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Farzam TAVANKAR, Rodolfo PICCHIO, Angela LO MONACO, Mehrdad NIKOOY, Rachele VENANZI, Amir Eslam BONYAD

WOUND HEALING RATE IN ORIENTAL BEECH TREES FOLLOWING LOGGING DAMAGE

Beech is the most important commercial species in the Caspian forests of Iran. Selective cutting and harvesting methods may adversely impact the quality of the residual trees, as the injuries make the trees prone to future disease, insect infestations or timber defects. Although attempts to better understand how wounds affect the residual trees have been made in many different contexts, there are still few investigations on uneven-aged forests. In this study the key objectives were to determine and model the healing rate for different wound parameters (width, length, and area of wound); to analyse the relationship between wound healing rate (WHR), tree diameter growth and tree height growth; to analyse the WHR in relation to wound position on the stem; and to analyse the relationship between WHR, width and area of wound in DBH classes and social classes, with the aim of enabling the prognosis of logging wounds.

Wounded beech trees were examined immediately after selective logging and after a 5-year period. The WHR was 31.2 ±7.7 cm^2 $year^{-1}$. The wound width healing rate (18.4 ±3.4 $mm{\cdot}year^{-1}$) was significantly higher than the wound length healing rate (4.5 ±1.6 $mm{\cdot}year^{-1}$). Only 12% of wounds were completely closed after a 5-year period, and 15 years are necessary for the complete closure of 80% of total wounds. The ratio of wound area to stem area at wound height (RWS) showed a more pronounced effect on diameter than on height. Regression analysis showed that WHR was correlated negatively with wound area and width and positively with tree diameter growth, but no significant relationship was found between height growth and WHR parameters. The WHR was significantly higher

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Farzam TAVANKAR (*farzam.iaukh@gmail.com; tavankar@aukh.ac.ir*), Department of Forestry, Khalkhal Branch, Islamic Azad University, Khalkhal, Iran; Rodolfo PICCHIO (*r.picchio@unitus.it*), Department of Agricultural and Forestry Sciences, Tuscia University, Viterbo, Italy; Angela LO MONACO✉ (*lomonaco@unitus.it*), Department of Agricultural and Forestry Sciences, Tuscia University, Viterbo, Italy; Mehrdad NIKOOY (*nikooy@guilan.ac.ir*), Faculty of Natural Resources, University of Guilan, Somehsara, Iran; Rachele VENANZI (*venanzi@unitus.it*), Department of Agricultural and Forestry Sciences, Tuscia University, Viterbo, Italy; Amir Eslam BONYAD (*bonyad@guilan.ac.ir*), Department of Forestry, Faculty of Natural Resources, University of Guilan, Somehsara, Iran

at an upper position than at a lower one, and statistical tests showed that the tree vertical layering classes had a significant effect on WHR. Finally, it was shown that WHRs in upper-storey trees are significantly higher than in the middle and lower storeys.

Keywords: *Fagus orientalis*, uneven-aged stand, single-tree selection, diameter growth, height growth, tree biosocial class

Introduction

Beech is the dominant tree species in many forest complexes, and it is the most important commercial species in the Caspian forests of Iran [Tavankar et al. 2015a]. Beech is a large tree and is common in highlands at elevations of 800-2000 m a.s.l. It is widespread on northern mountainside slopes, in cool areas, and in rich soils throughout the Caspian Sea region of Iran [Bonyad and Tavankar 2016]. These stands constitute approximately 17.6% of the area and 30% of standing volume [Amiri et al. 2013].

Since the end of the last century selective cutting has been the main silvicultural method in these forests, leading to mixed and uneven-aged stands. These are managed under the single-tree selection system, observing a cycle of 10 years, with the aims of improving the stand resilience and controlling the tree distribution [Tavankar et al. 2013]. Selection harvesting methods may adversely impact the quality of the residual trees, as the exposed xylem makes the trees prone to future disease, insect infestations or timber defects [Bettinger and Kellogg 1993; Han and Kellogg 2000; Hosseini et al. 2000; Vasiliauskas 2001; Szewczyk 2015]. Moreover, the damage may concern not only the stem but also the root system, depending on the cutting and extraction methods used. The damage may not be detectable immediately after harvesting. It is reported that the death of intact trees may occur years later [Picchio et al. 2018]. A wound or scar is the portion of the cambial zone where the cambium is killed by injury [Means 1989]. Trees compartmentalize the affected wood to protect the wound zone against infestation by fungi and bacteria [Shigo 1986], forming boundary zones within the bark [Biggs 1985]. Anatomical changes begin within the xylem, and include reduced tracheid or vessel lumina [Arbellay et al. 2013] or the production of callus tissue [Delvaux et al. 2010] – a thin layer of undifferentiated cells as a response to a wound that may help re-establish the cambium's continuity after wounding [Smith and Sutherland 2001].

Wound characteristics such as size, location and severity are the main factors that influence the wound healing rate and the future quality of damaged trees [Meadows 1993; Vasiliauskas 1994; Han and Kellogg 2000; Ezzati and Najafi 2010; Karaszewski et al. 2013]. Smith et al. [1994] studied the closure of logging wounds after 10 years in an Appalachian forest and reported that many small wounds, < 322 cm^2 in size, closed 5-10 years after logging. The wound healing rate is related to tree species and wound severity [Picchio et al. 2018].

Vasiliauskas [1994] suggested a 25-50 year healing period for a 10 cm wide wound in Norway spruce, while et al. [1997] indicated a 15-year period for complete healing of < 60 cm^2 wounds in Sitka spruce. Wound closure on forest trees may be a very important factor, restricting the colonization of wound-invading fungi [Vasiliauskas 2001].

The potential damage to residual trees is a managerial concern during cyclic harvesting in the same forest stand. Although attempts to better understand how injuries affect the residual trees have been made in many different contexts, there are still few investigations on uneven-aged forests. In a previous paper, Tavankar et al. [2015b] highlighted that logging wounds affected diameter growth, causing a sensitive reduction particularly in young trees, dependent on severity, location and size of wound and tree age, in an uneven-aged mixed forest in the Caspian region subject to selection cutting. This new research was developed and carried out in a different forest area, located at a higher elevation, to test whether the biosocial class of a wounded tree is a contributing factor. In this study the key objectives were to: 1) determine and model healing rate for different wound parameters (width, length, and area of wound); 2) analyse the relationship between wound healing rate, tree diameter growth and tree height growth; 3) analyse the wound healing rate in relation to wound position on the stem; 4) analyse the relationship between WHR and width and area of wound depending on DBH and social classes of beech trees after logging damage.

Materials and methods

Study area

This study was conducted in parcel 47 (41 ha) in district 1 of the Nav forests, which are located between 37°38'34" and 37°42'21"N and between 48°48'44" and 48°52'30"E. The elevation in the study area ranged from 1,350 to 1,650 m a.s.l. The mean annual precipitation is approximately 963 mm and the mean annual temperature is 8.8°C. The original vegetation of this area is an uneven-aged mixed forest dominated by *Fagus orientalis* Lipsky. The soil type is forest brown, and texture varies from sandy clay loam to clay loam. The silvicultural method applied in this forest is single-tree selection cutting. This silvicultural system makes it possible to maintain a self-sustaining forest of multiple age/size classes. Stand structure is regulated by harvesting a specific number of trees in each size class. Harvesting is repeated at regular intervals. This system maintains continuous forest cover and provides frequent entries for harvesting of forest products. It is one of the most suitable systems for the management of uneven--aged stands.

Logging operations in the area were carried out from December 2009 until January 2010. In total 191 trees (4.7 trees ha^{-1}) with a volume of 410 m^3 (10 $m^3 \cdot ha^{-1}$) were marked for harvesting on the total parcel area. The diameter at breast height 1.30 m (DBH) of the marked trees ranged from 20 to 115 cm, according to the criteria of the single-tree selection cutting system. The marked trees were felled, delimbed and topped at 20 cm dub (diameter under bark) using a Stihl MS 362 chainsaw with power 3.5 kW equipped with a bar of length 60 cm. Logs, ranging from 5.2 to 7.8 m in length, were then extracted from the felling site to roadside landings using a Timberjack 450C wheeled skidder equipped with a single-drum fixed winch. This had a power of 120 kW, a weight of 10.3 t and width and length 3.8 and 6.4 m respectively; further details are given by Bodaghi et al. [2018]. Although it was not possible in this study, this technology may be adapted by equipping the skidder with both a cable winch and a grapple, bringing interesting benefits as reported by Proto et al. [2018].

Data collection and analysis

All beech trees on which wounds were deeper than the bole bark (86 stems) were identified, numbered and marked immediately after logging (year 2010).

The experimental design considered the wound healing rate (WHR) as a dependent variable; the new independent variables were wound position (WP), wound area (WA), wound width (WW), wound length (WL), ratio of wound area to stem area at wound position (RWS), DBH at wounding time, diameter growth (DG), height growth (HG), and the vertical layering (biosocial position) of the wounded beech trees.

The position of each damaged tree was also identified on a topographical map using the global positioning system. On each damaged tree the following parameters were recorded after logging: diameter at breast height 1.30 m (DBH) and diameter at the height of the centre of the wound (DWH) (measured with a dendrometric calliper); tree height (TH) (measured with a Sunnto clinometer); cause of damage (i.e. felling or extraction); position (wound height (WH) from ground level); wound width (WW), wound length (WL) and wound area (WA). The wound area was determined by measuring the maximum length and width with a ruler (1 mm accuracy) and calculating the elliptical surface area, as described and applied by Picchio et al. [2011]. The wound position (WH) was determined using a tape to measure the vertical distance between the wound centre and the ground. The position of each wound was recorded in one of three classes: < 0.3 m, 0.3-1 m and > 1 m [Tavankar et al. 2015a]. Tree vertical layering was recorded using three classes: I) upper storey trees (UST), whose crowns receive light from all directions; II) middle storey trees (MST), whose crowns receive light from the upper direction; and III) lower storey trees (LST), whose crowns receive light indirectly. After 5 years (in 2015) the wounded trees were identified in the parcel area, and DBH, DWH, TH, WW, WL, and WA were remeasured, records being made of the occluded wounds and those that were still open.

The ratio of wound area to stem area at wound position (RWS) at the start and end of the study interval was calculated by equation 1 [Tavankar et al. 2015b]:

$$RWS = (WA/SA) \times 100 \quad (1)$$

where WA is the wound area (cm^2) and SA is the stem area at the centre of the wound (cm^2).

The 5-year diameter growth (DG) and height growth (HG) of damaged trees were calculated using equations 2 and 3 respectively [Clark and Clark 1992]:

$$DG = (DBH_2 - DBH_1)/t \quad (2)$$

$$HG = (TH_2 - TH_1)/t \quad (3)$$

where DG is the mean diameter growth ($mm \cdot year^{-1}$) in the study period, HG is the mean tree height growth ($m \cdot year^{-1}$) in the study period, DBH_1 and DBH_2 are the diameter at breast height at the beginning of the study and five years later, TH_1 TH_2 are the tree height at the start and end of the study interval (mm), and t is the time interval between the two measurements in years (5 years).

The wound healing rate (WHR) was analysed considering three wound parameters (WD): 1) wound width healing rate (WWHR) ($mm \cdot year^{-1}$); 2) wound length healing rate (WLHR) ($mm \cdot year^{-1}$); and 3) wound area healing rate (WAHR) ($cm^2 \cdot year^{-1}$). This was done using equation 4 [Tavankar et al. 2017c]:

$$WHRj = (WDij1 - WDij2)/t \quad (4)$$

where i indicates the number of the wound, j indicates the wound parameter (width, length, area), and t is the time interval between the two measurements.

To obtain a comparison and better understanding of the average values for WWHR, WLHR, and WAHR, these parameters were also calculated in percentage terms using equation 5:

$$WHR\% = [(WDij1 - WDij2)/WDij1] \times 100 \quad (5)$$

Statistical analyses

Normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene test) were checked. The Box Cox transformation was applied when necessary for data normalization. Then, the following tests were used for means comparison and relationship between dependent and independent variables, using SPSS 19 (IBM, NY, USA). The means of wound width, wound length, wound area, and ratio of wound area to stem area at the start (in 2010) and at the end of the study period (in 2015) were compared using the paired samples t test; the means of wound width and wound length at the start and end of the study period were compared using the independent samples t test; the means of wound width healing rate and wound length healing rate were compared using the independent samples t test; the effect of DBH class and wound position class on wound healing rate was analysed using ANOVA and the Duncan test, as was the effect of RWS class on diameter and height growth. Regression analysis was applied to test the following relations: between wound healing rate and wound width, length, and area; between wound healing rate and RWS; and between wound healing rate and diameter growth.

Results and discussion

Wound size and healing during the study period

The mean wound length was greater ($P < 0.01$) than the mean wound width at both measurement times (26.4 vs. 13.3 cm in 2010, $t = 8.35$; 20.8 vs. 6.6 cm in 2015, $t = 8.74$) (table 1), while the wound width healing rate (50.4%) was greater ($t = 5.58$, $\alpha < 0.01$) than the length healing rate (21.2%). The wound area was also larger in 2010 than 5 years later, exhibiting a healing rate of 42.8%. Similarly, the ratio of wound area to stem area (RWS) was larger immediately after logging, and the wound healing rate in terms of RWS was 65.6%.

The mean wound width was significantly reduced ($t = 11.70$, $P < 0.01$) from the year 2010 (13.3 cm) to 2015 (6.6 cm), as were the means of wound length, wound area and ratio of wound area to stem area (RWS), as demonstrated by the t paired test (table 1).

Table 1. Size of logging wounds, ratio of wound area to stem area (RWS) (mean ±SD) on beech trees (n=86) in two periods of measurements, and the wound healing rate (WHR%). The t paired column shows the difference between 2010 and 2015. Different letters show significant differences, verified by the Duncan test, between values in a given column (independent samples t test)

Wound	In 2010	In 2015	WHR (%)	t paired
Width (cm)	13.3 ±5.7^b	6.6 ±2.7^b	50.4 ±12.7^a	11.70**
Length (cm)	26.4 ±11.8^a	20.8 ±7.5^a	21.2 ±9.3^b	9.11**
Area (cm^2)	343.6 ±56.5	196.5 ±37.9	42.8 ±14.5	8.01**
RWS (%)	9.6 ±3.2	3.3 ±1.2	65.6 ±20.4	14.28**

Only 10 wounds were completely closed (12%), while 76 wounds (88%) were still open five years later (table 2). The only wounds which were completely closed were those with a width smaller than 4 cm. None of the wounds with a width larger than 12 cm were closed.

The wound width healing rate was significantly higher than the wound length healing rate ($F = 5.74$, $P < 0.01$; table 3).

The multiple regression analyses used to test the relationship between wound width healing rate and wound width were significant ($F = 194.9$, $P < 0.001$; equation 6 and fig. 1):

$$WWHR = 18.53 - 5.68 \cdot \mathrm{Ln}\,(WW) \quad (6)$$
$$(R^2 \text{ adjusted} = 0.695;\ SE = 1.617)$$

where WWHR is the wound width healing rate (mm $year^{-1}$) and WW is the wound width (mm).

Table 2. Frequency of closed wounds in wound width classes

Wound width (cm)	Wound width (n)	Closed wounds (%)
< 4	4	100
4-8	23	17.4
8-12	25	8.0
12-16	21	–
> 16	13	–
All wounds	86	11.6

Table 3. Wound healing rate (WHR) in beech trees over 5 years: ANOVA and Duncan test results. Different letters show significant differences between means

WHR	Max.	Min.	Mean ± SD
Width (mm·$year^{-1}$)	32.5	0	18.4 ±3.4[a]
Length (mm·$year^{-1}$)	13.6	0	4.5 ±1.6[b]
Area (cm^2·$year^{-1}$)	50.7	0	31.2 ±7.7

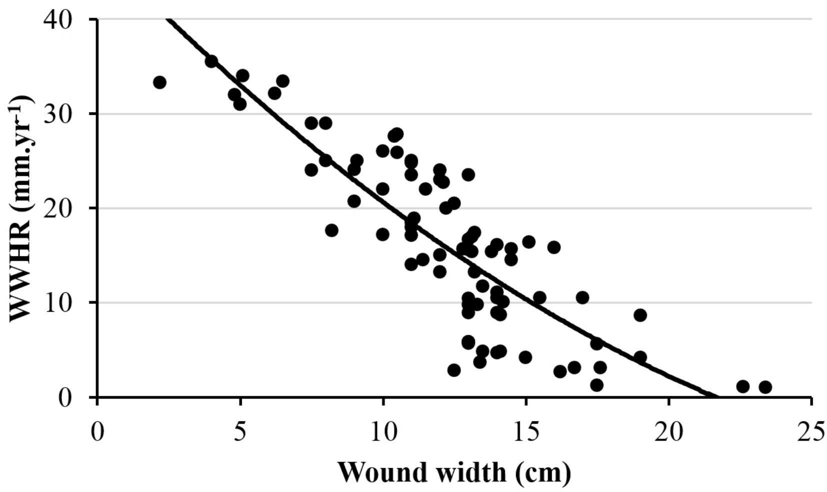

Fig. 1. Relationship between wound width in the year 2010 and wound width healing rate (WWHR) in the year 2015

The regression analysis showed that wound area healing rate (WAHR) decreased with increasing wound area (F = 118.08, P < 0.001; equation 7 and fig. 2):

$$WAHR = 5.6 \cdot 10^{-8} \cdot (WA)^2 - 0.167 \cdot (WA) + 89.34 \quad (7)$$
$$(R^2 \text{ adjusted} = 0.856; SE = 11.212)$$

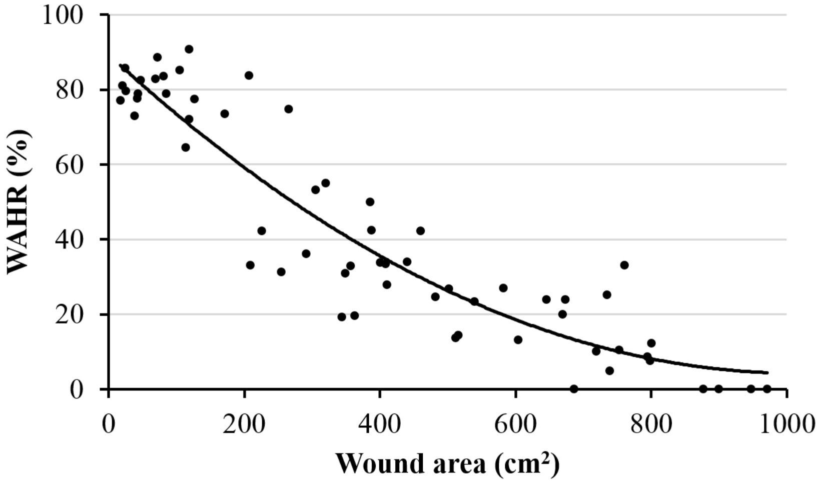

Fig. 2. Relationship between wound area in the year 2010 and wound area healing rate (WAHR)

A wound healing value of 17.9 (SD ±5.2) mm·y^{-1} was estimated in *Fagus orientalis* growing on a larger elevation range in the Hyrcanian forest [Tavankar et al. 2017c].

The WHR found in this study (18.4 ±3.4) showed no substantial difference from other studies in the Hyrcanian forests. Despite the higher elevation, the soil on the study site is rich and has good water conditions.

Early wound closure is generally due to greater increment. Dujesiefken et al. [2005] observed that closure of wounds took more time in European beech than in white and red oaks, due to the more intensive growth of oaks. Moreover, in *Fagus sylvatica* the wound healing rate values are noticeably lower than those observed in *Fagus orientalis* in this study [Neely 1970; Hecht et al. 2015].

Chano et al. [2015] found that wound closure is mainly driven from the lateral edges of the wound, as in this study. Slower progress of healing in callus formation at the upper and lower edges of artificially wounded beech has been reported [Hecht et al. 2015], and similar results have been found for alder and lime trees in the Caspian forest [Tavankar et al. 2017a; Tavankar et al. 2018].

Large wounds are difficult to close in a short time. The healing rate in width and in area decreased with increasing wound size. Vasaitis et al. [2012] reported the number of years needed to occlude wounds on *Picea abies* (L.) H.Karst stems at 3.6, 5.5, 10.4, 12.7 and 14.7 respectively when the wound width ranged from 1 to 5 cm. Smith et al. [1994] observed that many small logging wounds healed rapidly and faster growing species showed the most rapid closure. Broadleaves show increased growth near the wound, becoming unusually wider in the years after wounding. The basipetal flow of products and growth regulators in the stem determine healing tissue growth [Neely 1988; Arbellay et al. 2013].

Tavankar et al. [2017c] reported that, in a mixed broadleaf forest, the WHR was higher in the initial period after wounding, varying from 19.3 to 10 mm·year^{-1} after 5 and 15 years respectively. Fast wound closure makes the tree less prone to stem decay. With increasing closure time, the frequency and severity of decay also increased [Sheppard et al. 2016]. Large injuries on a stem are unfavourable for the quality of the future harvest, since a discontinuity, generating ring shake, persists under the wound, even when the wound is healed. Internal defects may develop in the form of discoloration and decay as a result of logging wounds [Wallis and Morrison 1975; Suzuki 2000; Shortle et al. 2010]. Injured timber is impaired in terms of both structural and aesthetic properties. Even closed wounds restrict the application of timber to low-value products such as firewood, with a consequent loss of financial value and lowering of future crop volumes [Meadows 1993; Han et al. 2000; Kiser 2011; Lo Monaco et al. 2015].

Impact of wounding on diameter and height growth

The mean diameter and height growth of wounded trees were 5.4 mm·y^{-1} and 33.9 cm·y^{-1} respectively. Results are given by RWS class in table 4.

The ANOVA test showed that the ratio of wound area to stem area at wound height (RWS) had a significant effect on both diameter growth ($F = 18.81$, $P < 0.01$) and height growth ($F = 7.84$, $P < 0.01$). The diameter and height growth of wounded trees declined with an increase in the ratio of wound area to stem basal area (RWS).

The Duncan test showed RWS to have a more pronounced effect on diameter than on height; moreover, both diameter and height growth were affected in the > 15% RWS class.

Table 4. Diameter and height growth (mean ± SD) of wounded beech trees by RWS class: ANOVA and Duncan test results. Different letters show significant differences among means

RWS (%)	n	Diameter growth (mm·year^{-1})	Height growth (cm·year^{-1})
< 5	21	6.8 ±2.1^{a}	36.6 ±13.7^{a}
5-10	19	6.6 ±1.9^{a}	35.7 ±13.1^{a}
10-15	30	5.5 ±1.1^{b}	34.2 ± 2.5^{a}
> 15	16	2.3 ±0.8^{c}	24.6 ±10.3^{b}
All trees	86	5.4 ±2.6	33.9 ±11.6

The regression analysis between wound area healing rate (WAHR) and ratio of wound area to stem area (RWS) at the time of logging was also statistically significant ($F = 83.54$, $P < 0.001$; equation 8 and fig. 3):

$$WAHR = 0.4 \cdot (RWS)^2 - 13.65 \cdot (RWS) + 118.9 \quad (8)$$
$$(R^2 \text{ adjusted} = 0.795;\ SE = 19.572)$$

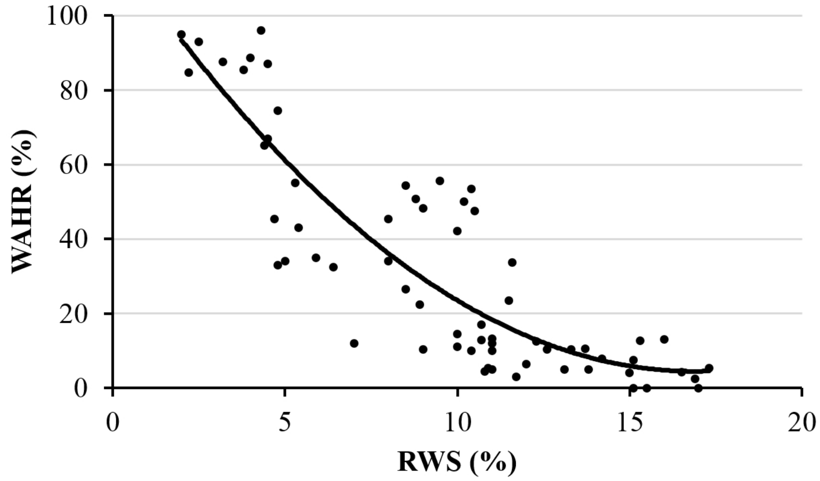

Fig. 3. Relationship between wound area healing rate (WAHR) and RWS%

The regression analysis between the wound width healing rate (WWHR) and diameter growth (DG) indicated that the WWHR rose with increasing DG ($F = 42.68$, $P < 0.01$; equation 9 and fig. 4).

$$WWHR = -0.0425 \cdot (DG)^2 + 1.156 \cdot (DG) + 13.76 \quad (9)$$
$$(R^2 \text{ adjusted} = 0.613;\ SE = 1.454)$$

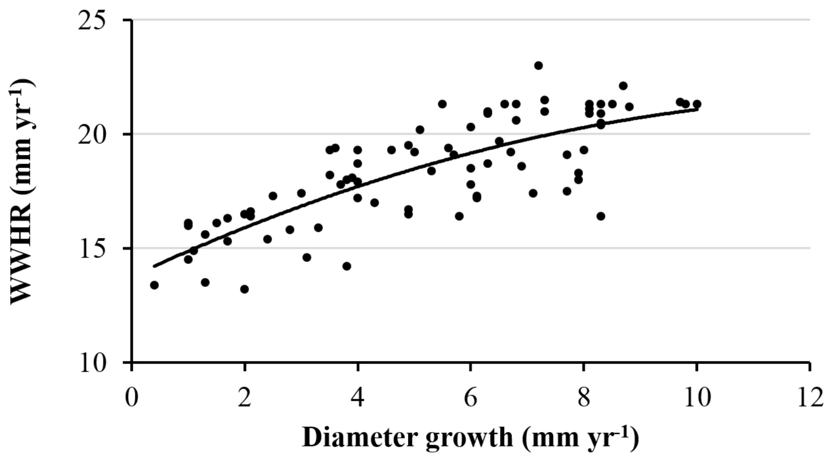

Fig. 4. Relationship between wound width healing rate and diameter growth

These results suggest that a larger size of wound relative to the size of the tree caused states of suffering. The effect of wounding should be observed relative to tree diameter. As RWS increased, tree response decreased – in terms of diametric growth and height, as well as WAHR. It has been previously reported that wounded trees showed no growth decrease in a pine plantation [Picchio et al. 2011], but the wounded trees may die over time [Tavankar and Boyard 2017; Picchio et al. 2018]. Reduction in diameter growth was observed on residual trees wounded after a selective logging operation [Tavankar et al. 2015b] in an even-aged mixed broadleaf forest. In the present study, height growth was less affected than diameter growth, particularly in for RWS below 15%. Only wounds of large relative size negatively influenced both diameter and height growth. These findings are probably linked to site fertility. Site quality determines the potential expression of tree height, conditioned by the availability of water, nutrients and sunlight. In fact, tree height in a forest usually indicates the site fertility [Oliveira-Filho et al. 2001; Baker et al. 2003; Cañellas et al. 2004].

The positive correlation between WWHR and diameter growth confirmed previous observations that more intensive growth produces faster healing [Vasiliauskas 1994; Vasiliauskas and Stenlid 1998; Vasiliauskas 1998; Ezzati and Najafi 2010; Sarayelou et al. 2015].

Wound healing depending on tree diameter, wound position (WH) and social position of wounded trees

ANOVA tests indicated that the tree's DBH class had significant effects on healing rates in terms of wound width ($F = 19.3$, $P < 0.01$), wound length ($F = 32.1$, $P < 0.01$) and wound area ($F = 14.7$, $P < 0.01$; table 5).

Trees in the 32.5-57.5 cm DBH class had the highest healing rates in terms of wound width (26.2 ±5.3 mm $year^{-1}$), wound length (7.2 ±2.1 mm $year^{-1}$) and wound area (43.1 ±9.5 cm^2 $year^{-1}$), as shown by the Duncan test.

Half of the wounds occurred in the lower position class. ANOVA tests indicated that the wound position class also had significant effects on the healing rates in terms of wound width ($F = 15.6$, $P < 0.01$), wound length ($F = 24.7$, $P < 0.01$) and wound area ($F = 30.1$, $P < 0.01$). Duncan tests showed that the healing rate of wounds increased with increasing wound height above ground level. Wounds in the lower height class had lower healing rates in terms of width, length and area.

The data showed no significant relationship between tree height (TH) and WHR parameters ($R^2 < 0.10$, $F > 0.05$) or between height growth (HG) and WHR parameters ($R^2 < 0.10$, $F > 0.05$).

ANOVA tests suggested a significant effect of the tree's biosocial position (upper storey, middle storey or lower storey) on WHR ($F = 49.5$, $P < 0.01$). Duncan tests also showed that the means of the WHR parameters (WWHR, WLHR, and WAHR) were significantly higher in upper storey trees (UST) than in middle storey trees (MST) and lower storey trees (LST).

Table 5. Wound healing rate (mean ± SD) for classes of tree in terms of DBH, wound position and vertical layering. Different letters show significant differences among the means

Parameters	n	Frequency (%)	Width healing rate (mm·year^{-1})	Length healing rate (mm·year^{-1})	Area healing rate (cm^2·year^{-1})
DBH (cm)					
7.5-32.5	18	20.9	6.0 ±1.4^c	1.6 ±1.7^c	12.4 ±3.6^b
32.6-57.5	21	24.4	26.2 ±5.3^a	7.2 ±2.1^a	43.1 ±9.5^a
57.6-82.5	31	36,1	22.1 ±4.2^b	5.2 ±2.0^b	38.7 ±8.1^c
> 82.6	16	18.6	18.5 ±3.1^b	4.0 ±1.0^b	30.3 ±7.2^d
Wound position (m)					
< 0.3	43	50.0	12.2 ±3.4^c	3.3 ±0.9^b	15.2 ±4.4^b
0.3-1	29	33.7	23.6 ±4.6^b	5.6 ±1.9^a	44.3 ±8.2^a
> 1	14	16.3	26.8 ±5.0^a	5.9 ±2.2^a	46.2 ±8.7^a
Vertical layering of tree					
Upper storey	30	34.9	24.5 ±6.2^a	6.1 ±2.0^a	41.2 ±7.3^a
Middle storey	35	40.7	20.3 ±4.8^b	4.4 ±2.0^b	29.4 ±7.6^b
Lower storey	21	24.3	11.8 ±3.5^c	2.5 ±1.2^c	19.7 ±5.0^c

Most wounded trees were found in the two central DBH classes (32.6-57.5 and 57.6-82.5 cm), with a combined frequency of approximatively 60%. Silvicultural activities in an uneven-aged structure require crossing the ground to reach the trees to be extracted. In this case, the volume harvested was 10 m^3·ha^{-1} and about 5 trees per hectare were extracted, with diameters ranging from 20 to 115 cm.

The high frequency of wounds due to extraction operations was mostly caused by the difficulty in moving within an uneven-aged forest, where the trees to be harvested are scattered [Tavankar et al. 2015b]. In every forest, but particularly in uneven-aged forests, pre-harvest planning, training of forest workers, adequate technologies and skilled operators are needed to reduce the risk of damaging residual trees [Gullison and Hardner 1993; Nikooy et al. 2010; Picchio et al. 2012; Bakinowska et al. 2016].

50% of the total number of wounds (43 wounds) occurred on stems at heights below 0.3 m. This is evidence that the injuries were inflicted during logging phases [Vasiliauskas 2001]. These results were very similar to those of other studies in the Caspian beech forests for a ground-based logging system [Naghdi et al. 2008; Tavankar et al. 2011; Tavankar et al. 2013; Tavankar et al. 2015b;]. The position of damage on the tree bole is important, because the primary value is located in the butt log and generally decreases in subsequent logs [Bettinger and Kellogg 1993]. Wounds located in the lower part, as these results confirm, are associated with the worst healing performance [Ezzati and Najafi 2010]. These wounds affected the more valuable part of the butt, lowering the future value of the harvest [Han et al. 2000; Alderman et al. 2004; Cassens 2004; Knoke et al. 2006; Naghdi et al. 2008; Majnounian et al. 2009; Nikooy et al. 2010; Jourgholami 2012; Karaszewski et al. 2013; Riesco Munoz et al. 2013].

The biosocial position of wounded trees was a discriminant for healing rate. Healing rate decreased from upper to lower storey trees, in agreement with the general observation that higher growth rates favour faster healing.

On the other hand, the modern cultural settings of sustainable forestry require the release of dying trees, snags and logs on the ground, to contribute to the maintenance of high biodiversity values [Christensen et al. 2005; Atici et al. 2008; Bertolotto et al. 2016]. Wounded trees are prone to decay and eventually die, thus generating snags and logs, which provide valuable habitats due to the larger diameters. Quality and quantity of coarse woody debris serve as indicators of environmental and ecosystem sustainability [Angelstam et al. 2003; Tavankar et al. 2014; 2017b] and forest management must maintain a reconstituting flow of dead wood [Behjou et al. 2018].

Conclusions

In this effort to enable the prognosis of logging wounds on Oriental beech trees, it was found that the wound width was more important than the wound length. The wound healing rate increased with increasing tree diameter growth and wound height from the ground, and decreased with increasing wound width and ratio of wound area to stem area at wound height. No significant relationships between tree height and wound healing rate parameters were detected. Tree biosocial layering plays a role in healing: the wound healing rate in upper storey trees was significantly higher than in the middle and lower storeys. The wound healing rate in middle age classes of beech trees (DBH 32.6-57.5 cm) was faster than in the lower and higher age classes.

The healing rate values, in terms of area, width and length, were high due to the richness of the soil. Based on the size of the wound (343.6 cm^2) and the healing rate (31.2 cm^2 $year^{-1}$), it can be concluded that about 11 years are needed for wound occlusion in the studied area. It should be noted that larger wounds require more time for occlusion. After 5 years only 12% of wounds were completely closed. It may be deduced that 15 years are necessary for the complete closure of 80% of total wounds.

The results provide additional information on correlations between logging wound parameters and their healing rates in uneven-aged beech forests. Previous studies have shown that the widths of winching wounds are larger than those of felling wounds; moreover, winching wounds are closer to ground level than felling wounds, and therefore require a longer time to heal. New logging technologies are needed in these forests to reduce damage to the remaining trees. Minimizing the quantity and intensity of damage to residual trees should be considered an important objective, so as to ensure future high-quality timber in forests managed by selection cutting.

These results are valuable for understanding the possible effects that logging damage may have on tree growth and trees' ability to repair such damage. At higher elevations this ability is maintained, as growth is sustained by adequate site fertility. However, a recovered wound will remain present inside the tree, partially compromising the technological quality of the wood. Pre-harvest planning and marking of the winching path before logging operations can reduce damage to trees in these forests. Adequate training of logging workers is needed to minimize damage to residual trees. Reducing logging damage to residual trees must remain a major objective in managed forests.

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