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# Logging damage to residual trees during sustainable harvesting of uneven-age stands in the Hyrcanian forests of Iran

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## Abstract

**Background:** The frequency of wounded trees and intensity of wounds during logging operations can have serious impacts on stand growth and forest sustainability. The aims of the study were to evaluate and compare stand (tree and regeneration) damage level, wound characteristics, and damage types occurring when using a cable skidder in salvage logging and selection cutting.

**Methods:** This study was conducted on four sites of mixed uneven-aged hardwood stands in the Hyrcanian forests of Iran. At two sites, salvage logging was applied (SL1 and SL2), and low-intensity selection cutting (SC1 and SC2) was applied at the other two. A systematic plot sampling design was used on the study area for damage assessment.

**Results:** The percentage of regenerating trees damaged was 2.8, 2.1, 4.3, 1.4 %, in SL1, SL2, SC1, and SC2, respectively. The corresponding percentage of damaged trees was 4.3, 3.7, 4.9, 1.7 %. Most of the damage (48–79%) to the stand occurred during the winching stage at all the sites. Most of the wounds were located on the bole (51–78%). The average wound height and wound size at selection cutting sites were significantly higher than at the salvage logging sites. The incidence of high-intensity wounds at the salvage logging sites (55% at SL1 and 57% at SL2) was higher than at the selection cutting sites (24% in SC1 and 30% in SC2). Regenerating beech (*Fagus orienalis* Lipsky) and alder (*Alnus subcordata* C.A.Mey) had the highest incidence of damage. The number of damaged trees increased with increasing winching distance.

**Conclusion:** Damage levels in stands during salvage logging and low-intensity selection cutting are lower (about a quarter) than the damage level to residual trees (12–23%) and regeneration (5–11%) from conventional selection cutting in uneven-aged mixed hardwood stands in the Hyrcanian forests. Because of the ecological and conservation value of deadwood, if the incidence of wind-fallen trees is low, the wood should be left in forest stands due to the high cost of salvage logging and the damage caused to residual and regenerating trees.

**Keywords:** cable skidder, logging damage, salvage logging, selection cutting, uneven-aged forest

## Introduction

Forest managers are concerned about the potential damage to residual trees from cyclic harvest re-entries into the same stand in forests managed under a selection cutting system (Picchio et al. 2012; Tavankar et al. 2015a). One of the most important challenges of single-tree selection cutting is damage to residual trees (Whitman et al. 1997; Sist et al. 2003; Nikooy et al. 2010; Behjou 2014). The damage caused to residual trees could endanger the goal of single-tree selection cutting because of a decrease in growth, increased incidence of decaying wood, and higher probability of mortality for severely damaged trees (Tavankar et al. 2017a). It should be noted that damage does not always lead to loss of quality or disease entry. Quality loss and fungi attack risk depend on wound intensity, tree size and species (Tavankar et al. 2015b, 2017c). After a tree is wounded, decay fungi may be confined to compartments within the tree through a process called compartmentalisation, but the ability to compartmentalise varies by tree species (Guyon et al. 2017). For example, fresh wounds on Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) or ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) are often covered with resin. However, wounds on non-resinous tree species, such as true firs (*Abies* spp.), generally result in more decay than do wounds on resinous species, such as pines (*Pinus* spp.).

Globally, salvage logging is becoming more prominent for active forest restoration purposes (Mercurio et al. 2010; Frattaroli et al. 2017) and to recover economic value from timber in disturbed forests (Kärhä et al. 2018). Logging damage to residual trees during selection cutting and salvage logging, can cause substantial loss of potential revenue at the final harvest due to reduced timber quality (Kiser 2011), reduced recovery of logs from damaged trees, and reduced tree growth (Vasiliauskas 2001). In some cases, logging damage to residual trees can result in their death (Tavankar et al. 2017b). The frequency of wounded trees and severity of wounds during logging operations may have detrimental impacts on stand growth and forest sustainability. Logging wounds on residual trees often become an entry points for fungal invasion (Vasiliauskas 2001), particularly in wounds that are close to ground level or in tree roots (Bettinger & Kellogg 1993; Camp 2002). Wounding can result in stem distortion and substantial losses of the volume and value of the final product (Meadows 1993; Lo Monaco et al. 2015). The most common (>90%) type of tree wounding is logging damage (Marchi et al. 2014; Tavankar et al. 2017a). Wound characteristics such as size, location, and severity are the main factors determining wound-healing ability and the impact on diameter growth of trees (Tavankar et al. 2015b). Bole wounds on residual trees are among the most common types of cable-skidder logging damage (Nikooy et al. 2010; Jourgholami et al. 2012; Tavankar et al. 2015a). The amount of diameter growth reduction in decayed wounds in beech (*Fagus orientalis* Lipsky) trees was reported to be 15.3% (Tavankar et al. 2015b). In an 85-year-old stand of spruce (*Picea abies* (L.) Karst.), in Belarus, which 6% of trees had 5-year-old logging injuries, saw-log yield decreased by 11 $m^3$ $ha^{-1}$ (Kovbasa 1996). Financial revenues at final harvesting in spruce (*Picea abies* (L.) Karst.) stands decreased by 7–20% due to wound decay in Austria (Steyrer 1992).

The extent and intensity of residual tree damage during logging operation depend on the harvest intensity (Fjeld & Granhus 1998; Gullison & Hardner 1993; Han et al. 2000; Sist et al. 2003; Behjo 2014; Tavankar et al. 2015a), site characteristics and topography (Picchio et al. 2012; Tavankar et al. 2015a), type and sizes of harvesting equipment (Bragg et al. 1994; Spinelli et al. 2010; Marchi et al. 2014), pattern of roads and skid trails (Gullison & Hardner 1993; Nikooy & Ershadifar 2012; Danilović et al. 2015), and experience and education level of logging workers (Nikooy et al. 2010).

Hyrcanian forests in Iran cover 1.8 million ha of the northern slopes of Alborz mountain from coastal of Caspian Sea to an elevation of 2,800 m. High biodiversity (growing about 148 woody species) and extensive wildlife habitat highlight the ecological importance of these forests. The structure of these forests is mixed broadleaves and they are mainly managed as uneven-aged high forests. The Hyrcanian forests have been managed by different silvicultural treatments: shelter wood-cutting from 1970 to 2000, selection cutting from 2000 to 2014, and restricted cutting to damaged and fallen trees from 2016 to the present. The main natural disturbance in the Hyrcanian mountain forests in the northern Iran is wind damage and some trees in these forests are blown over every year. In order to minimise the impacts of biological agents (fungi and insects) and to make active forest restoration, forest managers apply salvage logging in damaged stands. Another purpose of salvage logging is to earn income from the forest; however, it is not planned. In fact, the extensive removal of dead-wood resources by post-disturbance salvage logging may decrease biodiversity (Thorn et al. 2017). Salvage logging following windstorms removes the storm-created pit and mount system, leading to homogenised structures, altered microsite diversity, and altered assemblages of vascular plants (Waldron et al. 2014).

Damage level to residual trees during conventional selection cutting by chainsaw and cable skidder logging operation in Hyrcanian forests were previously reported (Behjou 2014; Nikooy et al. 2010; Tavankar et al. 2017a). However, there is little information about stand damage during salvage logging and low-intensity selection cutting in the Hyrcanian forests. The aims of the research were to evaluate and compare stand (tree and regeneration) damage level, wound characteristics, damaged types by salvage logging and selection cutting.

## Methods

The study was conducted in district No. 3 of the Nav watershed forest area between 37° 38' 34" to 37° 42' 21" N and 48° 48' 44" to 48° 52' 30" E, in Guilan province. Average rainfall is 1,050 mm $yr^{-1}$, with the heaviest rainfall in the summer and autumn. The soils are *Alfisols*, well-drained, and the texture varies between sandy clay loam to clay loam. The average daily temperature ranges from a few degrees below 0°C in December, January, and February, and up to +26°C during the summer. Dendrometric stand characteristics before logging operations commenced are shown in Table 1. Logging damage to residual trees were evaluated in four parcels in this district. In two parcels (No. 319 and 331) salvage logging was applied (SL1 and SL2), and in two other parcels (No. 318 and 321) low intensity selection cutting (SC1 and SC2) was applied. Dendrometric stand characteristics before logging, skid trail and corridors features, and dendrometric characteristics of extracted wood are shown in Tables 1, 2, and 3, respectively. Logging operations were carried out in summer 2016.

TABLE 1: Dendrometric stand characteristics before logging in four logging sites (SL: salvage logging, SC: selection cutting)

| | Logging site | | | |
|---|---|---|---|---|
| Item | SL1 | SL2 | SC1 | SC2 |
| Elevation (a.s.l. m) | 1,300–1,450 | 1,250–1,380 | 1,300–1,450 | 1,270–1,390 |
| Area (ha) | 33 | 29 | 32 | 27 |
| Tree density (stems $ha^{-1}$) | 279 | 277 | 170 | 281 |
| Mean DBH (cm) | 20.8 | 21.1 | 21.3 | 19.6 |
| Mean basal area ($m^2$ $ha^{-1}$) | 23.7 | 24.6 | 22.3 | 24.8 |
| Mean tree height (m) | 19.7 | 18.6 | 20.2 | 19.3 |
| Standing volume ($m^3$ $ha^{-1}$) | 299 | 250 | 196 | 205 |
| Mean ground slope (%) | 25.2 | 31.0 | 23.0 | 24.8 |
| Tree species composition (%) | Beech (57), Hornbeam (19), Maple (9), Alder (5), Other sp. (10) | Beech (65), Maple (20), Alder (7), Hornbeam (5), Other sp. (3) | Beech (60), Alder (20), Maple (8), Hornbeam (8), Other sp. (4) | Beech (69), Hornbeam (19), Maple (6), Alder (3), Other sp. (3) |

TABLE 2: Skid trail and corridors features in four logging sites (SL: salvage logging, SC: selection cutting)

| | Logging site | | | |
|---|---|---|---|---|
| Item | SL1 | SL2 | SC1 | SC2 |
| Skid trail length density (m $ha^{-1}$) | 22.7 | 19.6 | 20.1 | 22.5 |
| Mean skid trail slope (%) | 8.3 | 10.2 | 12.3 | 10.9 |
| Mean winching strip length (m) | 46.4 | 41.7 | 27.5 | 23.3 |
| Mean winching strip slope (%) | 39.9 | 41.0 | 31.5 | 38.6 |
| Mean number of logs per turn (N) | 1.9 | 1.8 | 1.8 | 1.9 |
| Mean log volume per turn ($m^3$) | 8.6 | 8.8 | 8.2 | 8.1 |

TABLE 3: Dendrometric characteristics of extracted wood in four logging sites (SL: salvage logging, SC: selection cutting)

| | Logging site | | | |
|---|---|---|---|---|
| Extracted wood | SL1 | SL2 | SC1 | SC2 |
| Parameters of extracted trees | | | | |
| Total number (stem) | 46 | 38 | 40 | 30 |
| Number density (stem $ha^{-1}$) | 1.4 | 1.3 | 1.3 | 1.1 |
| Total volume ($m^3$) | 308 | 240 | 348 | 120 |
| Volume density ($m^3$ $ha^{-1}$) | 6.7 | 5.8 | 8.7 | 4.0 |
| Mean DBH (cm) | 87.6 | 83.1 | 53.6 | 51.4 |
| Mean bole length (m) | 17.2 | 17.6 | 16.5 | 15.8 |
| Mean volume ($m^3$) | 6.4 | 6.1 | 4.3 | 4.2 |
| Parameter of extracted logs | | | | |
| Total number | 112 | 90 | 91 | 68 |
| Mean length (m) | 6.8 | 7.1 | 6.6 | 6.5 |
| Mean small diameter (cm) | 34.5 | 35.3 | 41.2 | 39.1 |
| Mean large diameter (cm) | 65.4 | 69.4 | 69.3 | 68.4 |
| Mean volume ($m^3$) | 4.5 | 4.9 | 4.7 | 4.2 |

Harvesting intensity in low selection cutting sites was light (4.4% and 1.9% of standing volume) (Tables 1 and 3) in comparison with conventional selection cutting in these forests. Trees were selected on the basis of close-to-nature silvicultural aims, i.e. creation of canopy gaps, especially in dense areas, regulation of light intensity on the forest floor to facilitate natural regeneration of beech trees, regulation of tree species composition, improve tree quality, and provide economic returns.

Ground-based timber extraction methods were applied in all stands. Skid trail and corridor features are shown in Table 2. Felling was done by chainsaw and timber extraction was done with a Timberjack 450C wheeled skidder (mass 9.8 T, width 3.8 m, length 6.4 m). The selected trees, which were scattered throughout the study area, were felled and cut into merchantable lengths (mostly 7.8 m, but occasionally 5.2 m) or to a 20 cm diameter under bark. Logs were then winched from the felling site (downhill) toward the skidder and skidded to roadside landings. The skidding operation was limited to the constructed skid trails. Before felling, the skid trails were planed and constructed. The skidding team consisted of a driver, a chaser, and a feller. The winching operation was controlled manually.

### Data collection

The study used a systematic sampling design to evaluate stand damage (Meadows 1993; Lotfalian et al. 2008; Nikooy et al. 2010). A grid with 100-m x 100-m spacing was laid out across the stand and a circular 0.1 ha plots placed at each grid intersection. The species, diameter at breast height (DBH) and condition (healthy or damaged) of all trees (DBH ≥7.5 cm) and natural regeneration (DBH <7.5 cm) were measured and recorded in each plot. The following parameters were recorded for each damaged tree: cause of damage (i.e. from felling, winching and skidding); damage location (i.e. crown, bole or root); and depth of damage. Because bark thickness differs among species found in the forest, the depth of damage was based on the nature of damaged tissue, i.e. I) low, bark removed, II) medium, phloem damaged, and III) high, wood damaged. The height of the wound centre from ground level was measured and the wound size was determined by measuring the maximum length, width and the ellipsoid surface area (Picchio et al. 2011). The shortest distance between the stumps of the cut trees and the skid trail was measured and denoted as the winching distance (WD). A count of damaged trees was undertaken at up to a distance of 5 m from each side of the winching route center.

### Data analysis

The proportion of residual trees damaged in each sample plot ($P_i$) was calculated as follows:

$$P_i = n_d / n_t \quad (1)$$

where, $n_d$ is number of damaged trees, and $n_t$ is total number of trees in the sample plot. To account for the non-normality of these data, they were transformed ($P_t$) prior to analysis as follows:

$$P_t = \mathit{Arcsin}\ \sqrt{P_i} \quad (2)$$

Following checking for normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene test), ANOVA and Duncan tests were applied to analyse the effect of different factors on the percentage of damaged trees and regeneration, wound size, and wound height. Regression analysis and Pearson correlation test were applied to test the relationship between number of damaged trees and winching distance at the logging sites. A non-parametric test was used to analyze the effect of logging methods on the wound severity, wound location, damage percentage at logging stages. All analyses were performed using SPSS 20 (IBM, NY, USA).

## Results

ANOVA results showed that there were significant differences in the percentage of regeneration and trees damaged across the different logging sites. The percentage of damaged regeneration in SL1, SL2, SC1, and SC2 was 2.8, 2.1, 4.3, and 1.4 %, respectively (Fig. 1a) whereas the percentage of damaged trees in SL1, SL2, SC1, and SC2 were 4.3, 3.7, 4.9, and 1.7 %, respectively (Fig. 1b). Duncan multiple tests showed that the percentage of damaged regeneration and trees at SC1 were significantly higher than at the other sites (Fig. 1a, and Fig. 1b). ANOVA results also showed that there were significant difference in wound height and size among sites (Table 4). Average wound height and size in the selection cutting sites (62.8 cm and 330 $cm^2$ in SC1 and 62.3 cm and 311.1 $cm^2$ in SC2) were significantly higher than at the salvage logging sites (38.7 cm and 208.3 $cm^2$ in SL1 versus 40.4 cm and 206.1 $cm^2$, respectively).

Most damage (48–79%) to stands (both trees and regeneration) across all the all logging sites occurred during the winching operation (Fig. 2a). The extent of winching damage at the salvage logging sites (79% in SL1 and 73% in SL2) was considerably higher than at the selection cutting sites (50% in SC1 and 48% in SC2). Deep wounds were most abundant at the salvage logging sites and shallow wounds were most common at the selection felling sites. The number of serious wounds in the salvage logging sites (55% in SL1 and 57% in SL2) was higher than at the selection cutting sites (24% in SC1 and 30% in SC2).

Significant differences in the percentage of damage at different logging stages and wound severity were found among logging sites (Table 5). The most frequent damage location across all logging sites was the bole (Fig. 3a). The extent of bole damage at the salvage logging sites (76% in SL1 and 78% in SL2) was higher than selection cutting sites (55% in SC1 and 51% in SC2). Crown damage was observed only in the selection cutting sites. Root damage was more common at the salvage logging sites (23.6% in SL1 and 22% in SL2) compared with the selection cutting sites (14.2% in SC1 and 11.9% in SC2).

Most damage occurred to residual trees in the 20–40 cm diameter class across all the logging sites (Fig. 3-b). More damage to larger trees (DBH >60 cm) was recorded at the selection cutting sites than at the salvage logging sites. The Chi-square tests showed that logging methods had a significant effect on damage location and the size of damaged trees (Table 5).

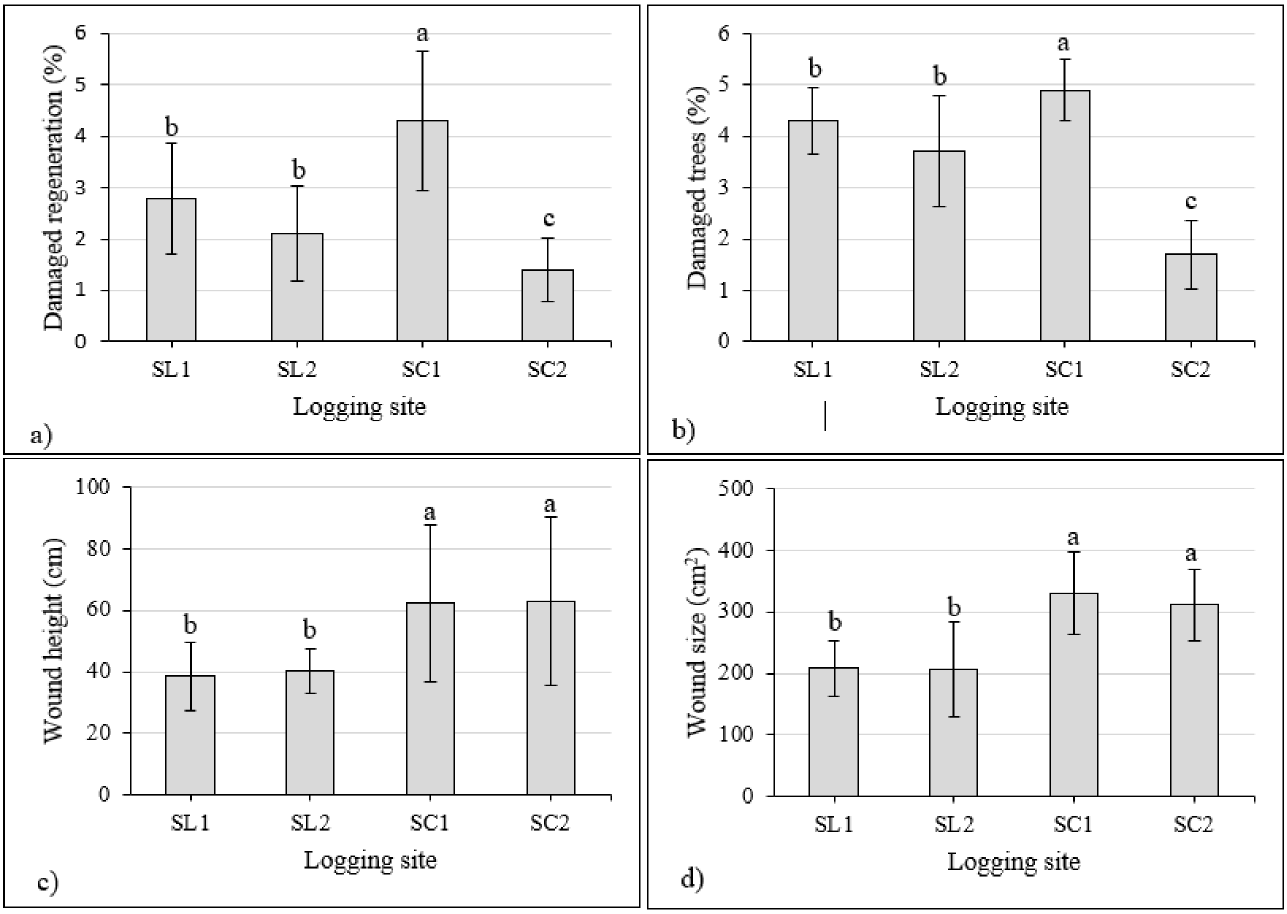



FIGURE 1: Damaged regeneration (a) and trees (b), height (c) and size (d) of wounds in in four logging sites (SL: salvage logging, SC: selection cutting)

TABLE 4: ANOVA results for analysis of logging methods on damage percentage to regeneration and trees, and height and size of bole wounds

| Variable | SS | DF | MS | F | P value |
|---|---|---|---|---|---|
| Regeneration | 0.131 | 3 | 0.044 | 21.99 | 0.000 |
| Tree | 0.151 | 3 | 0.050 | 80.14 | 0.000 |
| Wound height | 47,705 | 3 | 15,901 | 18.9 | 0.000 |
| Wound size | 1,165,499 | 3 | 388,499 | 102.6 | 0.000 |

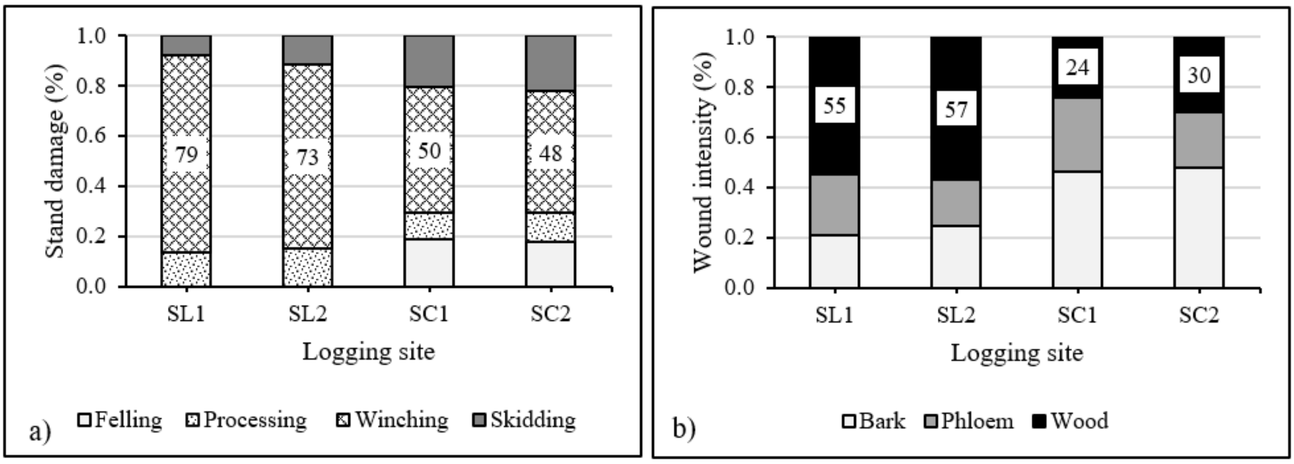
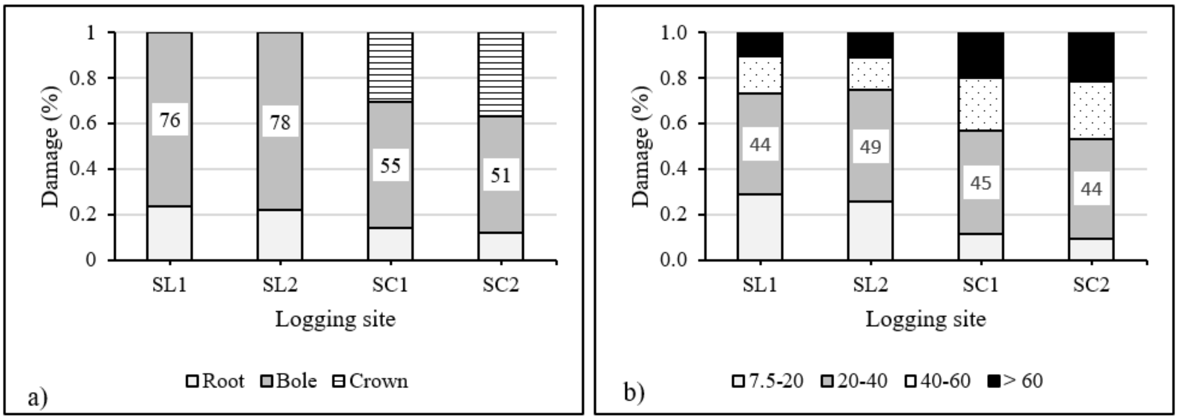



FIGURE 2: Stand damage during logging stages (a), and intensity of bole wounds (b) in in four logging sites (SL: salvage logging, SC: selection cutting)

TABLE 5: Results of chi-square tests to analyze the effect of logging methods on the wound severity, wound location, damage percentages at logging stages

| Variable | DF | Chi-Square | P Value |
|---|---|---|---|
| Logging stage | 9 | 58.8 | 0.000 |
| Wound intensity | 6 | 40.7 | 0.000 |
| Damage location | 6 | 83.8 | 0.000 |
| Damaged DBH | 9 | 26.5 | 0.002 |

FIGURE 3: Damage location (a) and DBH (b) of damaged trees in in four logging sites (SL: salvage logging, SC: selection cutting)




Beech (*Fagus orienalis*) was the most common regenerating species that was damaged across all the logging sites (Fig. 4a). Damaged beech regeneration at the selection cutting sites (4.3% in SC1 and 4.5% in SC2) was more common than at the salvage logging sites (3.3% in SL1 and 3.0% in SL2). The most commonly damaged tree species across all logging sites was alder (*Alnus subcordata* C.A.Mey) (Fig. 4b). In this case the percentage of damaged alder trees at the salvage logging sites (8.2% in SL1 and 7.6% in SL2) was higher than at the selection cutting sites (5.6% in SC1 and 4.2% in SC2). Results of the regression analysis and Pearson correlation tests showed that there was a significant positive correlation between winching distance and number of damaged trees (Table 6). Not unexpectedly, the number of damaged trees increased when winching distance increased in the all logging sites (Fig. 5).

## Discussion

Results of this study showed that less than 5% of regeneration and residual trees (i.e. 2.1 to 2.8% of regeneration and 3.7 to 4.3% of residual trees in salvage logging sites, and 1.4 to 4.3% of regeneration and 1.7 to 4.9% of residual trees in the selection cutting sites) were damaged using the harvesting methods employed. This was considerably lower than damage levels found in conventional selection cutting operations in the Hyrcanian forests. For example, Tavankar et al. (2015a) found damage levels of 12 to 23 percent to residual trees and 5 to 11 percent to regeneration.

Other studies in Caspian forests also found higher levels of damage to residual trees following selection cutting, e.g. 15.5% by Lotfalian et al. (2008), 19% by Naghdi et al. (2008), 19.7% by Nikooy et al. (2010) and 16.9% by Tavankar et al. (2015b). Even higher levels of damage (16–32%) to residual trees were found in a cut-to-length thinning operation in a young redwood (*Sequoia sempervirens* (D. Don) Endle.) forest in northern California (Hwang et al. 2018). Silva et al. (2018) evaluate the bole and crown damage and the incidence of leaning trees in the residual stand following timber harvesting in a secondary Atlantic rainforest in southern Brazil. They found that on average, 26% of the residual trees suffered some kind of damage, with 12.1% suffering moderate or severe damage.

Yilmaz and Akay (2008) in Turkish forests found that 14% of residual trees were damaged during felling and skidding operation. The study carried out by Ficklin et al. (1997) showed that about 22% of the residual trees was damaged by skidding operation using wheeled skidder. In a study conducted by Hartsoug (2003) in north-eastern Californian forests, it was shown that 23% of residual trees were damaged during ground-based logging. Hosseini et al. (2000) compared damage to natural regeneration caused by two logging systems (skidder and cable system) in the Caspian forests of Iran. They showed that damage to regeneration during log skidding were significantly more severe than in log yarding (11% vs. 5%). Whitman et al. (1997) showed that damage level to seedlings in a single tree selection cutting operation in northern Belize was 15%. The amount of damage to regeneration and trees obtained from our study was lower than previous studies in hardwood selection cuttings. The low intensity of logging operations in our

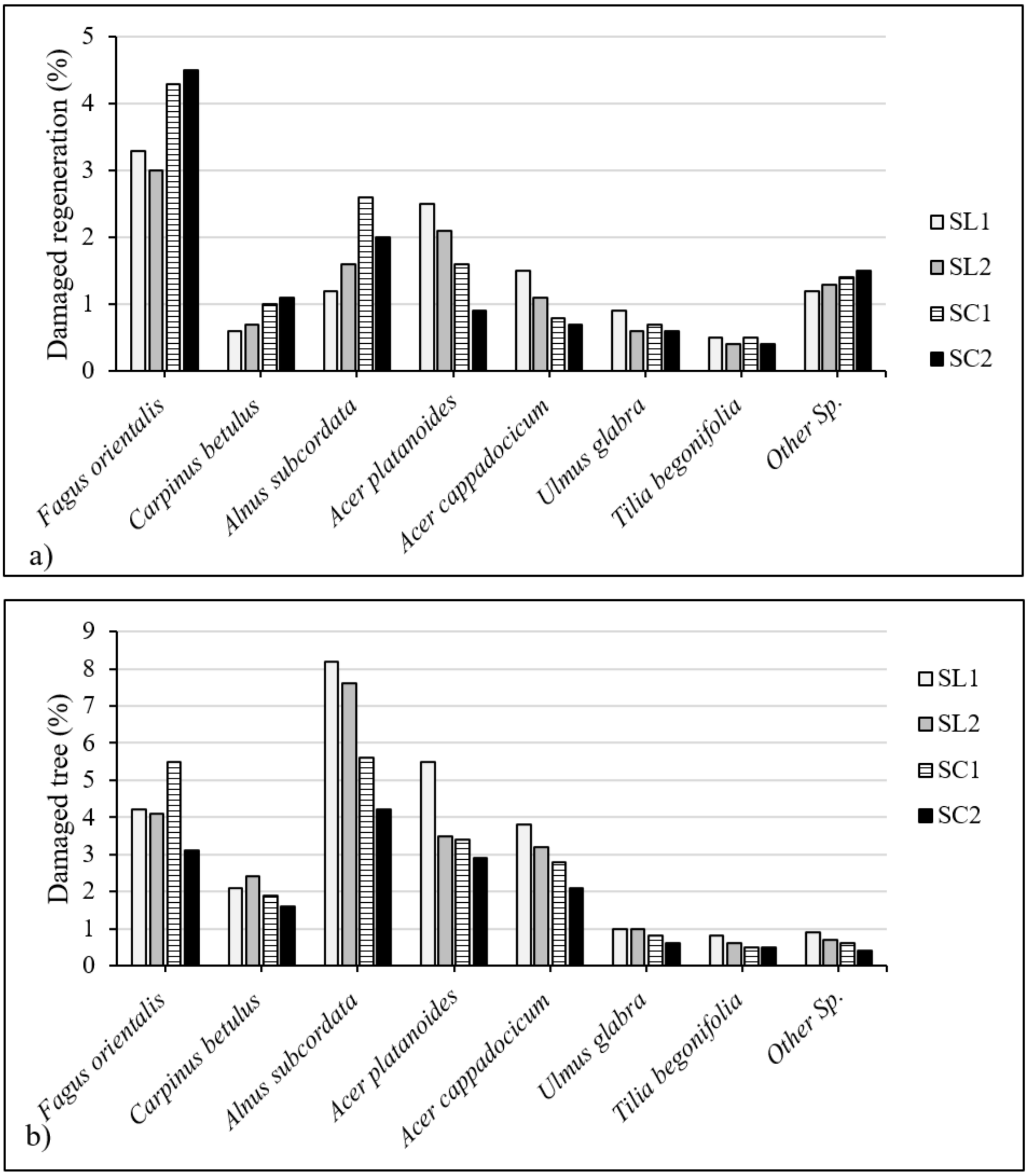



FIGURE 4: Damage to regeneration (a) and tree (b) species in in four logging sites (SL: salvage logging, SC: selection cutting)

TABLE 6: Results of regression analysis for relationship between number of damaged trees and winching distance in the logging sites

| Logging site | n | Equation | SE | $R^2$ adjusted | F value | P value |
|---|---|---|---|---|---|---|
| SL1 | 78 | $y = 1.1117x^{0.615}$ | 0.211 | 0.586 | 109.8 | 0.000 |
| SL2 | 66 | $y = 0.6672x^{0.7197}$ | 0.228 | 0.709 | 159.3 | 0.000 |
| SC1 | 78 | $y = 0.6277x^{0.7961}$ | 0.216 | 0.761 | 245.7 | 0.000 |
| SC2 | 72 | $y = 0.1802x^{1.1828}$ | 0.258 | 0.731 | 194.2 | 0.000 |

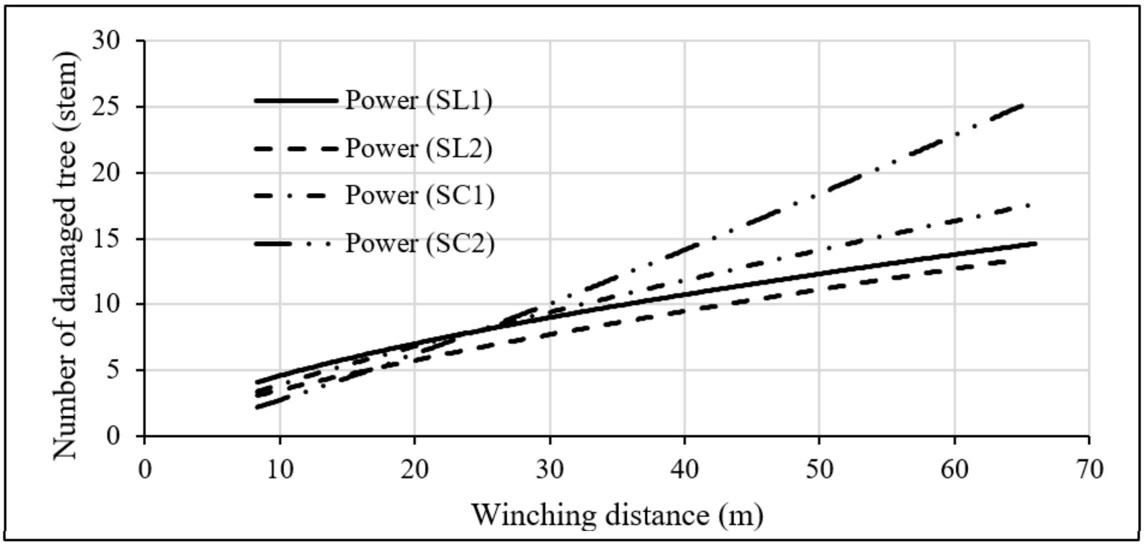



FIGURE 5: Relationship between number of damaged trees and winching distance in in four logging sites (SL: salvage logging, SC: selection cutting)

study is likely to be the main reason of low levels of damage observed in the residual stands.

Intensity, size and location of bole wounds are important factors in bole decay (Tavankar & Bonyad 2014; Câmpu & Borz, 2017). Results from our study showed that the average wound height and size at the selection cutting sites were significantly greater than at the salvage logging sites. This is most likely due to absence of the felling stage in salvage logging sites. Previous studies have shown that the size and height of felling wounds were higher than winching and skidding wounds (Tavankar et al. 2017b). One of the most important factors determining the healing rate of injured trees, is wound height (Vasiliauskas 2001; Tavankar et al. 2017b). The wounds near the ground are more likely to be exposed to wood rot-fungi than other wounds (Camp 2002; Metslaid et al. 2018). The average wound sizes in selection cutting sites (SC1 and SC2) and salvage logging sites (SL1 and SL2) were 330 $cm^2$, 311 $cm^2$, 208 $cm^2$, and 206 $cm^2$, respectively.

In the years after the wound is created, diameter growth (Tavankar et al. 2015b; Hecht 2015) and the quality of the wood (Bonyad & Tavankar 2016) are more affected by the size of the wound. Wounds larger than 1000 $cm^2$ are less likely to heal, ultimately leading to wood decay (Tavankar & Bonyad 2014). The size of the bole wounds created in during the winching and skidding stages has been reported as being smaller compared with those created during the felling stage (Tavankar et al. 2015a; Behjou 2014). Trees with injuries in the lower parts of stem and the root collar have the highest risk of decay.

At all the logging sites, most of tree and regeneration damage (48–79%) occurred during the winching stage. Winching is the major cause of damage to regeneration during cable skidder logging (Nikooy et al. 2010; Picchio et al. 2011; Badraghi el al. 2015). The share of winching damage at the salvage logging sites (79% in SL1 and 73% in SL2) was more than at the selection cutting sites (50% in SC1 and 48% in SC2). Picchio et al. (2012) and Marchi et al. (2014) note that snatch blocks can help to preserve regeneration and considerably reduce overall impact. Most bole wounds were deep (wood damaged) at the salvage logging sites, while at the selection cutting sites they were mostly light (bark damaged). Light wounds rarely lead to decay in the Hyrcanian forests. Previous studies have shown that tree species, age, wound size and height play the fundamental rule in the decay of the bole severe wounds (Tavankar & Bonyad 2014; Hecht 2015; Smith et al. 1994; Vasiliauskas 2001; Kartoolinejad et al. 2017). For trees with deep wounds in Hyrcanian forests, Tavankar and Bonyad (2014) found that 28% developed subsequent decay.

The extent of high intensity wounds at the salvage logging sites (55 and 57%) was higher than at the selection cutting sites (24% in SC1 and 30% in SC2). The bole was the most frequent location for damage at all the logging sites. The frequency of bole damage at the salvage logging sites (76% in SL1 and 78% in SL2) was higher than at the selection cutting sites (55% in SC1 and 51% in SC2). Furthermore, the extent of root damage at the salvage logging sites (23.6% in SL1 and 22% in SL2) was higher than at the selection cutting sites (14.2% in SC1 and 11.9% in SC2). All of crown damage and bole wounds higher than 2 m from the ground occurred in the tree felling stage. Trees with severely damaged crowns are more likely to die in the future.

Most of the damage occurred to beech (*Fagus orienalis*) regeneration at all the logging sites. Pure and mixed beech communities, are the most dominant forest communities in the natural Caspian forests (Marvie-Mohadjer 2006). These communities constitute approximately 17.6% of the area, 30% of standing volume and 23.6% of stem numbers in the Iranian Caspian forests (Amiri et al. 2013).

At all sites, the most commonly-damaged tree species was alder tree (*Alnus subcordata*). Previous research by Tavankar et al. (2017b) found that the wound healing rate of this species ranged from 0 to 17.3 $cm^2$ $yr^{-1}$ with a mean of 4.95 $cm^2$ $yr^{-1}$, and the diameter growth of wounded trees was 13.3% lower compared with sound trees.

The significant positive correlation between winching distance and number of damaged trees was consistent with results of other studies in a range of forest types (e.g. Bettinger & Kellogg 1993; Lotfalian et al. 2008; Naghdi et al. 2008; Nikooy et al. 2010; Jourgholami et al. 2012; Marchi et al. 2014).

Overall, one of the key requirements for a logging method in a sustainable forest management context is that it should result in minimal damage to the residual stand and soil (Naghdi et al. 2016). The study reported here provides important information on the nature and extent of damage in Hyrcanian forests following selection and salvage logging. Coupled with previous information on tree growth and wound decay, our results provide important information on the likely future impacts for treated stands.

## Conclusions

Results from our study showed that damage levels to residual trees during salvage logging and low intensity selection cutting were lower (about a quarter) than levels previously observed during conventional selection cutting operations. Our study showed that the severity of wounds on residual trees from salvage logging was higher than from selection cutting. Most of tree wounds occurred during the log winching stage. The present study confirms that with careful planning and execution, it is possible to decrease mechanised harvesting damage. Careful planning of skid trails and landings, using directional felling to inflict the smallest impact on the surrounding forest and skilled harvester labour are key to decreasing logging damage. Worker training and supervision are necessary to reduce logging damage. Pre-harvest planning to identify the winching corridors prior to log extraction can decrease stand and soil damage. Residual stand damage is a natural consequence of selective cutting and has been considered to be a problem in the management of uneven-aged forest stands. However, it is an avoidable risk and through minimising the level of damage subsequent stand growth and product quality can be improved.

## List of abbreviations

**ANOVA:** analysis of variance; **A.S.L.:** above sea level; **DBH:** diameter at breast height; **SC:** selection cutting; **SE:** standard error; **SL:** salvage logging; **SPSS:** statistical package for social sciences; **SS:** sum of squares; **DF:** degree of freedom; **MS:** mean of squares.

## Competing interests

The authors declare that they have no competing interests.

## Authors' contributions

AIB was the primary author. AIB, MN, and FT undertook the fieldwork. MN and RN provided critical revisions of the manuscript. FT compiled the data into spreadsheets and completed the statistical analyses. All authors read and approved the final manuscript.

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