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Source / Izvornik: **Glasnik za šumske pokuse: Annales Experimentis Silvarum Culturae Provehendis, 2009, 43, 19 - 36**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

Permanent link / Trajna poveznica: https://urn.nsk.hr/urn:nbn:hr:108:105371

D. Ugarković, I. Tikvić, Z. Seletković, M. Oršanić, I. Seletković, N. Potočić: Dieback of silver fir (*Abies alba* Mill.) in Gorski kotar in correlation with precipitation and temperature. Glas. šum. pokuse, Vol. 43, 19 – 36, Zagreb, 2009–10.

\UDK: 630*181.22+181.31

Original scientific paper
Izvorni znanstveni članak

DIEBACK OF SILVER FIR (*Abies alba* MILL.) IN GORSKI KOTAR IN CORRELATION WITH PRECIPITATION AND TEMPERATURE

ODUMIRANJE STABALA OBIČNE JELE (Abies alba MILL.) U GORSKOM KOTARU U ODNOSU NA KOLIČINE OBORINA I TEMPERATURE ZRAKA

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Received – *prispjelo*: 27.1.2010. Accepted – *prihvaćeno*: 1.3.2010.

Abstract

Silver fir is the most widely distributed and the most important commercial conifer species in Croatia. However, it is also the most threatened. The first records of its dieback in Croatia date from the beginning of the 20th century. Dieback has since evolved into a worrying phenomenon and a significant forestry problem. Dieback of silver fir is attributed to different causes. The objective of this work is to present the dynamics and intensity of silver fir dieback and establish the correlation between tree dieback and climatic factors in the area of two management units in Gorski Kotar. The data collected from two management units in Gorski Kotar (management units Brloško and Ravna Gora) over a ten-year period relate to dead trees of silver fir across the entire management unit area. The management units of Brloško and Ravna Gora epitomize a typical area of fir forests in Croatia. Regression models were used to obtain data on temperature and precipitation quantity for each compartment /subcompartment. Linear correlation coefficients were applied to establish the correlation between dieback intensity and climatic factors. The dynamics of tree dieback was analyzed on the basis of tree number and volume. There was a statistically significant increase in air temperature values in relation to the normal series of 1961 – 1990 in the study area. Precipitation decrease was also present, but it was not statistically significant. Considerable dieback of fir trees was recorded on the edge of the distribution range and in stands with a disturbed selection structure. A strong correlation was also found between air temperature, precipitation and growing stock of silver fir and dieback intensity. The paper also discusses the already familiar causes of silver fir dieback.

Key words: silver fir, dieback, dieback intensity, temperature, precipitation

Sažetak

Obična jela je najrašireniji i gospodarski najznačajnija četinjača u Hrvatskoj, ali istodobno i najugroženija šumska vrsta drveća. Prvi zapisi o njenom odumiranju u Hrvatskoj datiraju s početka prošlog stoljeća. Od tog vremena pa do danas ono je više ili manje zabrinjavajuća pojava i značajan problem u šumarstvu. Pojava odumiranja obične jele pripisuje se različitim uzročnicima. Cilj rada je bio prikazati dinamiku i intenzitet odumiranja stabala obične jele, te utvrditi ovisnost odumiranja stabala o klimatskim čimbenicima, na području dviju gospodarskih jedinica u Gorskom kotaru. Na području Gorskog Kotara (gospodarske jedinice Brloško i Ravna Gora) prikupljeni su podaci o odumrlim stablima obične jele na razini cijele gospodarske jedinice za desetgodišnje razdoblje. Gospodarske jedinice Brloško i Ravna Gora predstavljaju tipično područje jelovih šuma u Hrvatskoj. Regresijskim modelima dobiveni su podaci o temperaturi i količini oborina sa svaki odsjel/odsjek. Linearnim korelacijskim koeficijentima utvrđena je poveznost između intenziteta odumiranja i klimatskih čimbenika. Dinamika odumiranja stabala je analizirana na temelju broja stabala i volumena. Na području istraživanja utvrđeno je statistički značajno povećanje vrijednosti temperatura zraka u odnosu na normalni niz 1961.-1990. Smanjenje oborina je prisutno, ali nije statistički značajno. Utvrđeno je značajno odumiranje jelovih stabala na rubu areala i u sastojinama narušene preborne strukture, kao i jaka korelacija vrijednosti temperatura zraka, oborina i

drvne zalihe obične jele sa intenzitetima odumiranja. U radu su raspravljeni već poznati uzroci odumiranja stabala obične jele.

Ključne riječi: Obična jela, odumiranje, inenzitet odumiranja, temperatura, oborine

INTRODUCTION
UVOD

Dieback of single trees in forest ecosystems of Croatia has assumed catastrophic features, especially in view of the fact that this phenomenon primarily affects Croatia's principal tree species. Participating in the growing stock of Croatian forests with 9.4%, silver fir is the most threatened forest tree species in this country (Meštrović, 2001).

Silver fir dieback has been recorded in the whole of Europe, but in spite of numerous hypotheses related to this problem, differences in factors such as soil, climate and degree of air pollution make it difficult to establish the main causes (Krause et al., 1986).

The phenomenon termed "forest dieback" was confirmed in the Dinaric range of Croatia around 1954. This problem was first noted in fir and beech stands in the area of Fužine forest office (Glavač et al., 1986). Five-year research into the causes of fir dieback in Lika and Gorski Kotar was launched in 1968. Silver fir dieback is very important from a silvicultural aspect due to the consequences it produces, such as the absence of natural regeneration and disturbances in the management with forests (Malek, 1981; Korpel, 1985; Andrzejczyk et al., 1987; Matić et al., 2001). Fir forests are currently also characterized by a disturbed and unstable selection structure, which is responsible for a number of changes. These changes include very poor or completely absent natural regeneration of silver fir, a decrease in the growing stock in relation to the normal one, physiological weakening and decline of dominant trees, changes in the stand's microclimate, degraded forest soils caused by excessive weeds and erosion, reduced microbiological activity of the soil, the increasingly frequent onset of secondary pests that accelerate the process of tree dieback, and the aggressive expansion of common beech throughout the former sites of silver fir. According to Matić (1996), such a condition can be attributed to three groups of causes. The first group refers to inappropriate silvicultural treatments, the second to the occurrence of longer dry periods on the global and local level, and the third to the effects of acid rains and pollutants which reflect unfavourably on the air, water, soil and organisms. As shown by research of Glavač et al. (1986), beech and beech-fir forests in the Dinaric range of north-western Croatia are severely affected by remote air pollution. The authors confirmed a coincidence between the sites affected by air pollution and the sites of fir dieback. The negative effect of chemical substances in the atmosphere is progressively increasing, as confirmed by global climate changes every year (Schlaepfer, 1993; Mindaš et al., 2000). According to Prpić (1975), climate changes form the basic predisposition for the occurrence of silver fir dieback. Among these changes, warming and decreased humidity in the sites of fir forests are the most distinctive. In the view of the same author, the incidence of silver fir dieback is much lower in the optimum of the distribution range and much higher on the boundary of the distribution range towards warmer regions. Changes in the nutritional and physiological status, brought about by insufficient precipitation, are considered the main cause of decline and dieback of Spanish fir in the Pyrenees (Fromard et al., 1991).Dry periods as stress factors are one of the main reasons for dieback, increased damage and declining health of forest ecosystems of silver fir in Europe (UN-ECE and EC, 2003). Dry periods, especially in soils poor in calcium, have a negative effect on the Ca status and vitality of silver fir trees (Potočić et al., 2005).

According to Oszlànyi (1997), drought, climate change, and abrupt and sudden temperature oscillations are stress factors that result in the damage of forest ecosystems, the decline of the tree's assimilation apparatus and the subsequent degradation of the entire ecosystem.

Seletković et al. (1993) analyzed meteorological data collected from the Meteorological Station Zagreb – Grič to detect changes in temperature and precipitation regimes over the last 100 years. According to Matić et al. (1998), climate change is responsible for dieback of several tree species and of silver fir in particular, for the formation of stands with varying tree species ratios in the tree species composition, and even for the occurrence of other tree species. In commercial forests the intensity of tree dieback, as well as the health status of a stand, is illustrated by the volume of dead trees, or the volume of trees removed by salvage cuts (Capecki, 1981). Dieback intensity can also be expressed as the mortality percentage calculated as the ratio between the number of dead trees and the number of living trees (Busing et al., 1994; Markalas, 1992, Stanovsky, 2002; Tikvić et al., 2004; Turčani et al., 2003), or it can be expressed in absolute values in m^3 or m^3/ha (Siwecki et al., 1988). The objective of this work was to determine trends in macro-climatic elements (air temperature and precipitation quantity) and their deviations from the normal series 1961 – 1990 (according to WMO, 2001), and establish their correlation with the condition and trends in silver tree dieback in the study area.

RESEARCH FIELD, MATERIAL AND WORKING METHODS
PODRUČJE ISTRAŽIVANJA, MATERIJALI I METODA RADA

Field research conducted in the distribution range of beech-fir forests in Gorski Kotar encompassed the area of the management units of Brloško, Fužine Forest Office, and Ravna Gora, Ravna Gora Forest Office, part of Delnice Forest Administration (Figure 1). The climate in the study area is temperate warm rainy climate, with the mean annual air temperature ranging between 6.3 and 7.7 °C and the mean annual precipitation quantity ranging from 1,600 mm in the eastern part to 4,000 mm in the western part of Gorski Kotar (Lividraga) over the past three decades (Seletković, 2001). The parent material of the management units, according to the data from the management plans, is composed of limestones and dolomites of varying ages. The dominant soils are melanosol, brown and illimerized soil, rendzinas, dystric brown soil and brunipodzol. The relief is highly indented and irregular, being intersected by elevations, ditches, valleys and ridges. The management unit of Brloško is at an altitude between 720 and 1,090 m, and the management unit of Ravna Gora is at an altitude between 719 and 1,346 m.

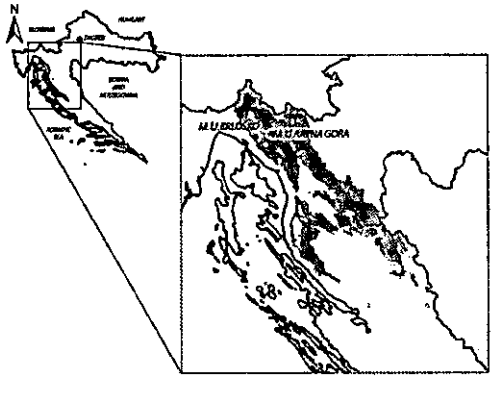


Figure 1 Position of the studied management units in the distribution range of silver fir (*Abies alba* Mill.) in Croatia.
Slika 1 Položaj istraživanih gospodarskih jedinica u arealu obične jele (Abies alba Mill.) u Hrvatskoj.

The management unit of Brloško is situated on the edge of the silver fir range towards the sea. The selection structure has been disturbed by tree dieback. The growing stock is predominantly accumulated on old trees above 50 cm dbh. The average growing stock in the management unit amounts to 276 m^3/ha, and the maximal growing stock reaches the amount of 726 m^3/ha. In terms of the percentage share of salvage cuts of silver fir trees in the total prescribed cut, the condition of silver fir trees is worse compared to the trees in the management unit of Ravna Gora (Management plans for management units of Brloško and Ravna Gora).

The management unit of Ravna Gora is situated in the interior of Gorski Kotar. The trees are in very good condition, and the stands contain the optimal growing stock. The average growing stock amounts to 163 m^3/ha and the maximal one to 380 m^3/ha.

The analysis of climate and climatic features in the research area was based on data on air temperatures and precipitation quantities collected from representative meteorological stations over a prolonged monitoring period (Table 1).

Table 1 List of meteorological stations with monitoring periods in the study area
Tablica 1 Popis meteoroloških postaja na području istraživanja sa razdobljem motrenja

Meteorological station *Meteorološka postaja*	Type of met. Station *Tip meteorološke postaje*	Altitude *Nadmorska visina*	Monitoring period *Razdoblje motrenja*
Vrelo Ličanke	Standard met. station	750	1975 - 2004
Lokve Brana	Standard met. station	774	1961 - 2004
Ravna Gora	Subordinate met. station	793	1961 - 2004

Linear trends of annual air temperatures and precipitation quantities were calculated (simple regression) and differences in annual values were tested with the Student's t-test using the data obtained from the mentioned meteorological stations and monitoring periods.

Mean annual air temperatures and mean annual precipitation quantities for the period 1995 – 2004 were tested with the T-test of independent samples and compared with mean annual values of the normal reference series 1961 ('75) – 1990. Dry years were determined using the normal series percentage method and the percentile method.

Data on the number and wood volume of dead silver firs by compartment and subcompartment in each management unit were obtained on the basis of annual assessment of the forest's health condition. The data refer to the ten-year period (1995 – 2004) and to the compartments and subcompartments in which tree dieback occurred over the monitored period.

The average rate of dieback change at the level of the whole management unit for the ten-year period was calculated using the chain index and the following formula:

$$DC = ((dead_{year+1}/dead_{year-1})*100) - 100$$

The mortality rate of silver fir is presented in absolute values (m^3 and m^3/ha).

Since the referent meteorological stations are situated at lower altitudes than those of the monitored compartments and subcompartments, regression models were used to obtain theoretical changes in mean annual air temperatures (°C) and mean annual precipitation quantities (mm) in correlation with altitude (Zaninović et al., 2004; Gajić-Čapka et al., 2003). Temperatures and rainfall were calculated for each monitored compartment /subcompartment.

A correlation analysis was used to establish the correlation between silver fir dieback and climatic, structural and relief factors.

Multiple regression was used to test the dependence of tree dieback on climatic, structural and relief factors. All the data were processed in the Statistica 6.0 and Klimasoft 2.0 programmes.

RESEARCH RESULTS AND DISCUSSION
REZULTATI ISTRAŽIVANJA I RASPRAVA

Changes in climatic features
Promjene klimatskih obilježja

Of all the climatic elements, air temperature and precipitation quantity are the ones most firmly linked to silver fir dieback. It is for this reason that we investigated their changes for as long a monitoring period as possible.

Linear trends in mean annual air temperatures (Table 2) have a positive prefix, which means that the temperature in the study area is rising. A trend in temperature increase is statistically significant, except for vegetation temperatures in the area of Lokve Brana Meteorological Station.

Table 2 Linear trends in annual and vegetational air temperatures and their significance.
Tablica 2 Linerani trendovi godišnjih i vegetacijskih temperatura zraka i njihova signifikantnost.

Met. Station *Meteorološka postaja*	Mean annual air temperatures (°C) *Prosječna godišnja temperatura zraka* (°C)		
	Linear trend	t	p
Vrelo Ličanke	y = 0,0643x + 6,3028	t (28) = 5,3869	0,0000*
Lokve Brana	y = 0,0164x + 6,7921	t (42) = 2,2895	0,0271*
Met. Station *Meteorološka postaja*	Mean annual vegetational air temperatures (°C) *Prosječna god. vegetacijska temp. zraka* (°C)		
Vrelo Ličanke	y=0,0779x + 11,3170	t (28) = 5,8804	0,0000*
Lokve Brana	y = 0,0158x + 12,277	t (42) = 1,9023	0,064

*significant at the level of 95 %

Air temperatures in the area of Vrelo Ličanke Meteorological Station on the edge of the distribution range, which contains the management unit of Brloško, increased more than air temperatures in the area of Ravna Gora Meteorological Station in the interior of Gorski Kotar, housing the management unit of "Ravna Gora".

According to the t-test results for mean annual air temperatures for the period 1995-2004 in relation to the referent series, a statistically significant increase in mean annual air temperatures of 1.1 °C and mean vegetation air temperatures of 1.2 °C was recorded in the area of Vrelo Ličanke Meteorological Station. These changes are also statistically significant for the interior of Gorski Kotar, but much less so than those on the edge of the distribution range. Thus, mean annual air temperatures increased by 0.48 °C in the area of the meteorological station Lokve Brana, and mean vegetational ones by 0.54 °C (Table 3). In their study of silver fir dieback in Northern Velebit, Tikvić et al. (2008) found that mean vegetational air temperatures rose by 1.1 °C and 0.7 °C in the area of Gospić and Zavižan Meteorological Stations, and that vegetational precipitation quantities dropped by 24.6 mm (Gospić) and 83.3 mm (Zavižan).

Table 3 Results of the Student's t-test of comparisom of annual and vegetational air temperatures for the period 1995 – 2004 with the referent series for Vrelo Ličanke and Lokve Meteorological Stations.
Tablica 3 Rezultati Studentovog t-testa usporedbe godišnjih i vegetacijskih temperature zraka razdoblja 1995. – 2004. sa referentnim nizom za meteorološke postaje Vrelo Ličanke i Lokve.

Station *Postaja*	Temperature *Temperatura*	Period *Razdoblje*	Mean *Aritm. sred.*	t-value	df	p
Vrelo ličanke	Annual *Godišnja*	1975 – 1990	6,82	-4,595	24	0,000*
		1995 – 2004	7,92			
	Vegetational *Vegetacijska*	1975 – 1990	11,96	-4,123	24	0,000*
		1995 – 2004	13,19			
Lokve	Annual *Godišnja*	1961 – 1990	7,02	-2,205	38	0,033*
		1995 – 2004	7,5			
	Vegetational *Vegetacijska*	1961 – 1990	12,46	-2,095	38	0,042*
		1995 – 2004	13			

* significant at the level of 95%

An increase in the mean annual and vegetational air temperature and the onset of climatic excesses important for the present climate change may cause stress conditions in tree species of narrow ecological valence, such as the silver fir. This refers primarily to direct ecological factors (warmth and water).

In addition to air temperature, which depends on cloudiness and air insolation, rainfall also has the greatest importance for the growth of vegetation, since it is one of the main sources of moisture in the soil and as such decisive for the supply of water to vegetation. The lack of precipitation, coupled with high air temperatures, weakens the resistance of silver fir to adverse factors. Changes in air temperatures also reflect on precipitation conditions (Kirigin 1975), which results in unfavourable conditions for the growth and development of forest vegetation.

Table 4 Linear trends in annual and vegetational precipitation quantities and their significance.
Tablica 4 Linerani trendovi godišnjih i vegetacijskih količina oborina i njihova signifikantnost.

Met. Station *Meteorološka postaja*	Annual precipitation quantities (mm) *Prosječna god. količina oborina* (mm)		
	Linear trend	t	p
Vrelo Ličanke	y= -14,145x + 2813,2	t (28) = -1,8595	0,0734
Ravna Gora	y= -2,53x+ 1977,5	t (42) = -0,8044	0,425
Met. Station *Meteorološka postaja*	Vegetational precipitation quantities (mm) *Vegetacijska količina oborina* (mm)		
Vrelo Ličanke	y= -6,1085x + 1093,9	t (28) = -1,1817	0,2472
Ravna Gora	y= -1,83x + 952,7	t (42) = -0,7608	0,451

* significant at the level of 95%

Linear equations of trends in precipitation quantities have a negative prefix, which means that the quantity of precipitation in the study area is decreasing. Linear trends are not statistically significant.

A decrease in precipitation quantities in the area of Vrelo Ličanke Meteorological Station on the edge of the distribution range is bigger than in the area of Ravna Gora Meteorological Station in the interior of Gorski Kotar.

Apart from an abrupt decrease in precipitation quantities, which has an adverse effect on the physiological tree functions, there is also an increase in air temperatures. This is particularly conducive to the development and spread of harmful insects, which inflict further stresses and damage the trees (Androić, 1969).

An increase in mean annual and vegetation air temperatures and the occurrence of climatic excesses important for the current climate change may cause stress conditions in tree species of narrow ecological valence, such as the silver fir. This refers particularly to direct ecological factors (warmth and water). Air temperature and soil moisture are limiting factors for the distribution of the majority of European forest tree species (Berninger, 1997).

Table 5 Results of Student's t-test comparing annual and vegetational precipitation quantities in the period 1995 – 2004 with the referent series for Vrelo Ličanke and Ravna Gora Meteorological Stations.
Tablica 5 Rezultati Studentovog t-testa usporedbe godišnjih i vegetacijskih količina oborina razdoblja 1995 – 2004 sa referentnim nizom za meteorološke postaje Vrelo Ličanke i Ravna Gora.

Station *Postaja*	Precipitation *Količina oborina*	Period *Razdoblje*	Mean *Aritm. sred.*	t-value	df	p
Vrelo ličanke	Annual *Godišnja*	1975 – 1990	2639,13	0,282	23	0,779
		1995 – 2004	2592,06			
	Vegetational *Vegetacijska*	1975 – 1990	1023,99	0,253	24	0,801
		1995 – 2004	997,35			
Ravna Gora	Annual *Godišnja*	1961 – 1990	1915,65	-0,662	38	0,511
		1995 – 2004	1982,88			
	Vegetational *Vegetacijska*	1961 – 1990	923,34	-0,087	38	0,93
		1995 – 2004	929,82			

A decrease in the quantity of precipitation on the edge of the distribution range of silver fir forests differs from that in the interior of the range. For the meteorological station Vrelo Ličanke, a decrease in annual precipitation quantities for the period 1995 – 2004 in relation to the "normal series" is 47 mm, and in vegetational ones it is 27 mm. For the meteorological station Ravna Gora, annual precipitation quantities decreased by 47 mm, whereas vegetational quantities decreased by only 6.50 mm. This decrease in precipitation quantities and in linear trends is not statistically significant (Table 5).

Tree dieback
Odumiranje stabala

Silver fir dieback in the management unit of Brloško for the period 1995 – 2004 is given in Figure 2. The lowest dieback intensity was recorded in 1998, when 3,852 m³ died, and the highest in 1995, when 14,020 m³ died.

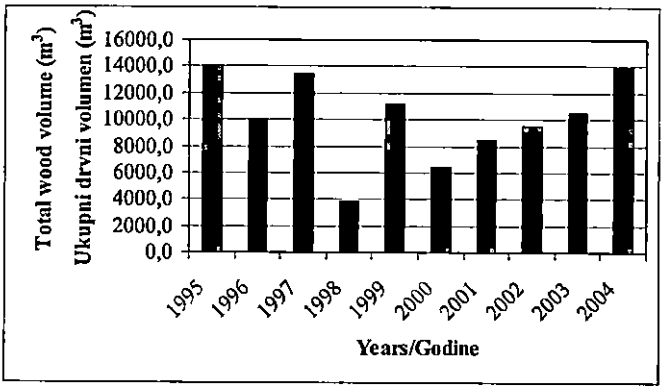


Figure 2 Total wood volume of dead silver fir trees in the management unit of Brloško from 1995 to 2004.
Slika 2 Ukupni drvni volumen odumrlih stabala obične jele u gospodarskoj jedinici Brloško od 1995. do 2004. godine.

According to the results presented in Figure 3, the lowest quantity of dead trees in the management unit of Ravna Gora for the period 1995 – 2004 was recorded in the year 2000. The quantity amounted to 425.9 m³. The highest number of dead trees was recorded in 1996 and amounted to 3,340.8 m³.

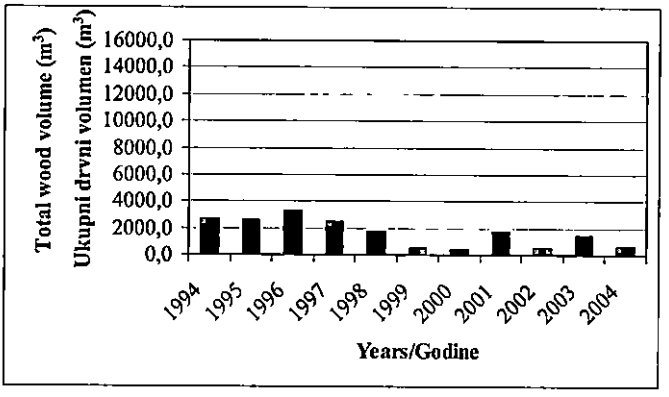


Figure 3 Total wood volume of dead silver fir trees in the management unit of Ravna Gora from 1995 to 2004.
Slika 3 Ukupni drvni volumen odumrlih stabala obične jele u gospodarskoj jedinici Ravna Gora od 1995. do 2004. godine.

In terms of mortality rate expressed as the volume of dead trees (m³) in Figures 2 and 3, significantly more severe silver fir dieback was recorded in the management unit of Brloško compared to that in the management unit of Ravna Gora.

Table 6 Rate of change by years and the average rate of change for the volume of dead trees (m^3) for the period 1995 – 2004.

Tablica 6 Stopa promjene po godinama i prosječna stopa promjene za volumen odumrlih stabala (m^3) za razdoblje 1995 – 2004. godine.

Management Unit *Gospodarska jedinica*		
Year *Godina*	Brloško %	Ravna Gora %
1995	0	0
1996	-28,85	28,96
1997	34,69	-25,13
1998	-71,33	-30,22
1999	188,57	-71,4
2000	-42,18	-14,68
2001	31,7	311,47
2002	11,9	-67,92
2003	11,46	150,8
2004	31,71	-55,5
$\hat{S}$	-0,09	-13,65

$\hat{S}$ – Average rate of change (*prosječna stopa promjene*)

The average rate of change for the management unit of Brloško related to dead wood volume (m^3) is - 0.09%, which represents slightly lower dieback intensity from 1995 to 2004. The management unit of Ravna Gora experienced a decrease in the mortality rate of silver fir. From 1995 to 2004, the average rate of change for dead wood mass (m^3) amounts to -13.65% (Table 6).

In the period between 1995 and 2004, the years 2000, 2001 and 2003 were dry years in the area of Vrelo Ličanke Meteorological Station. For the meteorological station of Lokve, dry years were 1995, 2000, 2001 and 2003, while 2000 and 2001 were dry years for the meteorological station of Ravna Gora (source DHMZ – State Hydro-Meteorological Office).

According to the results of chain indices and the rate of change of dead tree volume presented in Table 6, stands in the management unit of Brloško react more strongly to dry years compared to stands in the management unit of Ravna Gora. In the management unit of Brloško, every dry year is followed by an increase in dead tree volume; however, this is not the case with the management unit of Ravna Gora.

According to archive records, the summer of 2003 was by far the warmest since the year 1500 (Luterbacher et al., 2004). In that year the rate of change in the volume of dead trees in the area of Brloško increased by 11.46%, while in 2004 it increased by 31.71%. The rate of change of dead tree volume in the area of Ravna Gora increased by no less than 150.80% in 2003, whereas in 2004 it decreased by -55.50%.

Table 7 Average annual dieback intensities (m^3/ha, N/ha) and increment of silver fir (*Abies alba* Mill.) in the compartments and subcompartments affected by tree dieback (Management plans for the management units of Brloško and Ravna Gora).
Tablica 7 Prosječni godišnji intenziteti odumiranja (m^3/ha, N/ha) i prirast obične jele (Abies alba Mill.) u odjelima i odsjecima u kojima se pojavilo odumiranje stabala (Programi gospodarenja gospodarskim jedinicama "Brloško" i "Ravna Gora").

Management Unit *Gospodarska jedinica*	Dieback Intensity *Intenzitet odumiranja*		Annual Increment *Godišnji prirast*
	m^3/ha	N/ha	(m^3/ha)
Brloško	48,04	14	8,25
Ravna Gora	4,71	2	4,24

Dieback intensities in the area of Brloško exceed the increment several times, which has resulted in decreased growing stock of silver fir in some stands affected by catastrophic tree dieback.

The stands in the area of Brloško have higher increment (m^3/ha) in relation to the stands in the area of Ravna Gora. This is due to the fact that the accumulation of the growing stock in Brloško is above the normal model and that there are more trees in the third diameter class above 50 cm $d_{1.30}$ cm.

Intensive dieback leads to the formation of bigger or smaller gaps in stands, as well as to broken canopies, especially in cases in which the amount of salvage cutting is above the prescribed annual yield. Intensive salvage cuts alter the age structure and tree species composition of particular tree species (Stanovsky, 2002).

According to research by Idžojtić et al. (2005), such compartments are very vulnerable to intense infestations with the parasite European mistletoe (*Viscum album* ssp. abietis), and the situation is likely to deteriorate. The mortality rate of firs coincides with the intensity of mistletoe infestation (*Viscum album* ssp. abietis). There is a correlation between damage in silver fir forests and the incidence of mistletoe (Hofstetter, 1988).

According to Turčâni et al. (2003), salvage cuts are more frequently applied and are of a statistically significantly larger scale in more "polluted" stands. Since the forests of silver fir in Gorski Kotar are permanently exposed to harmful impacts of polluted air and precipitation, silver fir dieback will continue to affect them despite constant applications of salvage cuts.

Table 8 Average annual dieback intensity (m^3/ha) and participation percentage per diameter class in the studied management stands.
Tablica 8 Prosječni godišnji intenzitet odumiranja (m^3/ha) i postotak zastupljenosti po debljinskim razredima na području istraživanih gospodarskih jedinica.

Diameter class *Debljinski razred*	Brloško		Ravna Gora	
(cm)	m^3/ha	%	m^3/ha	%
I (10 – 30)	0,87	2	0,21	4
II (30 – 50)	7,05	15	0,79	17
III (> 50)	40,12	83	3,72	79

The largest dead wood mass of silver fir (m^3/ha) is in the third diameter class. As a rule, this refers to older and physiologically weaker trees. The highest values of dead wood mass (m^3/ha) per diameter class (Table 8, Figure 4) were recorded in the management unit of Brloško.

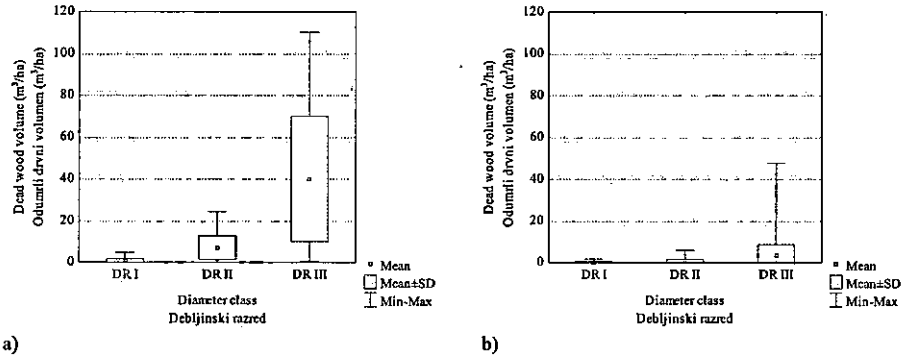


Figure 4 Dead wood volume of silver fir trees (m^3/ha) per diameter class, a) Brloško, b) Ravna Gora
Slika 4 Odumrli drvni volumen stabala obične jele (m^3/ha) prema debljinskim razredima a) Brloško, b) Ravna Gora

The participation percentage of salvage cuts or of dead wood mass of silver fir according to the prescribed annual yield in the management unit of Ravna Gora reaches up to 10%, whereas in the management unit of Brloško it reaches 100%. According to Oszlànyi (1997), a high percentage of salvage cuts (about 60% of the prescribed annual yield) is an indicator of disturbed ecological conditions and deteriorated health of forest ecosystems.

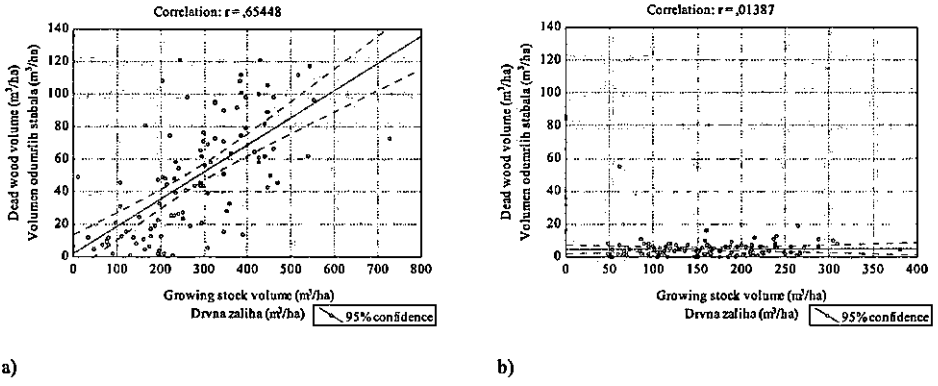


Figure 5. Statistical analysis of growing stock volume and dead wood volume (m^3/ha), a) management unit of Brloško, b) management unit of Ravna Gora.
Slika 5. Statistička analiza volumena drvne zalihe i volumena odumrlih stabala (m^3/ha) obične jele a) g.j. "Brloško" i b)"Ravna Gora".

A strong, positive and statistically significant correlation (r=0.65*) between the volume of dead silver fir trees (m^3/ha) and the growing stock of silver fir trees was found in the area of Brloško. The value of silver fir growing stock in the area of Brloško amounts to 726 m^3/ha, which is twice as much as the normal model for selection forests. The stands in Brloško have an unstable and disturbed selection structure, which Matić (1996) considers the reason for numerous changes.

These changes include, among other things, the absence of natural regeneration, an increase in the growing stock in relation to the normal one, ageing and physiological weakening, and the death of dominant trees. In contrast to Brloško, there is no correlation between the dead wood mass of silver fir (m^3/ha) and the growing stock of silver fir (m^3/ha) in the management unit of Ravna Gora. The growing stock of silver fir assumes values of up to 400 m^3/ha, which corresponds to the prescribed normal model for selection stands in this area (Figure 5).

A strong, positive and statistically significant correlation was established between dead wood mass (m^3/ha) and the stand's growing stock, mean annual temperatures and vegetation air temperatures (°C). A strong, negative and statistically significant correlation was established between dead wood mass of silver fir (m^3/ha) and annual and vegetation quantities of precipitation (mm) (Table 9).

Table 9 Linear correlation coefficient of silver fir mortality rate and climatic elements for the management unit Brloško. *Tablica 9 Linerani korelacijski koeficijent intenziteta odumrlih stabala obične jele i klimatskih elemenata za gospodarsku jedinicu Brloško.*

	m^3/ha	m^3	Annual temp. *God. temp.*	Veg. temp. *Veg. temp.*	Annual prec. *God. oborina*	Veg. prec. *Veg. oborina*
m^3/ha	1					
m^3	0,75*	1				
Annual temp. *God. temp.*	0,55*	0,32*	1			
Veg. temp. *Veg. temp.*	0,55*	0,32*	1,0*	1		
Annual prec. *God. oborina*	-0,55*	-0,32*	1,0*	-1,0*	1	
Veg. prec. *Veg. oborina*	-0,55*	-0,32*	-1,0*	-1,0*	1,0*	1

* significant at the level of 95%

With increased mean annual and vegetational air temperatures and decreased annual and vegetational precipitation quantities, the quantity of dead wood volume of silver fir trees increases statistically significantly. These results correspond to the results of other authors (Markalas, 1992; Thomas et al., 2002; Tikvić et al., 2008).

The compartments/subcompartments in Brloško manifest an accumulation of the growing stock and a disturbed selection structure (Figure 4a). Such stands are non-resistible to climate change and oscillations of macroclimatic elements.

According to research by Usčupulić et al. (2007), climate was the main factor in the process of tree dieback in forests of Bosnia and Herzegovina. Long-lasting droughts stretching over several years had an adverse effect on plant vitality and their resistance to biotic pests (mistletoe, fungi and insects), and favoured an excessive proliferation of bark beetles beyond their population threshold.

Multiple regression results presented in Table 10 for the area of Brloško show that the growing stock (m^3/ha) and the quantity of precipitation in the vegetation period (mm) have a statistically significant effect on the volume of dead trees (m^3/ha). The growing stock Increased above the normal model and lower precipitation quantities as independent variables explain the dependent variable, i.e. the volume of dead silver fir trees (m^3/ha) with 47%.

Table 10 Multiple regression (forward stepwise) for mortality rate of silver fir trees (m^3/ha) in the management unit of Brloško.
Tablica 10 Multipla regresija (forward stepwise) za intenzitet odumrlih stabala obične jele (m^3/ha) na području gospodarske jedinice Brloško.

Regression Summary for Dependent Variable: dead m^3/ha R= ,69362600 R^2= ,48111703 Adjusted R^2= ,47084212 F(2,101)=46,824 p						
	Beta	Std.Err.	B	Std.Err.	t(101)	p-level
Intercept *Intercept*			133,784	41,50538	3,22329	0,001707*
Growing stock m^3/ha *Drvna zaliha m^3/ha*	0,502235	0,085987	0,1283	0,02197	5,84082	0,000000*
Veg. prec. *Veg. oborina*	-0,275596	0,085987	-0,1083	0,0338	-3,20509	0,001808*

*significant at the level of 95%

In 1988, the forest range of Greek fir (*Abies cephalonica* L.) in Greece received only 60% of annual precipitation amounts, and 26% of annual precipitation in the vegetation period compared to the referent series of 1961 – 1987. Drought affecting Greece in 1988 caused physiological weakening of Greek fir and a gradation of secondary pests, which all resulted in catastrophic tree dieback in 1989 across Greece. The volume of dead trees was 2.2 times higher than the annual volume increment (Markalas, 1992). Markalas (1992) also recorded a significantly higher mortality rate of Greek fir in larger diameter classes, especially in those over 72 cm dbh.

As shown by the data in Table 11, no statistically significant correlations were established between dead wood mass and climatic elements in the management unit of Ravna Gora. Only between dead wood mass of silver fir and growing stock of silver fir was the correlation found to be positive, strong and statistically significant. The compartments / subcompartments in the management unit of Ravna Gora have the optimal growing stock and selection structure. As such, the stands are healthy and resistant to negative oscillations of macro-climatic elements.

Table 11 Linear correlation coefficient of mortality rates in silver fir and climatic elements for the management unit of Ravna Gora.
Tablica 11 Linerani korelacijski koeficijent intenziteta odumrlih stabala obične jele i klimatskih elemenata za gospodarsku jedinicu Ravna Gora.

	m^3/ha	m^3	Annual temp. *God. temp.*	Veg. temp. *Veg. temp.*	Annual prec. *God. oborina*	Veg. prec. *Veg. oborina*
m^3/ha	1					
m^3	0,54*	1				
Annual temp. *God. temp.*	0,02	0	1			
Veg. temp. *Veg. temp.*	0,02	0	1,0*	1		
Annual prec. *God. oborina*	-0,02	0	-1,0*	-1,0*	1	
Veg. prec. *Veg. oborina*	-0,02	0	-1,0*	-1,0*	1,0*	1

* significant at the level of 95%

The climate in the area of Ravna Gora does not have any significant effects on the volume of dead trees. As stated in the results of multiple regression, the volume of dead trees (m^3/ha) is statistically significantly affected by the inclination and the stands' growing stock (m^3/ha).

An increase in terrain slope and stands' growing stock above the normal model as an independent variable in the area of Ravna Gora explain the volume of dead trees by 6% (Table 12).

Table 12 Multiple regression (forward stepwise) for mortality rate (m^3/ha) in the management unit of Ravna Gora.
Tablica 12 Multipla regresija (forward stepwise) za intenziteta odumrlih stabala (m^3/ha) na području gospodarske jedinice Ravna Gora.

Regression Summary for Dependent Variable: odumrlo m^3/ha, R= ,28947615 R^2= ,08379644 Adjusted R^2= ,06758045 F(2,113)=5,1675 p						
	Beta	Std.Err.	B	Std.Err.	t(113)	p-level
Intercept *Intercept*			-1,88322	2,398404	-0,785195	0,433982
IncL *Nagib*	0,301004	0,093738	0,33155	0,10325	3,211121	0,001722*
Growing stock m^3/ha *Drvna zaliha m^3/ha*	0,097537	0,093738	0,00812	0,007801	1,040532	0,300314

* significant at the level of 95%

Stanovsky (2002) studied the influence of climatic factors on the health condition of forest ecosystems in the Czech Republic. Over the monitored ten-year period (1991 – 2000), the mortality rate trend coincided with the length of dry periods. Using a cross-correlation function he found statistically significant dependence between the length of the dry period (days) and the volume of dead trees. According to this author, the cause of catastrophic decline of lowland forest ecosystems in the Czech Republic lies in low amounts of precipitation in the vegetation period and secondary pest gradation. Despite climate changes or oscillation, the biggest problem in selection forests of beech and fir in Croatia is the irregular selection structure and excessive growing stock in relation to normal one. In some areas this leads to intensive silver fir dieback, as confirmed by the example of the management unit of Brloško. Matić et al. (1996) arrive at similar results and conclude that the biggest problem of selection forests of fir and beech in Croatia is their irregular selection structure. The authors believe that selection structure is the basic prerequisite for good-quality functioning of selection forests of fir and beech.

Fir dieback is caused by a combination of several factors, of which one can be dominant in one area, while some other can dominate in another area (Šafar, 1965; Prpić et al., 2001).

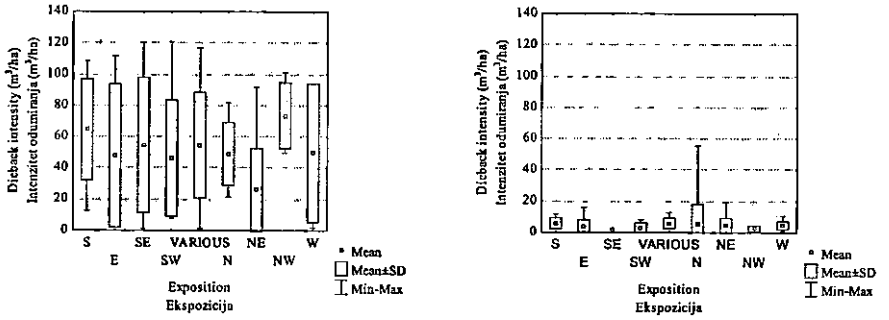
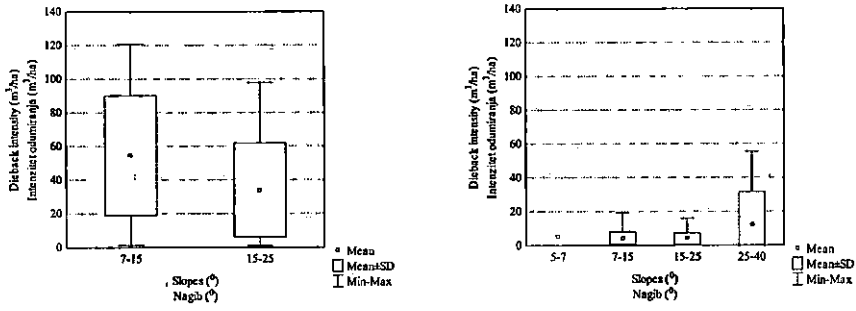


Figure 6 Dieback intensity of silver fir trees according to exposition classes a) Brloško, b) Ravna Gora.
Slika 6 Intenziteti odumiranja stabala obične jele prema klasama ekspozicije a) Brloško, b) Ravna Gora.

The lowest mortality rate in the area of Brloško was recorded on northern slopes, while the highest was noted in the subcompartments in north-westerly, southerly and westerly expositions. With regard to rising trends in mean annual and vegetation air temperatures, southerly and westerly expositions are becoming increasingly unfavourable for tree species with narrow ecological valence, such as the silver fir (*Abies alba* Mill.)

The lowest mortality rate of silver fir in the area of Ravna Gora was found in northerly and south-easterly expositions, while the highest was found in the subcompartments in different expositions.

Research undertaken by Tikvić et al. (2008) into silver fir dieback in Northern Velebit revealed the lowest volume of dead trees in northerly expositions and the highest in different variants of southerly expositions, as well as in subcompartments at different expositions.

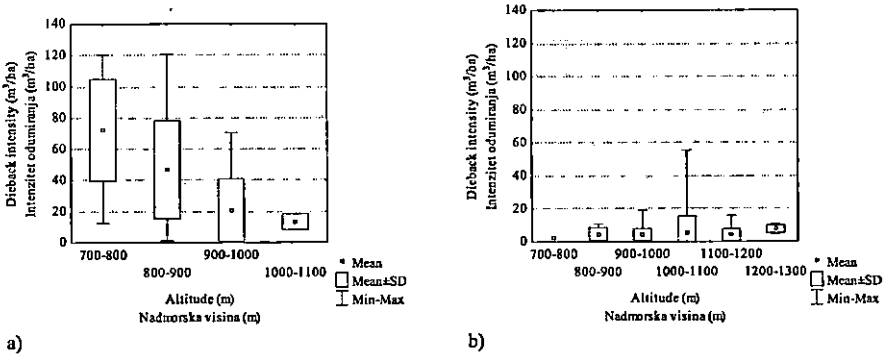


a) b)

Figure 7 Dieback intensity of silver fir trees according to classes of terrain slope a) Brloško, b) Ravna Gora.
Slika 7 Intenzitet odumiranja stabala obične jele prema klasama nagiba terena a) Brloško, b) Ravna Gora.

The highest values of dead tree volume in the management unit of Brloško were found at lowest altitudes and milder slopes (Figure 7 and Figure 8).

The most severe dieback in the management unit of Ravna Gora occurs on very steep slopes, whereas on other slopes dieback of silver fir trees is more or less even (Figure 7).



a) b)

Figure 8 Dieback intensity of silver fir trees according to altitude classes a) Brloško, b)Ravna Gora.
Slika 8 Intenzitet odumiranja stabala obične jele prema klasama nadmorske visine a) Brloško, b) Ravna Gora.

The highest mortality rate in the management unit of Ravna Gora occurred beyond 1,200 m above the sea and the lowest between 700 and 800 m above the sea (Figure 8). According to

the multiple regression results in this research (Tables 10 and 12), an increase in the stand growing stock is proportionately related to the increase in the dieback index of silver fir trees. Stands with larger growing stock were found at lower altitudes. They manifested a higher index of silver fir dieback compared to higher altitudes. The largest mortality rate values (m^3 and m^3/ha) were confirmed at lowest altitudes and milder slopes. The same results were also obtained by Tikvić et al. (2008) and Ugarković (2009). Interestingly, meteorological stations at lower altitudes recorded bigger climate changes and a larger number of dry years than those at higher altitudes (Tikvić et al. 2008). The management unit of Brloško is situated on the boundary of silver fir distribution range in Gorski Kotar. This in itself places it into a climatically adverse area for the development of these forest ecosystems.

CONCLUSIONS
ZAKLJUČCI

In relation to the referent series, mean annual air temperatures in the area of Vrelo Ličanke and Lokve Meteorological Stations rose by 0.5 to 1.1 °C in the period 1995 to 2004, while vegetational temperatures rose by 0.6 to 1.2 °C. This increase in air temperatures is not statistically significant. Lower annual precipitation quantities of 47 mm and vegetational quantites of 27 mm were recorded in relation to the referent series. Decreased precipitation quantities are not statistically significant.

The average rate of change in dieback intensity (m^3) is mildly falling and amounts to -0.09 % in the area of Brloško MU, while in the area of Ravna Gora MU it amounts to -13.65 %.

The highest mortality rate of silver fir was recorded in the management unit of Brloško, with the average annual mortality rate reaching 48 m^3/ha or 14 trees per ha. The average annual mortality rate in the management unit of Ravna Gora is 5 m^3/ha or 2 trees per ha.

Dieback intensities calculated for the stands affected by dieback in the area of Brloško MU were on average six times higher than stand increments. Dieback intensities were slightly higher than stand increments in the management unit of Ravna Gora.

The highest percentage of dead trees, as well as the average value of dead trees (m^3/ha) is in diameter class III.

The correlation between dead volume of silver fir (m^3/ha) and annual and vegetational air temperatures is positive, strong and statistically significant, while that between dead wood mass and annual and vegetational precipitation quantities is negative.

No correlation was found between the volume of dead silver firs and climatic elements in the area of the management unit Ravna Gora.

The correlation between the volume of dead silver firs and the stands' growing stock is strong, positive, and statistically significant in the area of Brloško, whereas in the area of Ravna Gora it does not exist.

Dead silver fir trees were found in all expositions, as well as in all classes of altitude and terrain slope.

In the area of Brloško the lowest rate of tree dieback was recorded in northerly, and the highest in north-westerly, southerly and westerly expositions. In the area of Ravna Gora, the lowest rate of tree dieback was also recorded in northerly expositions, while the highest was found in subcompartments at different expositions.

In Brloško, the highest rate of tree dieback occurs on mildly sloping terrains, whereas in Ravna Gora it takes place on very steep slopes.

In Brloško, the highest rate of tree dieback was recorded at lowest altitudes, but in Ravna Gora it was recorded at highest altitudes.

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