Oil Shale, 2009, Vol. 26, No. 1, pp. 73–83
doi: 10.3176/oil.2009.1.08

ISSN 0208-189X

IMPACT OF UNDERGROUND MINING OF OIL SHALE IN NORTHEASTERN ESTONIA ON SCOTS PINE AND NORWAY SPRUCE GROWING THEREON

A. LÄÄNELAID(a)*, D. ECKSTEIN(b), J.-W. SEO(b)

(a) University of Tartu, Institute of Earth Sciences and Ecology
Vanemuise 46, 51014 Tartu, Estonia

(b) University of Hamburg, Dept. of Wood Science, Division Wood Biology,
Leuschnerstr. 91, 21031 Hamburg, Germany

In the Kohtla mine, NE Estonia, Scots pines and Norway spruces were dendrochronologically studied to see if and how underground mining has impacted the trees. Pine and spruce show different species-specific increment patterns in the pre-mining as well as in the post-mining period. Tilting of trees was the most obvious appearance in the forest. This has led to compression wood in the tilted trunks that was more remarkable in spruce than in pine. It amounted to 3–4% of the trunk diameter. After the impact year 1998, the radial increment of spruce on all sample plots has notably increased whereas increment of pine has changed only insignificantly. Temperature and rainfall are of minor influence on the growth of these trees.

Introduction

Near Kohtla in Northeastern Estonia, oil shale has to a large extent been extracted from flat underground deposits above which forests are growing and agricultural fields are established. The oil shale bed is shallow of a thickness of about 10% of the overlying rock. The mining techniques applied left behind large underground cavities. After having taken about a two meters thick layer of oil shale out of a depth of about 30 meters, the land surface together with the forests or fields has been sinking by approximately one meter. Along the edges of the lowered ground, the surface became sloped and subsequently the trees at these areas often became tilted. These sloped, approx. five meters broad areas comprise about 6% of the subsided area.

Effects of underground mining of salt on trees have, for example, been studied by Yanosky and Kappel [1]; in their case study, however, it was not the mining as such which has affected tree growth but the salt which had

---

* Corresponding author: e-mail *alar.laanelaid@ut.ee*

physiologically impacted tree growth by the inflow of brackish water into a nearby forested wetland. Several mining/non-mining periods could retrospectively be identified on the basis of tree-ring width suppressions and releases during the last one hundred years. A situation like this can methodologically be approached as in forest decline studies [e.g., 2–4]; respective methods have also been suggested by Kuzmin and Kuzmina [5]. In Estonia, tree-ring widths of declining and non-declining pine trees have been compared [6]. A dendrochronological study, carried out on pines and spruces growing on a mining area abandoned in 2003, was aimed at answering the question if and how the lowering and the sloping of the surface influenced tree growth and in consequence impaired the timber quality.

Material

Study site

In the Kohtla mining area (Fig. 1, a), a sample plot was chosen above the 1998-mining activity. It is covered by a mixed forest of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) with birch (*Betula pubescens* Roth.) and aspen (*Populus tremula* L.). The forest vegetation type varies between *Vaccinium vitis-idaea* L. and *Vaccinium myrtillus* L. Oil shale has been removed from underground rectangles of approx. 200 m × 700 m; between them, stripes of about 10 to 20 m wide have remained untouched (Fig. 1, c) [7].

After mining in 1998 the surface has subsided (Fig. 1, c, in center), probably right after 1998 (further on referred to as mining event). Along the edges of these lowered rectangles the surface is sloped down (Fig. 1, d). In some places there are cracks in the ground of up to half a meter wide. The trees on such slopes are often tilted (Fig. 1, b); some trees can also be found tilted at the subsided areas.

Sample trees

One set of sample trees (22 pines and 19 spruces) was growing on one of the slopes; trees suspected of having root damage were marked [8]. From each tree, cores from two opposite radii were taken by an increment borer; one from the upslope side and another from the downslope side of the tilted trunks. Another set of sample trees (16 pines and 14 spruces) was selected on a subsided area; tilted trees were cored as described before; otherwise the cores were removed from the northern and southern sides of the trees. A further sample set of 10 pines and 4 spruces growing on one of the seemingly stable stripes between two subsided areas was taken for comparison and cored from northern and southern sides of each trunk. Altogether 48 pines and 38 spruces were sampled in spring/summer 2004 and their perimeter at 1.3 m height was measured; their height was 17–20 meters.

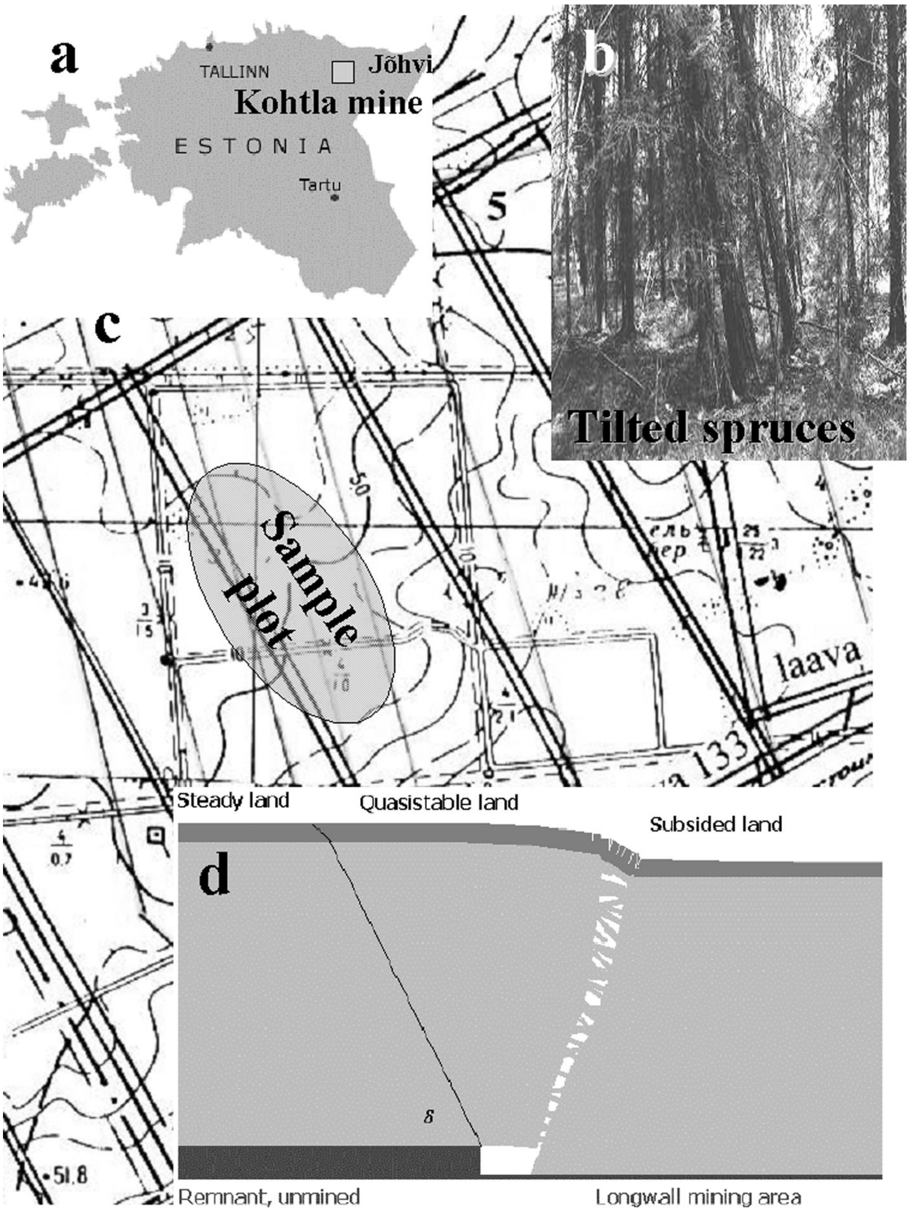

Fig. 1. a. Location of the Kohtla mining area in NE Estonia and of the meteorological station at Jõhvi, 10 km apart. b. Tilted spruces on the edge slope of the subsided area. c. Detail map of the mining area with the dendrochronological sample plot (oval-shaped); rectangles are subsided forest areas separated by stripes. d. Schematic cross-section through the underground mine after subsiding [9].

Methods

The tree-ring widths of the study trees were recorded in 0.01 mm units by the measuring device LINTAB and by program TSAP (Rinntech, Heidelberg, Germany). These increment time series were further processed by dendrochronological standard techniques [2, 10]. The quality of their cross-dating was checked by the program COFECHA [11] according to the mean correlation of each series with all other series per sample set. To enhance the common climatic signal in the tree-ring series, only dominant and co-dominant sample trees were chosen for further analyses. They were defined to have an above-average perimeter/age relation (further on, both categories are referred to as dominant). Altogether, 19 pines and 18 spruces turned out to be dominant. Their tree-ring width chronologies were compared to each other using the t-value [12] and the coefficient of coincidence (‘Gleichläufigkeit’) [13].

In the program ARSTAN [14], the increment series of pine and spruce up to 1997, i.e., in the pre-mining period, were de-trended to eliminate the biological age trend and to enhance the climatic signal. The resulting, so-called residual chronologies from 1924–1997 for pine and from 1914–1997 for spruce were tested against climate data by the program DendroClim2000 [15], using climate records of monthly mean temperature from 1953–1997 and of the monthly sum of precipitation from 1960–1997 from the Jõhvi Meteorological Station.

Results

The pines and spruces were about 57 and 61 years old, respectively, and their average annual increment during the 20-year period right before the onset of mining was 1.53 mm for pine and 2.13 mm for spruce. Their tree-ring chronologies in the pre-mining time were only poorly similar to each other ($t = 2.3$; coeff. of coincidence = 50.7%); further statistical descriptors of the tree-ring chronologies are summarized in Table.

The mean tree-ring series of pine and spruce, separated by the site features ‘stable’ ‘slope’ and ‘subsided’ were fairly similar when compared per tree species but characteristically different when compared between tree species (Fig. 2). Whereas the growth of pine followed a steadily decreasing age trend without remarkable amplitudes and even without obvious deviations from this trend during the post-mining period, the radial growth of

Table. **Statistical characteristics of the dominant pine and spruce tree-ring series. The statistics are described in [16]**

Average tree-ring series of dominant trees	Extension	Mean value of tree-ring width, mm	Standard deviation, mm	Auto-correlation	Mean sensitivity
Pine (19 trees)	1923–2003	2.99	1.50	0.85	0.143
Spruce (18)	1909–2003	2.92	1.33	0.88	0.155

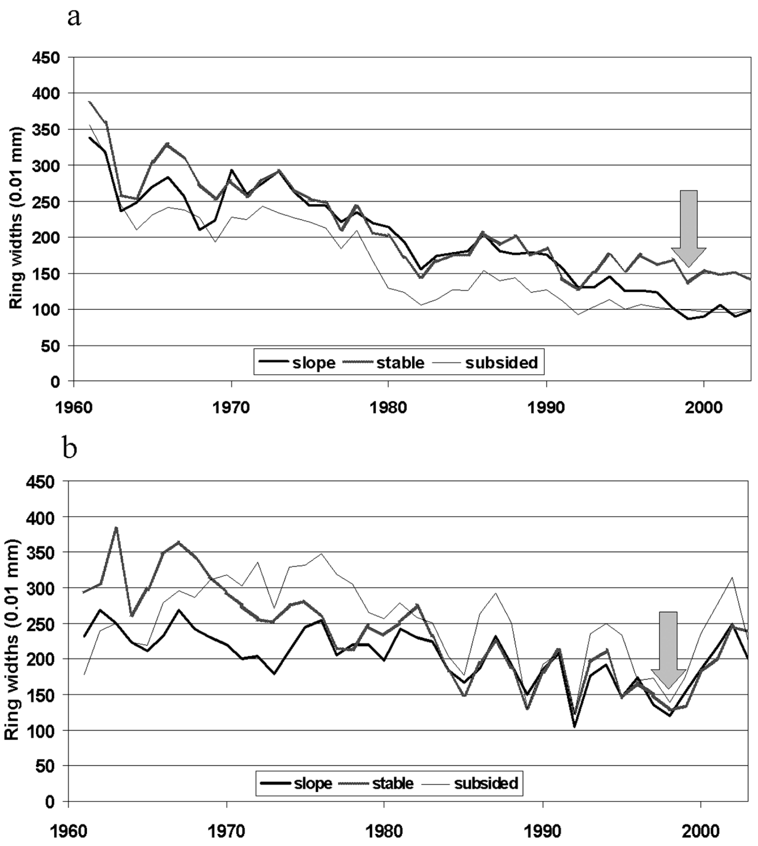

Fig. 2. Mean tree-ring series of pine (a) and spruce (b), each on three sites (stable, slope, subsided); arrow indicates the mining event.

spruce varied more from year to year and distinctly increased from 1999 onwards, independent from the three site features.

A special feature of the trees at the abandoned mining area is tilting. A comparison of the tree-ring widths in the up- and downslope radii of 13 pines and 6 spruces (Fig. 3) produced remarkable, species-related differences. From 1999 onwards the increment in the upslope radii decreased as a rule, whereas it increased in the downslope radii, but much more in spruce than in pine. The average tree-ring width of the pines during the five post-mining years and during the preceding 10 years is nearly the same (Fig. 4); in contrast, the spruces profit by the same situation in that their radial increment increased by more than 50% [17].

The radial growth of pine was favoured by an above-average warmth in March and July whereas precipitation did not play any significant role (Fig. 5a). The radial growth of spruce was advanced by below-average cool conditions in all months, significantly in January, combined with above-average rainfall in July (Fig. 5b). All in all, the climatic control of tree growth in the Kohtla mining area has been rather weak.

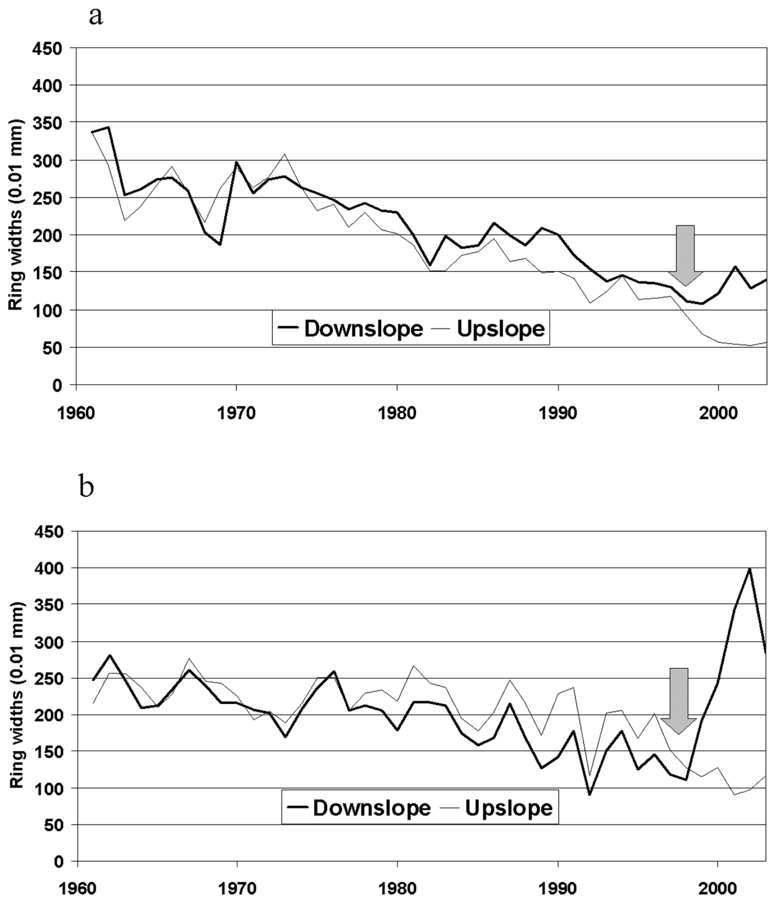

Fig. 3. Non-detrended tree-ring width time series of upslope and downslope radii of 13 tilted pines (a) and 6 tilted spruces (b); arrow indicates the mining event.

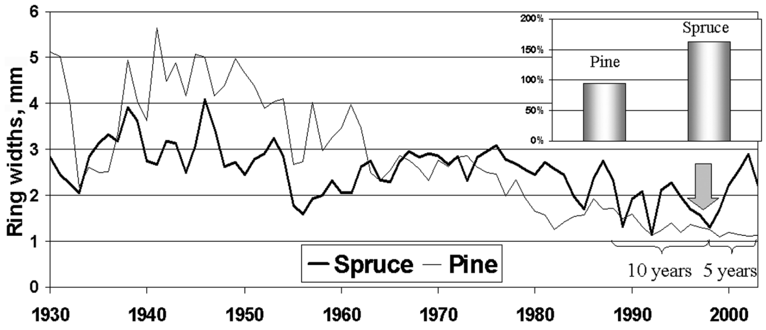

Fig. 4. Non-detrended tree-ring chronologies of dominant pine and spruce since 1930; arrow indicates the mining event. Inset: average tree-ring width throughout five years after the mining event in relation to the average during the preceding 10 years.

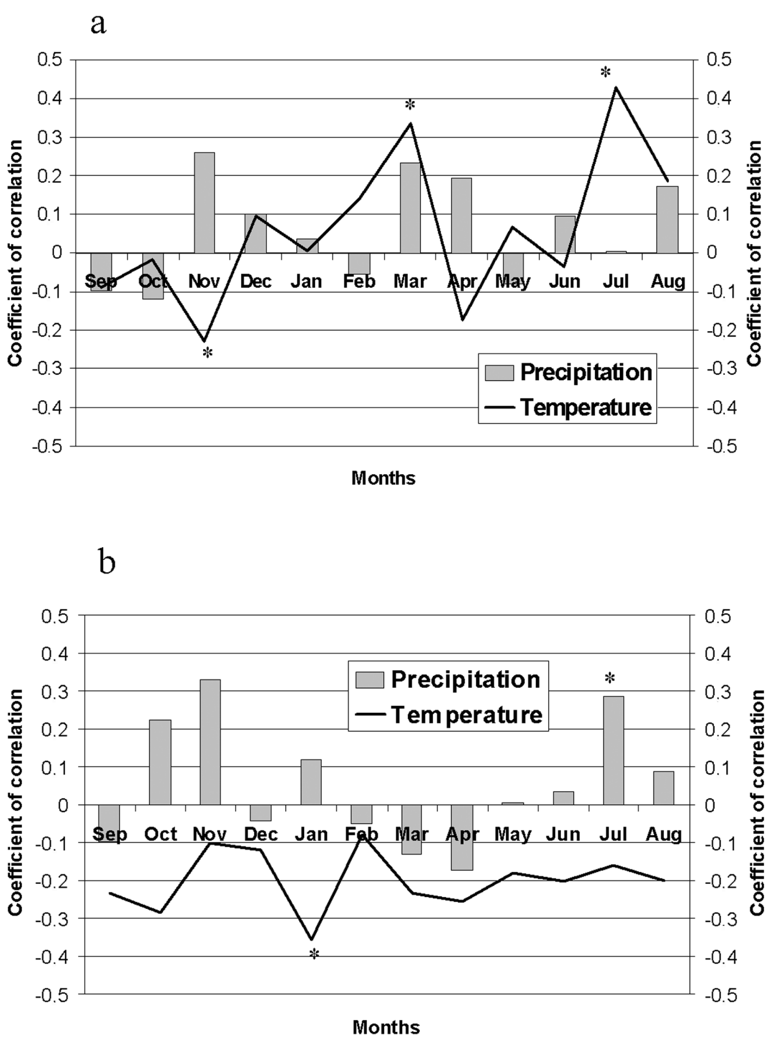

Fig. 5. Correlation of radial increment of dominant pine (a) and spruce (b) with the monthly mean temperature and precipitation from 1961–1997; star means statistical significance at the 95% level.

Discussion

Our study was aimed at checking if and how the mining-related lowering and sloping of the ground have affected the growth of trees. Alestalo [18] was among the first who used tree rings as well as changes in the shape of a tree trunk for dating and identifying geomorphic events and processes, such as mass movements, subsiding of the soil surface and the like. Since then, a variety of further applications have been reported [e.g., 19–21] and the term ‘dendrogeomorphology’ has been widely accepted and firmly established for such studies [22].

Pine and spruce in the Kohtla mining area respond differently to the prevailing climatic factors and therefore their tree-ring chronologies are highly dissimilar to each other, not only during the mining period but also in the pre-mining time. Whereas Estonian pine, in general, ‘archives’ a clear winter/early spring temperature signal [23], the climatic signal of the Kohtla pines is weak and less distinct. The Kohtla spruces, in contrast, are quite clearly favoured by below-average cool conditions from previous autumn to the end of the current summer, although not always significant. Results such as for pine are not available for Estonian spruce yet. According to a dendroclimatological study on spruce, distributed all over Lithuania, a warmer-than-average April to May combined with a wetter-than-average June will result in wide tree rings, and vice versa [24]. This distinct contradiction to our observation at Kohtla indicates that our study site is very likely not representative for Estonia as a whole.

The major feature visible at the trees and interpretable as being caused by the mining activity was tilting. After tilting, conifers normally start to form a specialized wood at the lower side of an inclined trunk, so-called compression wood [25–27]. Compression wood plays a crucial role in the regulation of a tree’s orientation in space; it ceases to form as soon as the stem has become upright again. As a vital tissue of gymnosperms, it is the result of the evolution of land plants since at least 300 million years [28]. Radial growth is usually increased on the compression wood side. Anatomically, compression wood differs strikingly from normal wood and in consequence the elasto-mechanical properties differ just as much. In living trees, compression wood has a higher compressive strength than normal wood, but when air-dried after felling it is inferior to normal wood in almost all strength properties [29]. Its greatest drawback is its exceedingly high longitudinal shrinkage and swelling. Hence, many of the properties of compression wood, while admirably suited for the living tree, are extremely undesirable in pulp wood and sawn timber and are considered to be a serious defect [30]. In sawn timber which contains both, normal and compression wood, the high longitudinal shrinkage of compression wood causes severe warping, distortion and cross checking. Compression wood has also been investigated early in the last century by the Estonian forest scientist Haller [31] who found that such reaction tissue is present in dominant conifers even with a straight trunk.

Both tree species started to form compression wood in 1998 just after the mining has caused sloping of the surface along the edges of the underground mining cavities, soil cracks on the slopes, and dropping of the surfaces above the underground mining cavities. The thickness of the compression wood formed during the last six years (1998–2003) amounts to 3–4% of the diameter of the trunk at 1.3 m height (maximum 6% in pine and 12% in spruce). Once the trunk will be re-straightened, the compression wood formation will cease; this will very likely happen within the next few years. In consequence, normal wood can be expected to be formed. It would be advisable to cut the tilted trees as long as the compression wood is still part of the outer zone of the trunks, because this outer part will normally be removed during the wood-working process of the stems and can thus not impair the quality of the timber. As the average age of the trees is about 60 years at the time being, the cutting age would then be approx. 70 years. From this point of view, short-term mining activities such as those in Kohtla do not affect the vitality of the living trees nor substantially impair the timber quality.

Soovik [32, 33] outlined that the influence of oil shale mining to the environment in NE Estonia has been positive in several aspects. This may be due to changes in the underground hydrology of the forest site [34]. Such a consideration is supported by the observation that underground mining has not reduced the productivity of agricultural crops in the field [32, 33, 35]. If the drainage in a wet forest is improved and the soil becomes dryer after meliorating by the underground mining, trees may even increase their radial increment. As spruce and pine have different demands on soil humidity, their reactions to changes of the water regime are expected to be different.

Conclusions

We cannot forecast the duration of a negative or a positive effect of an underground mining activity on the growth of trees. The abruptly increased growth of spruce may turn back again and stabilize on its pre-mining level. Also the water regime can get worse and decrease the annual increments of the trees. To substantiate such effects it is necessary either to look for sample plots at earlier abandoned mining areas or continue sampling of trees at the present plots in the coming years. Such new sample plots should differ in their site conditions. For example, in some places there are flooded forests in former mining areas, where tree growth has decreased or trees have even died. The study of tree growth on abandoned mining areas should be continued in several directions to establish the effects of soil subsidence at various forest sites, to measure the effects of soil dropping to different tree species, and to observe the changes of tree increment due to soil dropping in a long-term perspective.

Acknowledgements

We are indebted to the Head of the Environment Department of AS Eesti Põlevkivi (the Estonian Oil Shale Company), Kalmer Sokman, and to the senior inspector of the Environment Service, Toomas Tint, for introducing us into the forest situation in the mining area, and to students of the University of Tartu, Merli Palmik and Vivian Uibo, for their help in field work.

REFERENCES

1. *Yanosky, T. M., Kappel, W. M.* Effects of solution mining of salt on wetland hydrology as inferred from tree rings // Water Resources Research. 1997. Vol. 33, No. 3. P. 457–470.
2. *Cook, E. R., Kairiukstis, L. A.* (eds.), Methods of Dendrochronology. Applications in the Environmental Sciences. – Kluwer, Dordrecht, The Netherlands, 1990. 394 pp.
3. *Kairiukštis, L., Skuodiene, L., Vaičys, M., Ozolinčius, R., Armolaitis, K., Petniunas, V., Stravinskiene, V., Grigaliunas, J., Kilikevičius, G.* Methods of Forest Decline and Environment Assessment: Application in Regional Monitoring. Kaunas, Girionys, 1992. 62 pp.
4. *Stravinskiene, V.* Dendrochronological indication of climatic factors and anthropogenic environmental trends in Lithuania. Summary of the Habilitation Thesis. Biomedical Sciences, Ecology and Environmental Sciences. – Kaunas, 2000. 43 pp.
5. *Kuzmin, A. V., Kuzmina, L. I.* Elaboration of the methodical complex structure and an empirical basis for analysing many years dynamics of developing coniferous stands in the regional scope // Conifer growth variability during the Holocene in Northern Europe / Kolström, T., Lindholm, M., Viinanen, R. (eds.). Univ. of Joensuu, Fac. of Forestry, Res. Notes. 2000. Vol. 108. P. 65–77.
6. *Läänelaid, A.* A dendrochronological study of decline of pine stands in South Estonia // Proc. Estonian Acad. Sci. Biol. 1994. Vol. 43. P. 89–97.
7. *Liblik, V., Toomik, A., Rätsep, A.* Environmental effect of closed and to-be-closed mines // Environment and oil shale mining in North-East Estonia. Publ. No. 9 / Liblik, V., Punning, J.-M. (eds). 2005. Tallinn, 2005. P. 31–52 [in Estonian].
8. *Toim, L., Velström, J.* An expert's opinion, 02.07.2003. 2003. 3 pp. + Suppl. (unpubl. manuscript in AS Kohtla Kaevandus) [in Estonian].
9. *Reinsalu, E., Valgma, I.* Geotechnical processes in closed oil shale mines // Oil Shale. 2003. Vol. 20, No. 3 SPECIAL. P. 398–403.
10. *Läänelaid, A.* Tree ring data from Estonia collected in 1999 // Conifer growth variability during the Holocene in Northern Europe / Kolström, T., Lindholm, M., Viinanen, R. (eds.). Univ. of Joensuu, Fac. of Forestry, Res. Notes. 2000. Vol. 108. P. 107–117.
11. *Holmes, R. L.* Computer assisted quality control in tree-ring dating and measurement // Tree-Ring Bull. 1983. Vol. 43. P. 69–78.
12. *Baillie, M. G. L., Pilcher, J. R.* A simple cross-dating program for tree-ring research // Tree-Ring Bull. 1973. Vol. 33. P. 7–14.
13. *Eckstein, D., Bauch, J.* Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit // Forstwiss. Centralblatt. 1969. Vol. 88, No. 1. P. 230–250 [in German].
14. *Grissino-Mayer, H. D., Holmes, R. L., Fritts, H. C.* The International Tree-Ring Data Bank Program Library, version 2.0 user's manual. – University of Arizona, Tucson, 1996.
15. *Biondi, F., Waikul, K.* Dendroclim2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies // Computers & Geosciences. 2004. Vol. 30, No. 3. P. 303–311.
16. *Fritts, H. C.* Tree Rings and Climate. – Academic Press, New York, 1976. 567 pp.
17. *Läänelaid, A., Palmik, M., Uibo, V.* Growth of spruces and pines on subsided area of oil shale mine // XXIX Estonian Naturalists' Congress. Nature of Oil Shale Region. / Puura, I., Pihu, S. (eds.). – Tartu, 2006. P. 57–67 [in Estonian].

18. *Alestalo, J.* Dendrochronological interpretation of geomorphic processes // Fennia. 1971. Vol. 105. 140 pp.
19. *Krapiec, M., Margielewski, W.* Use of dendrogeomorphological analysis in age determination of surface mass movements // Zeszyty Naukowe AGH, Geologia. 1991. Vol. 17, No. 1–2. P. 67–81.
20. *Heikkinen, O.* Using dendrochronology for the dating of land surfaces. // Dating in exposed and surface contexts / Beck, C. (ed.). – University of New Mexico Press, Albuquerque, 1994. P. 213–235.
21. *Bräuning, A.* Zur Anwendung der Dendrochronologie in den Geowissenschaften // Die Erde. 1995. Vol. 126. P. 189–204 [in German].
22. *Gärtner, H.* Dendrogeomorphology // Glacial landforms, tree rings. / Elias, S. A. (ed.). Encyclopedia of Quaternary Sciences, Vol. 2. Elsevier, The Netherlands. 2007. P. 979–988.
23. *Läänelaid, A., Eckstein, D.* Development of a tree-ring chronology of Scots pine (*Pinus sylvestris* L.) for Estonia as a dating tool and climatic proxy // Baltic Forestry. 2003. Vol. 9, No. 2. P. 76–82.
24. *Vitas, A.* Tree rings of Norway spruce (*Picea abies* (L.) Karsten) in Lithuania as drought indicators: dendrochronological approach // Polish J. Ecol. 2004. Vol. 52, No. 2. P. 201–210.
25. *Wardrop, A. B., Dadswell, H. E.* The nature of reaction wood. III: Cell division and cell wall formation in conifer stems // Aust. J. Sci. Res. 1952. Vol. 5. P. 382–398.
26. *Westing, A. H.* Formation and function of compression wood in gymnosperms // Bot. Rev. 1965. Vol. 31. P. 381–480.
27. *Timell, T. E.* Origin and evolution of compression wood // Holzforschung, 1983. Vol. 37. P. 1–10.
28. *Zobel, B. J., van Buijtenen, J. P.* Wood variation. Its causes and control. – Springer Series in Wood Science, Springer Verl., Berlin, New York, Tokyo, 1989. 363 pp.
29. *Panshin, A. J., de Zeeuw, C.* Textbook of Wood Technology. 3rd edition. – McGraw-Hill Book Company, New York, London, Sydney, 1970. 705 pp.
30. *Timell, T. E.* Compression Wood in Gymnosperms. Vol. 1. – Springer Verl., Berlin, New York, Tokyo, 1986. 706 pp.
31. *Haller, B.* Investigations on eccentric radial increment of conifers // Mitteilungen der Forstwissenschaftlichen Abteilung der Universität Tartu No. 24. 1935. Tartu. 162 pp. + Tables [in Estonian].
32. *Soovik, E.* Inventure of 13 grounds on Kohtla and Ahtme mines for assessment of the effect of underground mining. – 2003. 10 pp. (unpubl. manuscript in AS Kohtla Kaevandus) [in Estonian].
33. *Soovik, E.* The actual influence of mines // Eesti Loodus. 2004. No. 7. P. 39 [in Estonian].
34. *Rull, E., Liblik, V., Pensa, M.* Changes in the plant cover of deformed surface forest areas // Environment and oil shale mining in North-East Estonia. Publ. No. 9 / Liblik, V., Punning, J.-M. (eds.). Tallinn, 2005. P. 88–95 [in Estonian].
35. *Anonymous.* Assessment of underground mining of oil shale for the productivity of the agricultural land // Final report of the VI stage of contract No. 1027/EP. Estonian Research Institute of Agriculture, Saku, 2003. 17 pp. (unpubl. manuscript in AS Eesti Põlevkivi) [in Estonian].

Presented by E. Reinsalu
Received May 29, 2008