Frequency and variability of missing tree rings along the stems of *Pinus halepensis* and *Pinus pinea* from a semiarid site in SE Spain

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**Abstract**

We studied the occurrence of missing rings (MR) around and along the stems of three *P. halepensis* and three *P. pinea* trees growing in a semiarid Mediterranean site in SE Spain. Tree-ring analyses were performed along 8 radii on stem discs taken at 1 m distances from the base to the top of the trees. The tree rings analysed showed that 19% were missing in *P. halepensis* and 10% in *P. pinea*. MR were recorded in 61% of *P. halepensis* and 24% of *P. pinea* in the years analysed. Dry conditions from January to May and high late winter to spring temperatures seem to be the main climatic elements promoting MR in both species. In our research into *P. halepensis*, the frequency of MR gradually decreased from the bottom upward, but no such pattern was observed in *P. pinea*. Most tree rings were missing only locally (LMR), indicating that wood formation occurred every year in at least some part of a tree, and the tree rings were often discontinuous around and along the stem. Since the frequency of LMR greatly varies around and along the stem, our results suggest that serial sectioning along the stem provides more information on wood formation and responses of trees to environment than studying the samples at breast height only. The disadvantage of the technique is that, as in our study case, research is based on a limited sample size, since it requires destructive sampling with tree felling, which is not usually possible or desirable on highly vulnerable semiarid forest ecosystems.

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**1. Introduction**

Tree-ring series are often used as archives of past climatic events that may also induce the formation of very narrow rings (e.g. Sarris et al., 2007). In extreme cases, tree rings may be partly or entirely missing. Missing xylem tree rings (MR) are common in conifers and particularly in trees growing in Mediterranean conditions (Raventós et al., 2001). They indicate an absence of wood production by the cambium in particular years, due to different stresses, such as unfavourable climate events, competition, disease and others (e.g. Cherubini et al., 2002).

Dendrochronological studies and research into MR are commonly based on samples taken at breast height, disregarding the fact that the productivity of cambium may greatly vary around and along the stem (Grabner and Wimmer, 2006; Raventós et al., 2001).

The cambium of trees growing in forest stands generally produces less wood in the lower parts of the stem (e.g. breast height) and more in the upper parts of the tree which is in the physiological vicinity of the crown, where the availability of products from photosynthesis and growth-inducing hormones is higher (Forest et al., 2006). In agreement with this, different studies suggest that the frequency of MR is expected to be higher near the tree base (e.g. Lorimer et al., 1999; Torelli et al., 1986). On the other hand, some studies have shown that the frequency of MR can be higher in the upper part of a stem, particularly in trees that have suffered sudden damage to the crown (e.g. Krause et al., 2003).

MR may be especially important in species growing at their distribution limits, where growth rates are generally low (de Luis et al., 2007, 2009a). Previous dendrochronological studies in *P. halepensis* and *P. pinea* from semiarid coastal sand dunes in SE Spain, using cores from the breast height, showed a high frequency of MR in recent years due to dryness and other disturbance factors (Raventós et al., 2001). However, this study did not provide information on variation in MR frequency around and along the stem, which would be important for better understanding of the physiological status of the trees.

The aim of this paper was (i) to study the frequency and variability of MR around and along the stems in *P. halepensis* and *P. pinea* from a semiarid site in SE Spain and (ii) to identify the main climatic factors promoting their incidence.
2. Material and methods

2.1. Study area and trees

The study site is a sand dune ecosystem located close to the southern distribution limit of Aleppo pine \((P.\ halepensis\ Mill.)\) and stone pine \((P.\ pinea\ L.)\) at Guardamar del Segura (38°6′N, 0°40′W; 5 m a.s.l.) in SE Spain. According to the closest meteorological station, located 1 km from the study area, the climate is thermo-Mediterranean and semiarid with a mean annual temperature of 17.9°C and mean annual precipitation of 276 mm during the period 1936–2005. In the period from 1989–2005 mean annual temperature was 18.7°C and mean annual precipitation 300 mm.

The trees under study grow in a mixed, even-aged forest stand of \(P.\ halepensis\) and stone pine, \(P.\ pinea\), planted during the period 1900–1909 from saplings of local provenance to protect the Guardamar village against the movement of the sand dunes from the coastal area.

2.2. Sampling, crossdating and measuring

In October 2005, we felled 3 \(P.\ halepensis\) and 3 \(P.\ pinea\) dominant and isolated trees without any visible damage and anomalies. The least distance from the nearest neighbour was 5 m. Trees were small to medium sized. \(P.\ halepensis\) were, on average, 6.8 m high and 96 years old and their DBH (diameter at breast height) was 15.7 cm. \(P.\ pinea\) were, on average 4.4 m high, 81 years old with DBH of 17.2 cm. We took discs from the base of the felled trees and then at approximately every metre up to the crown. In the end a total of 21 sections of \(P.\ halepensis\) and 14 sections of \(P.\ pinea\) were analysed.
The discs were dried for one week at room temperature and then in a drying chamber (temperature 60 °C). Later they were sanded by sanding machine (paper grids 40, 80 and 120) and then by hand (paper grids 280, 360 and 500).

For crossdating, we took digital pictures of each section, identified signature rings along 8 oriented radii (N, NE, E, SE, S, SW, W and NW) and dated them with the help of a previously constructed master chronology for the same site (Raventós et al., 2001; de Luis et al., 2008a). Then the crossdated tree-ring widths were measured along 8 radii of each disc to the nearest 0.01 mm, using the TSAP Win programme and LINTAB™ 5 measuring device.

The frequency of missing tree rings (MR) in each particular section was calculated for each calendar year. MR in the wood were more precisely assigned to two types: locally missing rings (LMR) – tree rings that were locally (partly) missing in some parts of the tree and totally missing rings (TMR) – tree rings that were missing around and along the whole stem.

To test the effect of sample height on the frequency of MR we used simple correlation. Since the number of tree rings decreased with tree height, comparisons were made for the period 1989–2005 (17 years) which was covered by all discs.

In both species, the relation between MR frequency and climate data was explored using correlation function analysis, enabling long-term age/size effects to be removed by using a nonlinear logistic equation applied to observed frequency series of MR. Next, residual series of the MR frequency were correlated with monthly mean temperatures and the monthly sums of precipitation series for each year from the previous September to the current December. We also used running temporal windows to identify the main climatic period responsible for MR formation. In these cases, comparisons were made both for the recent period 1989–2005 (17 years), which was covered by all discs, and for the period 1950–2005 (54 years).

3. Results

3.1. Tree-ring data and missing tree rings

In the six trees, we analysed 35 sections and 8 radii per section and measured 18702 tree rings (12200 in P. halepensis and 6502 in P. pinea). We recorded LMR in 61.2% and 24.4% of the years analysed in P. halepensis and P. pinea respectively (Fig. 1).

From these, we identified 2293 (P. halepensis) and 660 (P. pinea) missing rings, representing 18.8% of total tree rings in P. halepensis and 10.2% in P. pinea (Fig. 1). In both species, the frequency of LMR has increased in the last few years. In the period 1989–2005, they were detected in 100% and 76% of the years and represented 44.7% and 33.2% of analysed tree rings (P. halepensis and P. pinea respectively). In the two periods, both the entire and the recent, frequency of MR was higher in P. halepensis.

Comparison of different levels in the stem showed that the frequency of LMR gradually decreased from the lower to the upper part of all P. halepensis trees (p < 0.05) (Fig. 2a). Correlations of LMR frequencies with sample height in P. halepensis were 0.84, 0.77 and 0.87 respectively for the trees numbers 1, 2 and 3. However, no significant relation was established for P. pinea trees (Fig. 2b).

To summarise, the frequency of locally missing rings (LMR) was surprisingly high, but it was rare to find rings that were totally missing (TMR), which were only identified in four trees in 1995 (P. halepensis tree numbers 1 and 2; P. pinea tree numbers 1 and 2), in one tree in 1999 (P. pinea tree number 2) and in one tree (P. pinea tree number 1) in 2001. It must be noted that 1995 was the driest year in the second half of the 20th century and that 2001 was extremely dry. In the remaining years, rings formed at least in one part of the tree.

3.2. Climate factors triggering missing rings

Dry conditions from January to May, and high temperatures during late winter and spring were found to be the main climatic factors promoting MR in both species (Fig. 3). Despite similarities, P. halepensis was shown to be more sensitive to drought than P. pinea at the beginning of the growing season, whereas P. pinea seemed to be more sensitive to temperature variations during winter. Additionally, in both species, we found that the influence of precipitation and especially temperature has increased in the recent period (1989–2005) in comparison with the results obtained for 1950–2005 period (Fig. 3).

4. Discussion

We found that, in the semiarid Mediterranean site with prolonged drought periods and high temperatures, the frequency of LMR was surprisingly high, mainly in P. halepensis, although the selected trees did not have visible signs of damage or decline. These results confirm that, with increasingly severe environmental conditions, production of wood may be partly or totally absent. In conifers, several outer sapwood tree rings are able to conduct water (e.g. Pallardy, 2008), therefore, lack of tree ring formation in a particular year should not endanger tree survival (Cherubini et al., 2002; Sass-Klaassen et al., 2008). However, long-term disturbances in wood production by the cambium often lead to physiological problems associated with disturbed water transport and reduced capacity for storage of reserve assimilates (Bigler et al., 2004; Wunder et al., 2008).

This might be the case in the trees in our study, where we observed that the frequency of MR has increased in the recent period, although the 80-year-old trees are still far from the age.
which is naturally characterized by reduced wood production due to ageing (de Luis et al., 2009b).

Different factors may be the cause of recent increased frequency of LMR. However, dry conditions during January to May and high temperatures during late winter and spring were found to be the main climatic factors promoting MR in both species. As a consequence, the first potential cause of an observed increase in MR could be related to increasing stress conditions due to rising temperatures and decreasing precipitation (de Luis et al., 2009a, 2010) recorded in Spanish Mediterranean areas, including our study site, since the mid 1970’s.

Due to water deficiency and subsequent stomata closure, dryness also affects photosynthesis, which decreases and consequently fewer carbohydrates are available for radial growth (Sitte et al., 1999). Since radial growth generally starts at the top of the tree, the decreased availability of carbohydrates causes reduced wood formation in the lowermost part of the tree. This was particularly noticeable in the *P. halepensis* analysed, but not in *P. pinea*. Despite similarities, some significant differences have also been identified in the climate—growth relationship (de Luis et al., 2009b), suggesting that different physiological mechanisms rule the xylogenesis of the two species. However, many eco-physiological reasons for observed differences are still not sufficiently understood. In the future, fully controlled experiments would be needed to identify and prove such processes in both pine species used in our study.

In addition to climate, other important stressors might contribute to frequency of MR. Various studies have shown that other factors, such as the increased influence of marine spray (Raventós et al., 2001) or ozone, might lead to the alteration or death of needles, in turn leading to decreased photosynthetic production and reduced availability of assimilates for wood production (Raddi et al., 2009). However, in the two studied species, no significant bias was found in the frequency of MR in relation to orientation at any height level (Novak, 2007). This was shown for both the entire and the recent period and suggests that exposure of trees to wind does not seem to play a significant role in the frequency of MR.

Fig. 3. Correlation coefficients calculated for the period 1989–2005 for residual LMR frequency series and monthly precipitation and mean monthly temperature from Guardamar from previous September (Sep-1) to current December (Dec). Dotted horizontal lines indicate significance levels at the 95%.
The trees on coastal sites also often suffer problems under-ground (e.g. root damage). This is a frequent problem which is becoming more common on sandy coasts throughout the Medi-
terranean region, due to increasing tourism activities affecting coastal erosion (Raddi et al., 2009). Accordingly, underground problems are associated with disturbed water and mineral uptake, leading to reduced wood production, particularly in the lower parts of the stems (e.g. McLaughlin et al., 2002).

Differential effects of these potentially important factors or synergistic interactions among them were not determined by our study. However, since the effect of such stressors is likely to increase in the future, an increased incidence of MR may also continue. This could endanger the survival of trees on the edge of their distribution area.

5. Conclusions

Semiarid pine woodlands often represent the only forest type near the coast. They are of great ecological and economic importance in protecting the soil from erosion, controlling water shortage and providing a positive effect on tourism activities.

Reduced growth accompanied by an increased number of MR can help to predict impending tree mortality in conifers and, to this end, dendrochronology can help to record tree decline prior to visible signs of crown damage. This could be especially important in semiarid ecosystems bordering on the distribution limits of many forest species anywhere in the world.

Our results indicate that P. halepensis and P. pinea growing in semiarid conditions frequently had missing rings. Nevertheless, the tree rings were often discontinuous around and along the stem. This indicates that, in most trees, wood formation occurred every year in at least some part of a tree.

Since the frequency of MR greatly varies around and along the stem, our results suggest that serial sectioning along the stem provides more information on wood formation and responses of trees to environment than studying the samples at breast height only.

The disadvantage of the technique is that it requires destructive sampling with tree felling, which is not usually possible and desirable on highly vulnerable ecosystems, where every tree is of great importance. Here, it must be emphasised that our findings are based on only 6 trees and therefore generalizations need to be made with caution.

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