the frequency of the –4.1 to –6.0°C interval only, and it was not included in the other (higher-temperature) intervals. The total sum of minus temperatures was calculated and compared between individual height zones at each location.

Data were assessed by means of a binomial test with subsequent multiple comparisons described by Anděl (1998), based on previous proofs of Hayter (1984) and significant differences examined on a 95% level of confidence. The features of the test were as follows: let n_i be the number of measurements of variable x and x_i the number of observations in which the variable x showed a positive result. Further K be the number of compared variables. The difference between the j^{th} and i^{th} quantity is statistically significant (on an α level of confidence) when equation:

$$\left[arcsin\left(\frac{x_i}{n_i}\right) - arcsin\left(\frac{x_j}{n_j}\right)\right] \geq \sqrt{\frac{1}{8}\left(\frac{1}{n_i}+\frac{1}{n_j}\right)}\, q_{K,\infty}^{\alpha} \qquad (1)$$

where:

x_i, x_j – variables,
n_i, n_j – number of measurements of variables,
j^{th}, i^{th} – sequence of measured values,
$q_{K,\infty}^{\alpha}$ – critical value of the studentized range.

RESULTS

The general dynamics of frost episodes in frost hollows in this study resembles the typical examples given by Geiger (1950). The typical course of a frost event is presented in Fig. 1, with a rapid decrease in temperature following the sunset (point A in Fig. 1), then, when dew point temperature is reached, the temperature decrease is decelerated (point B in Fig. 1). The next reduction in the rate of temperature decrease or even a temperature increase could be due to wind, clouds or fog (point C in Fig. 1). The lowest temperature is usually reached at the point when the sunrise begins (point D in Fig. 1), followed by a rapid temperature rise. The one-day amplitude of soil temperature (10 cm under the ground) is negligible.

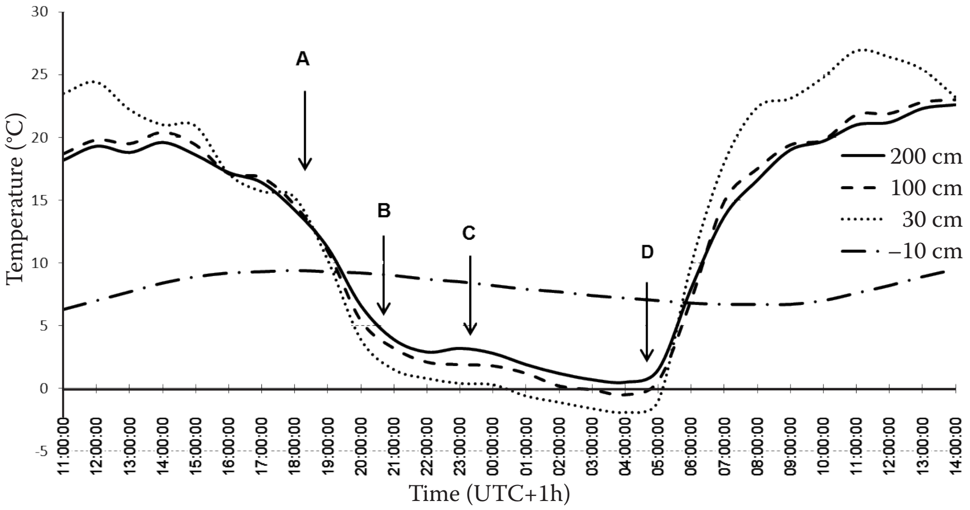

Fig. 1. Dynamics of a typical frost episode from May 9–10, 2011 in Jelenka sample plot

Table 2. Minimal temperatures recorded in May and June, 2011–2012

Year	Height (cm)	Jelenka	Jelení stráň	Promenádní	Smědavská
2011	200	–9.5	–4.6	–6.1	–11.1
	100	–10.4	–6.1	–8.7	–
	30	–12.4	–7.0	–11.2	–12.9
2012	200	–6.1	–1.4	–3.0	–7.4
	100	–6.9	–3.7	–6.2	–8.6
	30	–7.8	–3.5	–8.7	–8.8

values with different letters are significantly different from each other at α = 0.05 (results of a binomial test with subsequent multiple comparisons), – data missing due to technical problems

Despite technical problems and interruptions in the measurements (due to damage by mice and UV radiation), extensive data was acquired. The sub-zero temperatures would usually occur only during the clear and calm nights (only very rarely during the day when there was a heavy advection of cold arctic air often connected with the snowfall). On the other hand, nocturnal frost episodes can occur quite often, even in the summer months in this locality. The lowest recorded extreme temperature within the measuring period occurred in Smědavská silnice when during the frost period on May 3–4, 2011 the temperature dropped down to –12.9 °C at 5:00 (= UTC + 2 h); simultaneously at Jelenka station the temperature decreased to –12.4 °C (Table 2).

Table 3. Frequency of freezing nights and freezing hours in Jelenka sample plot in 2010

Interval (°C)	Height (cm)	f.n.	f.h.
–0,1 to –2	200	5^{a}	11^{a}
	100	4^{a}	17^{a}
	30	4^{a}	23^{a}
–2,1 to –4	200	0^{a}	0^{a}
	100	1^{a}	1^{ab}
	30	2^{a}	5^{b}
–4,1 to –6	200	0^{a}	0^{a}
	100	0^{a}	0^{a}
	30	0^{a}	0^{a}
≤ –6,1	200	0^{a}	0^{a}
	100	0^{a}	0^{a}
	30	0^{a}	0^{a}
Total	200	5^{a}	11^{a}
	100	5^{a}	17^{ab}
	30	6^{a}	28^{b}

values with different letters are significantly different from each other at α = 0.05 (results of a binomial test with subsequent multiple comparisons); f.n. – freezing nights, f.h. – freezing hours

Frequencies of freezing nights and hours are presented in Tables 3 and 4. Table 3 shows the values in the Jelenka locality in 2010. There was only a minor difference in the number of freezing nights between monitored zones, but the amount of freezing hours was considerably different, the zone of 30 cm above the ground experiencing the highest amount of them; the difference between 200 cm and 30 cm zones was significant according to the binomial test.

Table 4. Frequency of freezing nights and hours in June 1–30 in 2011 and 2012

Interval (°C)	Height (cm)	Jelenka		Jelení stráň		Promenádní		Smědavská silnice	
		f.n.	f.h.	f.n.	f.h.	f.n.	f.h.	f.n.	f.h.
2011									
–0.1 to –2	200	4^{a}	40^{a}	1^{a}	25^{a}	0^{a}	22^{a}	5^{a}	31^{a}
	100	3^{a}	33^{a}	1^{a}	21^{a}	4^{b}	36^{a}	–	–
	30	7^{a}	41^{a}	3^{a}	23^{a}	4^{b}	37^{a}	8^{a}	36^{a}
–2.1 to –4	200	2^{a}	14^{a}	1^{a}	12^{a}	3^{a}	12^{a}	4^{a}	35^{a}
	100	5^{a}	27^{ab}	1^{a}	15^{a}	3^{a}	12^{a}	–	–
	30	1^{a}	32^{b}	1^{a}	15^{a}	5^{b}	30^{b}	1^{a}	27^{a}
–4.1 to –6	200	1^{ab}	11^{a}	1^{a}	9^{a}	1^{a}	11^{a}	1^{a}	10^{a}
	100	0^{a}	10^{a}	1^{a}	12^{a}	1^{a}	7^{a}	–	–
	30	4^{b}	14^{a}	1^{a}	8^{a}	0^{a}	3^{a}	5^{a}	26^{b}
≤ –6.1	200	2^{a}	12^{a}	0^{a}	0^{a}	1^{a}	1^{a}	3^{a}	20^{a}
	100	3^{a}	14^{a}	1^{a}	1^{ab}	2^{a}	12^{b}	–	–
	30	3^{a}	22^{a}	1^{a}	7^{b}	3^{a}	19^{b}	3^{a}	26^{a}
Total	200	9^{a}	77^{a}	3^{a}	46^{a}	5^{a}	46^{a}	13^{a}	96^{a}
	100	11^{a}	84^{a}	4^{a}	49^{a}	10^{a}	67^{ab}	–	–
	30	15^{a}	109^{a}	6^{a}	53^{a}	12^{a}	89^{b}	17^{a}	115^{a}
2012									
–0.1 to –2	200	5^{a}	16^{a}	3^{a}	19^{a}	3^{a}	14^{a}	8^{a}	29^{a}
	100	6^{a}	21^{ab}	3^{a}	15^{a}	5^{ab}	18^{a}	10^{a}	43^{a}
	30	11^{a}	40^{b}	3^{a}	16^{a}	12^{b}	41^{b}	12^{a}	42^{a}
–2.1 to –4	200	1^{a}	5^{a}	0^{a}	0^{a}	1^{a}	7^{a}	1^{a}	5^{a}
	100	0^{a}	5^{a}	1^{a}	8^{a}	1^{a}	3^{a}	3^{a}	10^{a}
	30	3^{a}	8^{a}	1^{a}	8^{a}	1^{a}	5^{a}	4^{a}	14^{a}
–4.1 to –6	200	0^{a}	6^{a}	0^{a}	0^{a}	0^{a}	0^{a}	0^{a}	3^{a}
	100	0^{a}	4^{a}	0^{a}	0^{a}	0^{a}	6^{b}	0^{a}	2^{a}
	30	0^{a}	3^{a}	0^{a}	0^{a}	1^{a}	2^{ab}	0^{a}	2^{a}
≤ –6.1	200	1^{a}	1^{a}	0^{a}	0^{a}	0^{a}	0^{a}	1^{a}	5^{a}
	100	1^{a}	4^{a}	0^{a}	0^{a}	1^{a}	1^{ab}	1^{a}	7^{a}
	30	1^{a}	6^{a}	0^{a}	0^{a}	1^{a}	7^{b}	1^{a}	7^{a}
Total	200	7^{a}	28^{a}	3^{a}	19^{a}	4^{a}	21^{a}	10^{a}	42^{a}
	100	7^{a}	34^{ab}	4^{a}	23^{a}	7^{ab}	28^{a}	14^{a}	62^{a}
	30	15^{a}	57^{b}	4^{a}	24^{a}	15^{b}	55^{b}	17^{a}	65^{a}

values with different letters are significantly different from each other at α = 0.05 (results of a binomial test with subsequent multiple comparisons), – data missing due to technical problems, f.n. – freezing nights, f.h. – freezing hours

Table 5. Sums of sub-zero temperatures (°C)

Height (cm)	Jelenka		Jelení stráň		Promenádní		Smědavská silnice	
	2011	2012	2011	2012	2011	2012	2011	2012
200	–234.5	–62.3	–96.1	–13.7	–122.1	–27.9	–353.2	–86.7
100	–279.9	–73.7	–127.8	–34.9	–190.7	–57.9	–	–138.0
30	–399.9	–110.4	–151.0	–33.4	–303.6	–113.0	–477.1	–146.1

values with different letters are significantly different from each other at α = 0.05 (results of a binomial test with subsequent multiple comparisons), – data missing due to technical problems

Table 4 shows the frequency of freezing nights (f.n.) and freezing hours (f.h.) in all locations measured in 2011 and 2012. The lowest zone above the ground experienced the highest number of freezing nights in all locations situated in frost hollows. A statistically significant difference was found in Promenádní in 2012 between the 200 cm and 30 cm zone. In the slope-situated location Jelení stráň the number of freezing nights was comparable in all three zones and not significant and the total amount of frost episodes was lower than in the sites situated in the valley bottom.

The number of freezing hours was highest at the 30 cm zone above the ground in all locations, with Jelení stráň being the least prominent again. Significant differences were recorded within plots located in the valley. In the 2011 data, statistical significance was found in Promenádní plot between the 200 and 30 cm zone. In the 2012 data, a significant difference was found in Jelenka plot between the 200 and 30 cm zone and in Promenádní between 200 and 30 cm as well as between 100 and 30 cm. These results point out the prominence of the near-ground zone (+30 cm) in terms of duration of late frosts in this location. Our data confirmed the results reported in Balcar et al. (2009).

According to the total amount of freezing hours the evaluated season in 2011 was much colder than that following in 2012. Data in Table 5 confirmed the trend that the zone closest to the ground level experiences most of the severe temperatures during frost episodes, the total sum of sub-zero temperatures is highest in the 30 cm zone in all plots located frost hollows. The difference in the sum of sub-zero hourly records between 100 and 30 cm was generally more distinct than that between the 200 and 100 cm zone in frost hollows, whereas in slope-located plots the contrast is somewhat smaller.

The sole data from 2010 are from the Jelenka sample plot located in the valley:

Height (cm)	200	100	30
Temperatures (°C)	–8.8	–17.1	–34.5

These data showed less frequent occurrence of late frosts than in the two successive seasons, but the trend of temperature differences along each suggested zone was maintained.

The values of minimal temperature are shown in Table 6. Differences in the severity of frost between different heights above the ground were repeatedly proved in both the slope locations and frost hollows. However, the sum of freezing hours and nights is significantly higher in the valley while slope locations are experiencing only a fraction of freezing time compared to frost hollows (Table 7). Individual differences in the accumulated sum of sub-zero temperature values from summer 2012 are documented in Table 8.

Table 7. Sum of freezing hours and freezing nights in 2012

Height (cm)	Freezing hours		Freezing nights	
	ridge	valley	ridge	valley
200	11	154	4	40
100	27	231	6	50
30	72	357	20	71

DISCUSSION

Our results are in agreement with conclusions of Špulák (2009b), who also described greater differences between temperatures and more frost

Table 6. Minimal temperature values in June and July 2012 (°C)

Height (cm)	Ridges						Valleys						
	Jelení stráň	Střední hřeben	Jizerka	Hlídková	Pytlácké kameny	Český vrch	Promenádní	Smědavská	Jelenka	Kosodřevina	Lánský	Panelka	Celní cesta
200	0.1	–1.4	–0.2	0.6	–0.3	–1.6	–1.4	–2.6	–2.9	–2.3	–2.7	–2.7	–2.5
100	–0.4	–1.6	–1.5	–1.5	–1.7	–2.3	–2.3	–3.2	–2.8	–2.6	–3.3	–2.6	–2.9
30	–0.7	–1.7	–3.0	–3.1	–3.1	–3.4	–4.4	–3.6	–3.7	–3.5	–4.8	–3.0	–3.1

Table 8. Accumulated sum of sub-zero temperature values from summer 2012 (°C)

Locality	Height (cm)		
	200	100	30
Ridge			
Jelení stráň	0	–1.1	–1.9
Jizerka	–0.2	–3.7	–11.0
Hlídková	0	–4.2	–12.4
Pytlácké kameny	–0.4	–6	–17.5
Český vrch	–4.5	–7.9	–13.1
Střední hřeben	–4.3	–5.6	–8.0
Valley			
Panelka	–10.5	–38.1	–59.4
Jelenka	–11.5	–10.8	–18.9
Promenádní	–4.1	–7.1	–30.6
Smědavská	–17.5	–26	–54.8
Kosodřevina	–39.6	–65.9	–109.9
Lánský	–28.3	–64.4	–151.5
Celní cesta	–28.5	–45.2	–73.8

episodes at low heights above the ground. In this study, more severe freezing episodes generally occurred near the ground (+30 cm) and in the literature this is associated with severe damage to tree buds situated in the zone between the ground level and 1 m above the ground (Balcar et al. 2011). The dynamics of a frost episode and duration of frost during the night have to be considered among many factors associated with the vitality of planted trees. These findings could serve as a provisional reason for testing the large-sized planting stock (saplings) under such conditions.

Severe frost damage or mortality can usually begin to occur (depending on the tree species) if the temperature drops below –2 to –5°C during the active growing season when the seedling is not in a hardened condition (Spittlehouse, Stathers 1990). It is supposed that particularly severe injuries to forest trees by late frosts can develop when relatively high temperatures occur by daylight and the temperature of a subsequent night drops below 0°C. Frost extremes are considered among the factors which caused the birch dieback in the Sudeten Mountains in 1996/97 (Balcar 2001). Steyerer (2011) reported that the occurrence of large differences in temperature within 24 hours between the day and night at the beginning of vegetation season caused abiotic damage to many trees of various species in many Austrian regions. The frost-drought caused by the combination of solid frozen soil and extreme fluctuation of air temperature resulted in water deficiency in aboveground parts of plants.

CONCLUSION

Great differences in microclimatic conditions from site to another are obvious (Jelenka × Jelení stráň), given by differences in the relief and subsequently variation in the pattern of cold air flow. The most severe temperature extremes are expected in cold valleys, whereas the localities situated on the slopes and ridges only several meters above the valley bottom hardly experience any late frost episodes in spring. It was found that the most severe late frost episodes take place in the lowest layer above the ground.

The aim is to adopt the right silvicultural and reforestation methods that enable both the good survival and growth and also optimal cost effectiveness. Significant occurrence of severe late frost episodes in the layer of air immediately above the ground in frost-hollow sites supports the proposal to test further the method of reforestation with advanced large-sized planting stock.

Acknowledgements

The data were processed at the Truba Research Station (Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague).

References

Anděl J. (1998): Statistické metody. [Statistical Methods.] Praha, Matfyzpress: 274.

Balcar V. (2001): Some experience of European birch (*Betula pendula* Roth) and Carpathian birch (*Betula carpatica* W. et K.), planted on the ridge part of the Jizerské hory Mts. Journal of Forest Science, ***47*** (Special Issue): 150–155.

Balcar V., Špulák O. (2006): Poškození dřevin pozdním mrazem a krycí efekt lesních porostů při obnově lesa v Jizerských horách. In: Jurásek A., Novák J., Slodičák M. (eds): Stabilizace funkcí lesa v biotopech narušených antropogenní činností v měnících se ekologických podmínkách. [Stabilisation of Forest Functions in Biotopes Disturbed by Anthropogenic Activity.] Sborník z konference. Opočno, 5.–6. 9. 2006, Opočno, VÚLHM: 125–132.

Balcar V., Špulák O., Kacálek D. (2009): Příspěvek k problematice porostotvorné funkce jehličnatých dřevin – tlumení mrazových extrémů v horách. [Contribution to role of conifers in stand-forming proces – moderating of frost extremes in mountains.] Zprávy lesnického výzkumu, ***54***: 157–165.

Balcar V., Špulák O., Kacálek D., Kuneš I. (2011): Obnova lesa ve vyšších horských polohách postihovaných extrémními mrazovými stresy. [Introducing of Broad-leaved and Fir Admixture into Coniferous Stands in the Jizera Mts.] Jíloviště-Strnady, VÚLHM: 36.

Balcar V., Špulák O., Kacálek D., Kuneš I. (2012): Klimatické podmínky na výzkumné ploše Jizerka. II. – teplota, vítr a sluneční svit. [Climatic conditions in the Jizerka experimental plot. II – temperature, wind and radiation.] Zprávy lesnického výzkumu, ***57***: 160–172.

Bäucker B., Eisenhauher D.R. (2001): Damage to Common birch (*Betula pendula* Roth) in higher altitudes of the Ore Mts. (Erzgebirge). Journal of Forest Science, ***47*** (Special Issue): 150–155.

Blennow K. (1998): Modelling minimum air temperature in partially and clear felled forests. Agricultural and Forest Meteorology, ***91***: 223–235.

Geiger R. (1950): The Climate Near the Ground. Cambridge, Harvard University Printing Office: 482.

Greene G., Nelson F. (1982): Performance of a frost hollow as a hemispherical thermal radiometer. Archives for Meteorology, Geophysics, and Bioclimatology, ***32***: 263–278.

Hawe J., Short I. (2012): Poor performance of broadleaf plantations and possible remedial silvicultural systems – a review. Irish Forestry, ***69***: 126–147.

Hayter A.J. (1984): A proof of the conjecture that the Tukey-Kramer multiple comparisons procedure is conservative. The Annals of Statistics, ***12***: 61–75.

Jordan D. N., Smith W. K. (1995): Microclimate factors influencing the frequency and duration of growth season frost for subalpine plants. Agricultural and Forest Meteorology, ***77***: 17–30.

Jůza P., Starostová M., Sklenář K. (2011). Naměřená minima teploty vzduchu na vybraných horských stanicích v Čechách. [Minimal air temperatures measured at some mountain stations in Bohemia.] Meteorologické zprávy, ***64***: 10–17.

Kuneš I., Baláš M., Koňasová T., Zahradník D., Balcar V., Špulák O., Kacálek D., Jakl M., Jaklová Dytrtová J. (2012): Cultivation of speckled alder under harsh mountain conditions. Journal of Forest Science, ***58***: 234–244.

Langvall O., Ottosson Löfvenius M. (2002): Effect of shelterwood density on nocturnal near-ground temperature, frost injury risk and budburst date of Norway spruce. Forest Ecology and Management, ***168***: 149–161.

Slodičák M. et al. (2009): Lesnické hospodaření v Jizerských horách. [Forestry Management in Jizerské hory Mts.] 2nd edition. Hradec Králové, Lesy ČR; Jíloviště-Strnady, VÚLHM: 232.

Spittlehouse D.L., Stathers R.J. (1990): Seedling Microclimate. Victoria, B.C., British Columbia Ministry of Forests: 28.

Steyerer G. (2011): Abiotische Schäden im Winter und Frühjahr. Forstschutz Aktuell, ***53***: 30–31.

Strasser L. (2011): Schwarzes Laub und braune Nadeln – Spätfrost in Bayern. Forstschutz Aktuell, ***53***: 28–29.

Špulák O. (2009a): Náhradní porosty smrku pichlavého a jejich přeměna bukem lesním. [Substitute Forest Stands of Blue Spruce and Their Conversion by European Beech.] [Ph.D. Thesis.] Česká zemědělská univerzita v Praze: 124.

Špulák O. (2009b): Příspěvek k poznání teplotních souvislostí prosadeb jehličnatých porostů náhradních dřevin. [Contribution to study of temperature relationships of interplantings in coniferous substitute tree forest stands.] Zprávy lesnického výzkumu, ***54*** (Special): 53–61.

Vysoudil M. (1997): Meteorologie a klimatologie pro geography. [Meteorology and Climatology for Geographs.] Olomouc, Vydavatelství Univerzity Palackého: 233.

Received for publication November 10, 2013
Accepted after corrections December 19, 2013

Corresponding author

Bc. Josef Gallo, Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences,
Department of Silviculture, Kamýcká 1176, 165 21 Prague 6-Suchdol, Czech Republic; e-mail: xgalj700@studenti.czu.cz