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Effect of logging wounds on diameter growth of beech (*Fagus orientalis* Lipsky) trees following selection cutting in Caspian forests of Iran

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Abstract

Background: Logging damage to residual trees during selection cutting may lead to serious economic losses in terms of both timber quality and diameter growth reduction. In this study, we investigated the effect of logging operations on residual tree damage and the consequence of injuries on diameter growth in an uneven-aged mixed forest dominated by beech (*Fagus orientalis* Lipsky).

Methods: The diameter growth of 56 wounded and 56 unwounded beech trees were compared 12 years after selected logging of other trees had taken place in an Iranian Caspian forest.

Results: Of total logging wounds, 25.0 % (14 wounds) were caused by felling operations and 75.0 % (42 wounds) were caused by winching operations. The reduction in diameter growth of wounded beech trees was only observed in the breast height DBH range below 55 cm. The diameter growth of wounded trees was 8.1 % lower than in unwounded trees. The vertical distance from the ground of wounding was a significant factor in diameter growth. Wounds that were larger than 200 cm² in area significantly reduced diameter growth of beech trees. Whether wounds were closed or open wounds had no significant effect on diameter growth but decayed wounds reduced diameter growth by 15.3 %.

Conclusions: This study suggested that intensive logging wounds reduce diameter growth, especially in young beech trees. In addition to the intensity, size and position of wounds and tree age, the reduction of diameter growth was related to the ratio of wound size to stem area.

Keywords: *Fagus orientalis* Lipsky; Felling; Logging damage; Tree growth; Winching

Background

Impact on residual trees and/or to the regeneration of forest after forest harvesting continues to be one of the major concerns of forest managers responsible for implementing selection harvests (Reisinger and Pope 1991; Smith et al. 1994; Nikooy et al. 2010). The reduction of the negative effects of felling and extraction is one of the main goals when achieving sustainable forest management (Sist and Nguyen-Thé 2002). Skinned bark and exposed sapwood, root damage and broken branches are the most common forms of damage occurring during forest logging (Vasiliauskas and Stenlid 2007). When the bark is torn from living trees, physiological changes and cell

differentiation occur in the area surrounding the injury and callus starts to develop from the living bark towards the centre of the wound (Neely 1979). Stem wound and root damage are also potential means of entry for organisms causing decay and pitch rings (Shigo 1966; Pechmann 1974; Dimitri 1983). Because of potential decreased tree vigour and increased likelihood of attack by insects or diseases, logging injury to the remaining trees may lead to serious economic losses in terms of timber quality at the final harvest (Kiser 2011), wood losses of damaged trees and tree growth reduction (Ohman 1970; Vasiliauskas 2001).

Several studies on logging damage have highlighted that a number of factors affect the susceptibility to and effect of mechanical injury. These include the following: tree species (Bettinger and Kellogg 1993; Vasiliauskas 2001), silvicultural treatment (Bettinger et al. 1998), logging

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season (Limbeck-Lilienau 2003), logging methods (Bragg et al. 1994; Spinelli et al. 2010; Marchi et al. 2014), harvesting system (Han and Kellogg 2000), site characteristics (Sist et al. 2003), amount of timber removed during harvest (Fjeld and Granhus 1998; Gullison and Hardner 1993), design of the extraction trails (Gullison and Hardner 1993), and skill of the personnel operating the equipment (Wallentin 2007; Nikooy et al. 2010). The effect of damage on tree growth has been also investigated showing contrasting results. Some studies clearly indicated that growth losses occur in damaged trees, and in some cases, these can seriously offset the gains from harvesting (Vasiliauskas 2001). Shea (1961) recorded a reduction in diameter growth in injured Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco). Isomäki and Kallio (1974) verified a decrease by 35–40 % in both radial and height growth in Norway spruce (*Picea abies* (L.) H. Karst.) trees with root collar damage following logging and a 15 % reduced growth due to stem damage. Other studies showed stem wounds in Norway spruce may result in growth rate losses ranging from 14 to 25 % (Baader 1956; Vanek 1957). In contrast, Vasiliauskas and Stenlid (2007) recorded an increase in radial growth in injured stems of ash (*Fraxinus excelsior* L.). Finally, a number of investigations failed to reveal any significant effect of stem wounds on the increment of Norway spruce (Vasiliauskas 1994), western hemlock (*Tsuga heterophylla* (Raf.) Srag.) (Shea 1961), oak (*Quercus robur* L.) (Vasiliauskas 1998) and Corsican pine *Pinus nigra* subsp. *salzmannii* var. *corsicana* (Loudon) Hylander (as *Pinus laricio* Poiret) (Picchio et al. 2011). It is difficult, therefore, to make a general conclusion on what effect mechanical stem damage has on tree growth (Vasiliauskas 2001). Also, most of the studies on this topic are quite dated, mainly related to conifer species and, most importantly, approach the effect of damage on tree growth taking into consideration the effect of damage caused by animals rather than logging. Studies on this topic are still limited, especially in broadleaved stands, and the long-term effects of damage are not well known (Mäkinen et al. 2007). In order to improve logging methods, a better knowledge about the long-term impact of forest operations is needed (Whitman et al. 1997; Tavankar and Bonyad 2014).

Beech is the most industrial commercial tree species among more than 80 broadleaved trees and shrubs in the Caspian forests (Marvie-Mohadjer 2006). Pure or mixed oriental beech stands represent the most important forest communities in the natural Caspian forests (Marvie-Mohadjer 2006). These stands constitute approximately 17.6 % of the area, 30 % of standing volume and 23.6 % of stems number in the Iranian Caspian forests (Amiri et al. 2013).

In this study, we investigated the effect of a logging operation on residual tree damage and the consequence of injuries on diameter growth in an uneven-aged mixed forest dominated by beech in the Caspian forest of Iran. In detail, the aims of this study were the following: (i) to assess the long-term effects of logging damage on both diameter growth and wound condition after 12 years since logging and (ii) to analyse the relation of intensity, size and location of injuries with beech diameter growth.

Methods

Study area

This study was conducted in parcel 35 in district 1 of Nav forests, located between 37°38'34'' to 37°42'21'' N and 48°48'44'' to 48°52'30'' E. Elevation in the study area ranged from 950 to 1350 m a.s.l. The mean annual precipitation is approximately 950 mm, and the mean annual temperature is 9.1 °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 between sandy clay loams to clay loam. The silvicultural method applied in this forest is single selection cutting. Logging operations in the area were carried out in December 1999 and January 2000. In total, 216 marked trees (6.75 trees ha⁻¹) were scattered in the parcel area (32 ha), and these have a volume of 688 m³ (21.5 m³ ha⁻¹). The diameter at breast height (DBH) of the marked trees ranged from 20 to 135 cm. The marked trees were felled, limbed and topped at 20 cm dib (diameter inside bark) by chain saw. Logs, ranging from 5.2 to 7.8 m in length, were then extracted from the felling site to the roadside landings using a Timber-jack 450 C wheeled skidder. The weight of the skidder was 9.8 t, and its width and length were 3.8 and 6.4 m, respectively.

Data collection and analysis

Immediately after logging (year 2000), all wounded beech trees (56 stems) were identified, numbered and marked. 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 (DBH, 1.30 m) and diameter at wound height (DWH) (measured by dendrometric calliper in mm), damage severity (i.e. type of damaged tissues: bark, phloem, wood fibres), cause of damage (i.e. felling or extraction), and position and size of wounds. The wound size was determined by measuring the maximum length and width by a ruler (1 mm accuracy) and calculating the ellipse surface area (Picchio et al. 2011). The wound sizes were then classified in three classes: < 100, 101–200 and > 200 cm². The position of the wound was determined with a tape measuring

the distance between the wound centre and the ground. The position of each wound was recorded in three classes, < 0.3 m, 0.3–1 m and > 1 m (Limbeck-Lilienau 2003). A neighbouring unwounded beech tree with similar characteristics (i.e. DBH, height, vitality, crown class of all the trees—i.e. dominant, codominant subdominant, etc.) was selected for comparison with each wounded tree. After 12 years (i.e. in year 2012), the wounded and unwounded trees were identified in the parcel area, and DBH and condition of wounds were reexamined and classified in three types: closed, open and decayed (Han et al. 2000). The 12-year period diameter growth of damaged and undamaged trees was calculated using Eq. 1 (Clark and Clark 1992):

$$DG = (DBH_2 - DBH_1) / t \quad (1)$$

Where DG is diameter growth ($\text{mm} \times \text{year}^{-1}$), DBH_1 and DBH_2 are diameter at breast height at the start and end of interval (mm), respectively, and t is time interval between two measurements (years). Reduction of diameter growth was calculated using Eq. 2:

$$RDG = (UDG - WDG) / UDG \quad (2)$$

Where RDG is reduction of diameter growth, UDG is unwounded diameter growth and WDG is wounded diameter growth.

After checking for normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene test), a paired t test was applied to compare means of diameter growth (DG) in wounded and unwounded trees.

A non-parametric test (Spearman) was applied to test the relationship between the following: DBH vs. wound severity, wound position vs wound severity, wounded area vs. wound severity, wounded area vs. wound position, and wound position vs. DBH.

Regression analysis was applied to test the following relationships between: (i) diameter growth and tree age for both damaged and undamaged trees; (ii) wound size and tree diameter at the time of logging; (iii) diameter growth and wound position; and (iv) reduction of diameter growth and ratio of wound size to stem area. All analyses were performed using SPSS 19 software (IBM, NY, USA).

Results and discussion

Of total logging wounds, 25 % (14 wounds) were caused by the felling operation and 75 % (42 wounds) were caused by the extraction operation (Table 1). Normally, the extraction operation is considered to be one of the major sources of wounds in selection cuttings, but this view is only partially correct. During the logging operations, in particular during the felling phase, some trees marked for retention are accidentally destroyed during

Table 1 Frequency of wounds by cause of wound

Cause of wound	Closed		Open		Decayed	
	(n)	(%)	(n)	(%)	(n)	(%)
Felling	10	71.4	3	21.4	1	7.2
Extraction	11	26.2	15	35.7	16	38.1

the felling of big trees nearby. In these cases, there are no wounds on trees but only dead trees. After 12 years following wound occurrence, 71.4 % of felling wounds were closed, while only 26.2 % of extraction wounds were closed. The number and percentage of open and decayed extraction wounds were higher than felling wounds—38.1 % of extraction wounds were decayed after 12 years. This is a consequence of the correlation between wound position and wound severity. For the extraction wounds, normally the first metre of the stem was damaged and the wounds were large and deep, extending below the bark down into the wood. These are ideal conditions for infection by diseases in particular fungi.

Picchio et al. (2012) studied improved winching techniques designed to decrease stand damage in the forests of central Italy. They reported that the use of a snatch block decreased by one-quarter the frequency of wounded trees from 50 to 36 %.

The frequency of wounds for DBH classes by cause of wound is shown in Table 2. From the analysis of all the trees wounded, 4 wounds (7.1 %) were found on trees with $DBH < 20$ cm, 15 wounds (26.8 %) on trees with DBH ranging from 20 to 40 cm, 24 wounds (42.9 %) on trees with DBH ranging from 41 to 60 cm, and 13 wounds (23.2 %) on trees with $DBH > 60$ cm. In each DBH class, the frequency of extraction wounds was higher than the frequency of felling wounds. This distribution of wounded trees, with the major frequency in the two central DBH classes (20–40 cm and 41–60 cm) is mainly due to the structure of the uneven-aged forest. In these forests, normally there are small groups of trees coetaneous, with high density and the operation of “thinning” is more intensive in the groups of the two central DBH classes. The probability of damage depends on the felling intensity and the trees density (Picchio et al. 2012). Residually damaged trees were highly concentrated near

Table 2 Frequency of wounds for each DBH class by cause of wound

Cause of wound	DBH (cm)							
	<20		20–40		41–60		>60	
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)
Felling	1	25.0	2	13.3	5	20.8	6	46.2
Extraction	3	75.0	13	86.7	19	79.2	7	53.8

the skid trails as showed in other studies (Solgi and Najafi 2007; Ezzati and Najafi 2010).

The results of the Spearman correlation analysis are shown in Table 3. The only statistically significant correlation was between wound severity and wound position ($P < 0.01$). In this case, the correlation was negative because the wounds closer to the ground were more severe. This is due mainly to the skidded logs impacting the standing trees and was rarely due to the impact of the trees with the tractor.

The average annual growth of wounded and unwounded beech trees after 12 years is shown in Table 4. Overall, there was no significant difference ($P > 0.05$) in the diameter increment of wounded trees compared with unwounded trees. In detail, the reduction of diameter growth in wounded beech trees was related only to wound size, severity and condition but only for some specific typologies of wounds characteristics. In order of importance, wounds $>200 \text{ cm}^2$ led to greatest reduction of diameter growth (29.3 %; $P < 0.05$), followed by the wound condition, defined as “decayed”, (which caused a RDG of 15.3 % ($P < 0.001$)) and lastly the depth of the wound. When the damage has affected the wood fibres, the average RDG was 13.2 % ($P < 0.001$). Also for a Norway spruce forest, width and depth of the logging injury correlated positively with the decrease in growth (Isomäki and Kallio 1974).

Wound size is one of the most important characteristics related to decay (Hunt and Krueger 1962; Han and Kellogg 2000). As found also by Vasiliauskas (2001), most of the resulting wounds occur near the base of the tree and are up to 200 cm^2 in size. Since logging injury usually occurs on the lower parts of trunk, wound decay in a tree affects the most valuable timber (Picchio et al. 2011; Tavankar et al. 2013).

Of all wounds recorded on beech trees, 55.3 % (31 wounds) occurred at a height lower than 0.3 m from the ground, 26.8 % (15 wounds) occurred between 0.3 to 1 m height and 17.9 % (10 wounds) occurred at a height higher than 1 m.

The results of this study indicated that most skidder-logging wounds (55.3 %) occurred in the near ground level of the bole ($< 0.3 \text{ m}$) and were associated with a

10.7 % reduction in diameter growth relative to unwounded trees. The location of wounds from ground-based logging operations observed in this study is consistent with results from other published studies (Naghdi et al. 2008; Tavankar et al. 2011). The higher incidence of damage near the base of the tree is important because the butt log is generally the most valuable log in a tree (Bettinger and Kellogg 1993). Han and Kellogg (2000) suggested that artificial tree protection rigging such as rub pads along extraction corridors should be used to prevent damage on stump and stems.

Twelve years after the trees were wounded, 37.5 % of wounds were completely healed, 32.1 % were still open and 30.4 % were decayed. Trees with decayed wounds showed significant reduced diameter growth in comparison with undamaged ones ($P < 0.01$).

The multiple regression analyses applied to test the relationship between diameter growth and tree DBH (closely related to age) of both wounded and unwounded were statistically significant ($P < 0.001$). The results are shown in Eq. 2 and Fig. 1:

$$DG = 8.27 - (0.037 \times DBH) - (0.415 \times TC) \quad (3)$$

$$(R^2 \text{ adjusted} = 0.162; SE = 1.521)$$

Where DG is the diameter growth of tree (mm year^{-1}), and TC is the tree condition (0 for unwounded and 1 for wounded).

Diameter growth of wounded trees was lower than for unwounded trees in small trees ($DBH < 55 \text{ cm}$), and the greater the tree diameter the smaller the differences. Thus, growth of wounded and unwounded trees was similar when DBH was greater than 55 cm.

The regression analysis between wound size and tree diameter at the time of logging was also statistically significant ($P < 0.001$), and the results are shown in Eq. 3 and Fig. 2:

$$WS = 72.6 * \ln(DBH) - 128.6 \quad (4)$$

$$(R^2 \text{ adjusted} = 0.373; SE = 45.37)$$

Where WS is the wound size. Only 37.3 % of the variability of the wound size was explained by DBH.

The regression analysis showed diameter growth of wounded trees increased with increasing wound position (height from ground level), (Fig. 3).

The results of the regression analysis between DG of wounded trees and wound position (WP) indicated two different situations depending on wound position. Thus, the relationship was significant for wounds positioned below 0.5 m of height (Fig. 3 and Eq. 4; $R^2 \text{ adjusted} = 0.95$; $SE = 0.24$; $F = 579.7$, $P < 0.01$), but there was no relationship between DG and wounds positioned over 0.5 m from ground level ($R^2 \text{ adjusted} = 0.25$, $F = 6.99$, $P < 0.05$).

Table 3 Results of Spearman correlation analysis

Variables	N	Correlation coefficient	Sig. (2-tailed)
DBH vs. wound severity	56	0.025	0.853
DBH vs. wound position	56	0.042	0.751
Wound size vs. wound position	56	0.131	0.336
Wound size vs. wound severity	56	-0.018	0.893
Wound position vs. wound severity	56	-0.747	0.000**

** $\alpha = 0.01$.

Table 4 Mean \pm SD of diameter growth of unwounded, wounded and reduction of diameter growth (RDG) of beech trees 12 years after wound occurrence in related to wounds characteristics

Wounds characteristic	<i>n</i> paired	Unwounded (mm.year ⁻¹)	Wounded (mm.year ⁻¹)	RDG (%)	<i>t</i> paired	<i>P</i> value
Wound position (m)						
<0.3	31	6.63 \pm 1.8	5.92 \pm 1.8	10.7	1.48	0.148
0.3–1	15	6.66 \pm 0.6	6.06 \pm 1.4	9.9	1.64	0.124
>1	10	6.35 \pm 2.2	6.45 \pm 0.9	-1.6	0.18	0.862
Wound size (cm ²)						
<100	9	5.96 \pm 1.1	5.93 \pm 0.9	0.5	0.04	0.966
101–200	31	6.25 \pm 1.2	6.20 \pm 1.0	0.8	0.24	0.812
>201	16	7.36 \pm 1.5	5.21 \pm 2.1	29.3	2.92*	0.010
Wound severity						
Bark	9	6.74 \pm 0.9	6.72 \pm 0.9	0.3	0.03	0.972
Phloem	14	6.50 \pm 0.9	6.46 \pm 1.1	0.6	0.07	0.871
Wood	33	6.60 \pm 1.1	5.73 \pm 1.4	13.2	4.22**	0.000
Wound condition						
Healed	21	6.72 \pm 0.8	6.60 \pm 1.0	1.8	1.27	0.217
Still open	18	6.67 \pm 1.0	5.88 \pm 1.4	11.8	1.94	0.069
Decayed	17	6.54 \pm 1.0	5.54 \pm 1.5	15.3	5.48**	0.000
All trees	56	6.59 \pm 1.65	6.05 \pm 1.54	8.1	1.80	0.078

* $\alpha = 0.05$; ** $\alpha = 0.01$.

$$DG = 1.09 + 28.46 \times WP \quad (5)$$

Where DG is diameter growth (mm.year⁻¹) and WP is wound position (m) from the ground level.

This result suggests that the severity of wounds increased with decreasing height from ground level and/or due to an increased likelihood of pathogen attack in wounds close to ground level.

The regression analysis between the reduction of diameter growth and ratio of wound size to stem area is shown in Fig. 4. The results indicated that the reduction of diameter growth increased with increasing ratio of wound size to stem area above 0.1 ($F = 24.9$, $P < 0.01$).

The results of regression analysis are shown following equation:

$$RDG\% = 491.07(RWS)^2 - 87.81(RWS) + 6.75 \quad (6)$$

(R^2 adjusted = 0.51; SE = 4.62)

Where RDG is the reduction of diameter growth and RWS is the ratio of wound size to stem area.

This study evaluated the effect of logging wounds on diameter growth of standing beech trees in the Caspian forest 12 years after selection logging. Pre-harvest planning and identification of the winching area before logging operation commences can reduce damage to the

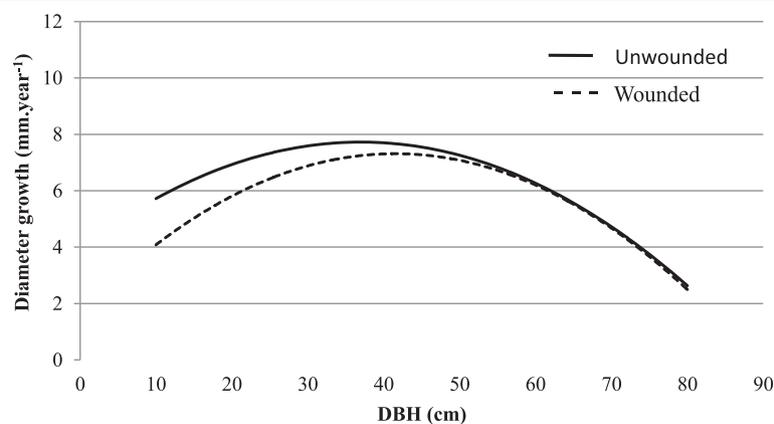
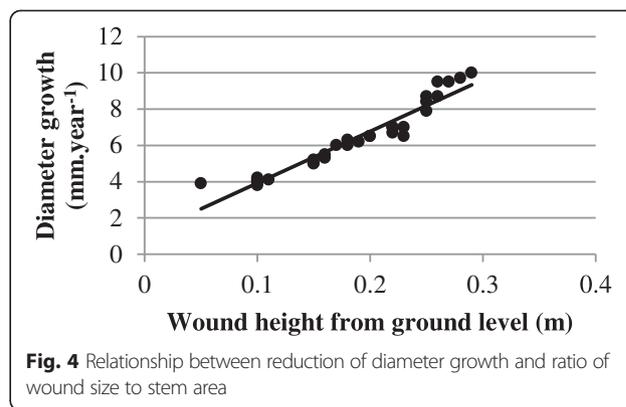
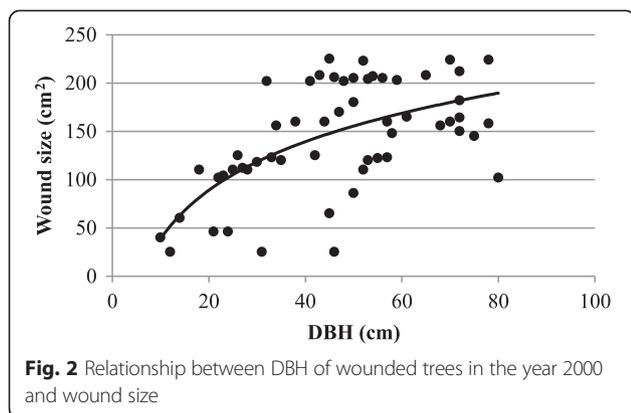


Fig. 1 Relationship between annual diameter growth of wounded and unwounded trees and their DBH in the year 2000



standing trees in these forests. Also, skid-trail planning before a felling operation can reduce the skidding damage (Naghdi et al. 2008; Majnounian et al. 2009). The skidder and chain saw operators are important factors that can influence productivity and environmental impacts during logging operations. It has been reported that residual stand damage decreases substantially by careful planning and skilful operators (Cline et al. 1991; Pinard et al. 30). Nikooy et al. (2010) reported that skilled operation of a skidder can decrease the level of damage. So training of forest workers can be useful to reducing logging damage to the residual stand. All workers should be made aware of the purpose of the selection cutting and that both minor and major injuries to the residual stands as well as excessive ground disturbance may result in significant volume losses (Davis and Nyland 1991) and natural regeneration of the forest (Picchio et al. 2012).

Conclusions

This study shows that logging wounds cause a substantial reduction (8.1 %) in diameter growth of residual trees left after a selective logging operation. Our results showed that the effect of bole wounds on diameter growth depended on their severity, location and size, and tree age. Young beech trees were more sensitive to

logging wounds. Residual stand damage is an unavoidable risk of selection cutting, but the level of damage should be minimised to assure quality timber from future harvests. The results of this study indicated also that tree extraction has a high potential for residual stand damage, and intensive wounds occurred during extraction operations. It is important to minimise damage, both to the number of trees damaged and the extent of damage to any individual tree.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors read and approved the final manuscript.

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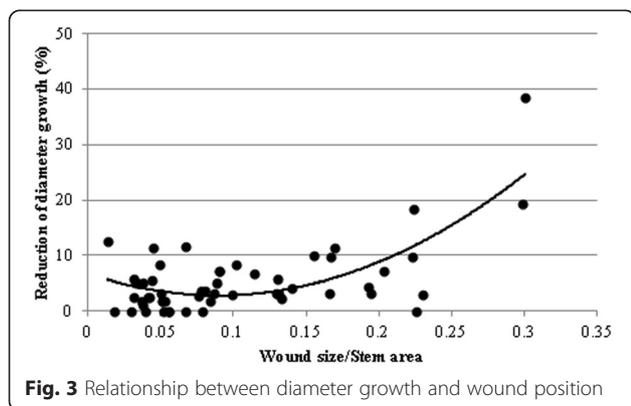
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