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Analysis of the mechanical properties of wood attacked by *Xylotrechus arvicola* (Coleoptera: Cerambycidae) larvae, and its influence on the structural properties of the plant

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Summary

***Xylotrechus arvicola* is an invasive insect on *Vitis vinifera* in the main wine-producing regions of the Iberian Peninsula. *X. arvicola* larvae bore into the grapevine wood and make galleries, which cause structural damages to the plant. The aim of this study was to investigate how grapevine wood infested by larvae affects the mechanical properties of the plant in comparation with those of uninfested wood. Samples of grapevine wood uninfested and infested by larvae were collected from vineyards. Compression and flexural strengths as well as simulated structures of grapevine wood in field, in relation to harvest weight by variety, were used to quantify the wood mechanical properties. Infested wood endured a lower strength and normal tension, and exhibited a reduction in the structural capacities in the simulation of harvest weight of 'Cabernet-Sauvignon' variety (up to 62.0 %). 'Tempranillo' (despite its high mechanical slenderness values) and 'Cabernet-Sauvignon', were the varieties that showed a higher resistance on trunks and branches, respectively. A lower bending moment was observed on the infested branches of all varieties. Changes in the mechanical properties of infested wood suggest a decrease in mechanical resistance of wood attacked by larvae that could contribute to the rupture of the infested grapevine over time. Grapevine wood attacked by *X. arvicola* larvae could be more sensitive to mechanical external factors in vineyards such as strong winds, harvest weight and vibration exerted by harvesting machines.**

Key words: *Vitis vinifera*; *Xylotrechus arvicola*; wood borer; wood properties; mechanical strengths.

Introduction

Wood being a biological material is readily degraded by fungi and termites (Syofuna *et al.* 2012) but, one of the most important causes of damage to wood materials are insects (Sen *et al.* 2017). According to Sen *et al.* (2017), insects belonging to the Cerambycidae, Anobidae and Lyctidae families play an important role in damaging wood materials and causing economic losses. *Xylotrechus arvicola*, which belongs to the Cerambycidae family from the Coleoptera class, is one example of wood-damaging insect that is observed especially in the main wine producing regions of Spain, attacking wood from different varieties of vine (*Vitis vinifera*).

Xylotrechus arvicola (Coleoptera: Cerambycidae) is a xylophagous polyphagous beetle native to riverside trees with several reported hosts, *i.e. Quercus*, *Carpinus*, *Castanea*, *Fagus*, *Populus*, *Salix*, *Tilia*, *Morus*, *Sorbus*, *Crataegus*, *Malus*, *Cydonia* and *Prunus spinos*a L. (Rosales: Rosaceae) (Bahillo 1997, Biurrun *et al.* 2007, Moreno 2005, Vives-Noguera 2000). Its geographical distribution is holomediterranean, spreading around Europe, Minor Asia and northern Africa (Nikitsky *et al.* 2016, Villiers 1978). Since Ocete and Del Tió (1996) described *X. arvicola* as a grapevine (*V. vinifera*) pest in Spain for the first time, the insect has spread across the country through the main wine producing regions (Rodríguez and Ocaña 1997, Ocete and Lópeez 1999, Pelaéz *et al.* 2001, Ocete *et al.* 2002). Similarly, two more species of wood-borers, *Trogoxylon impressum* Comolli (Coleoptera: Lyctidae) and *Xyloperthodes cf. incertus* Lesne (Coleoptera: Bostrichidae), have been described as grapevine pests in Israel and Central Europe (wine-growing areas in Switzerland, Germany and Austria), the former, and South Africa, the latter (Halperin and Geis 1999, Allsopp and Knipe 2004).

Damage to grapevines is caused by *X. arvicola* larvae which bore into grapevine plants to feed on wood making galleries within the plant for up to two years (Moreno 2005). Moreover, indirect damage originates from adult emerging holes which are the entry point for fungal diseases (García-Benavides *et al.* 2013) such as *Diplodia seriata* (De Not), *Eutypa lata* (Tul and Tul), *Phaeoacremonium aleophilum* (Gams, Crous, Wingf., Mugnai), *Phaeomoniella chlamydospora* (Crous and Gams), and *Formitiporia mediterranea* (Fisch). Consequently, infection of fungal diseases on grapevines will produce a series of impacts on host plants, e.g. stunting growth and low quality grapes (Ocete *et al.* 2002,

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García-Benavides et al. 2013). In severe attacks, plants die due to the damaged vascular tissue, which hinders the sap transport throughout the plant, and then they need to be replaced with the corresponding long lasting economical losses (Ocete et al. 2002). A typical vineyard affected by *X. arvicola* will show numerous broken branches due to the larvae galleries weakening the wood structure of the plant (García-Ruiz 2009, García-Ruiz et al. 2012). Some of the suitable measures to control *X. arvicola* consist of removing the rhytidome of the vines (Peláez et al. 2006) or pruning affected branches below the area showing galleries (Ocete et al. 2004), to regrow vine structure, which could be time consuming and economically draining, rendering these techniques unsustainable (Peláéz et al. 2006). Nonetheless, the renovation of attacked branches is easier in vines with bush training system than those with bilateral cordon training systems (Rodríguez-González et al. 2016).

Wood structural resistance is of paramount importance owing to the many functions it performs within the plant. Moreover, the significance of that information could be greatly improved by the knowledge of the effect of wood-damaging pests on wood mechanical properties. For instance, the Emerald Ash Borer (EAB) *Agrilus planipennis* Fairmare (Coleoptera: Buprestidae), which has become a really important pest that can actually decimate white ash *Fraxinus americana* (Lamiales: Oleaceae) populations in North America, has been thoroughly studied (Persad et al. 2013, Persad and Tobin 2015, Finley et al. 2016) to provide more information in how wood-borers´ galleries affect structure and material properties of woody plants, and all the implications this has. However, there is virtually no empirical information on grapevine wood material resistance, albeit needed. Such information would allow the estimation of the wood performance under mechanical stresses, e.g. wind, grape carrying capacity, bunch carrying capacity and mechanical harvest. The present study aimed to estimate the wood resistance loss in a vineyard affected by *X. arvicola* to providing more information about which would be the variety in which there could be a greater loss of production (due to breakage of grapevines wood) by the attack of this insect pest in a vineyard.

Thus, the objective of this study was to investigate how grapevine branches and trunks infested by *X. arvicola* larvae support compression and flexural stresses compared to the uninfested wood in order to shed some light on this important topic by considering the factors affecting wood resistance and isolating the corresponding variables to get comparable empirical data.

Material and Methods

Grapevine wood and characteristics: Three vineyards where severe pruning was taking place to rebuild the plant structure and avoid *X. arvicola* spreading were visited in 2017. The vineyards were located in two Protected Denomination of Origin (PDO), which is a certification to distinguish quality food products of a particular region (UE Reg. No. 1151/2012 published on 21 November 2012), called 'Ribera del Duero', located in Peñafiel (Valladolid) and 'León', located in Gordoncillo (León). These vineyards were planted uniformly with the same *V. vinifera* variety, 'Tempranillo', 'Cabernet-Sauvignon' and 'Prieto Picudo', respectively. In any case, vineyards were surrounded by other vineyards. More details regarding the vineyards are shown in Tab. 1.

Experimental conditions: Trunks and branches from different grapevines between 20 to 29-years-old, which previously were exposed to *X. arvicola* attack over various years were cut from the grapevine in the vineyards. The wood samples (previously cut) were collected and taken to the laboratory to study the cumulative effects of larvae feeding in the structure and material properties of grapevine wood over time. The samples were randomly selected from infested and uninfested trunks and branches per grapevine and variety ('Tempranillo', 'Cabernet-Sauvignon' and 'Prieto

Table 1

Details of the selected vineyards with PDO

	Ribera del Duero	Ribera del Duero	León
Location	Peñafiel	Peñafiel	Gordoncillo
Province	Valladolid	Valladolid	León
Coordinates	41° 36´ 25.9´´ 4° 6´ 12.3´´	41° 35´ 45.7´´ 4° 5´ 27.3´´	42° 08´ 14.9´´ 5° 25´ 41.6´´
Height above sea level (m)	754	754	747
Annual average temperature (°C)	11	11	11.7
Average rainfall (mm)	450	450	500
Soils (texture)	Sandy loam	Sandy loam	Loamy clay
Training system of vines	Espaldera (Cord Royat)	Espaldera (Cord Royat)	Espaldera (Cord Royat)
Training system characteristics	Spur pruning over two branches (1.0 m) per trunk (0.7 m)	Spur pruning over two branches (1.0 m) per trunk (0.7 m)	Spur pruning over two branches (1.0 m) per trunk (0.7 m)
Vitis vinifera variety	Tempranillo	Cabernet-Sauvignon	Prieto Picudo
Plantation frame (m x m)	(3 x 1.50)	(3 x 1.40)	(3 x 1.50)
Age (years)	26	29	20

Picudo') in order to do a comparison between infested and uninfested wood within the same variety.

The European Standard EN 14251:2003 (Structural Round Timber, Test Methods) (Aenor 2003) was used to establish the parameters to be measured in the samples (previous to testing) of each variety. Trunks and branches diameter and length for all samples were measured according to the aforementioned European Standard. The samples that did not fulfil the requirements of the EN 14251:2003 standard were not considered for testing. To ensure the same moisture content in the varieties, the samples were air-dried for 30 d and then kept in an oven at 30 °C ± 1 °C for 48 h prior to the mechanical testing. According to the European Standard EN 14251:2003, to calculate the moisture content of the wood samples, 10 specimens of each variety and part of the plant (trunks and branches with a diameter greater than 75 mm and without knots) were dried in the aforementioned laboratory and oven conditions and were weighed at the beginning and at the end of the drying process. The following equation (equation 1) was used to calculate the moisture percentage of the wet wood samples.

$$\mathrm{MS} = \frac{\mathrm{WS - DS}}{\mathrm{DS}} \times 100 \qquad (1)$$

where, MS (Moisture Samples) in percentage; WS (Wet Sample) in grams; DS (Dry Sample) in grams.

Mechanical testing: The effects of *X. arvicola* larvae on the wood properties and resistance of branches and trunks of the different *V. vinifera* varieties were evaluated in this study using two standard experiments: a compression test for the grapevine wood trunks and a flexural test for the grapevine wood branches.

All trunks and branches were tested with a hydraulic press (*i.e.* an universal press of compression and bending) of the EIC brand (Engineering, Instrumentation and Control) exhibiting a maximum load of 2000 kN. This apparatus applies the load by means of a pump that generates oleohydraulic pressure and collects the data by means of a data logger. The EIC software collects the data of both the total applied load and voltage. Moreover, the data processing was also assisted by the EIC software, in which the loading rate was the same for the whole experiment, with a value of 200 N/s. The trunks were oriented vertically to mimic the compression strength suffered in field conditions, with the surfaces of both ends cut perpendicular to the longitudinal axis of the sample (Fig. 1A). The branches were oriented horizontally, preferring when possible the topside down position, to mimic the downward bending stress endured in the field. A device was employed to support the specimens and force a loading span of 30 cm (18 times the branch nominal diameter to minimize shear stresses), and then the central load was applied (Fig. 1B). Trunks and branches that twisted or slipped during the tests were omitted from the analyses.

Experiment 1: Compression test of grapevine wood trunks (Fig. 2A). In the compression test, different dimensions from each wood trunk sample were determined: 3 measurements of the minimum diameter and 3 measurements of the maximum diameter in the sections of each sample (approximates a circular section), the total sample length of the sample, the curvature (*i.e.* the greatest length from the

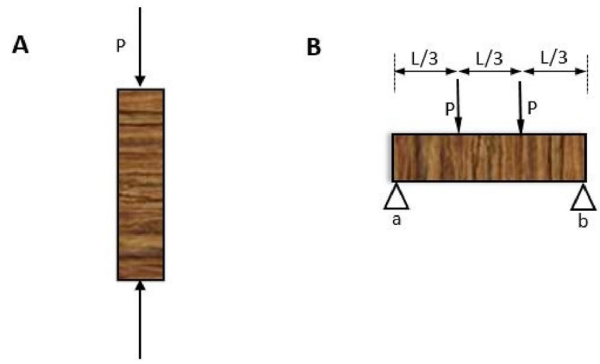

Fig. 1: **A**) Scheme of the compression test in trunks (P axial force applied until breakage); **B**) Scheme of the flexural test in branches: 'a' and 'b' were the supporting points in the extremes of the device. The P forces were applied in central third of the specimen until breakage.

Fig. 2: **A**) Compression test of grapevine wood trunks; **B**) Flexural test of grapevine wood branches.

horizontal plane to the longitudinal axis of the sample) and the number of knots (if the sample had them). The presence of knots in this kind of wood is almost unavoidable, however as their size is similar for similar diameter sizes on samples with the same age and pruning methodology, their effect on the strength behaviour should be negligible.

For the infested trunk samples, measurements of the number of adult exit holes per surface area and presence or absence of galleries appearing on both ends of the sample were also registered. The compressive strength (fc,0) of the samples was calculated according to the European Standard EN 14251:2003 and the following equations 2-5:

$$\Lambda = \frac{lk}{i} \quad \text{(slenderness)} \qquad (2)$$

$$i = \sqrt{\frac{\mathrm{I}}{\mathrm{A}}} \quad \text{(turning radius} \qquad (3)$$

$$I = \frac{\pi r^4}{4} \qquad (4)$$

$$A = \pi r^2 \qquad (5)$$

where, A: mechanical slenderness (dimensionless); lk: buckling length or length of the test piece (mm); i: turning radius; I: moment of inertia (dimensionless); A: cross sectional area (mm^2); r: radio (mm); fc,0: compression strength (MPa); fc,0 = F/A, where F is force (Newtons) and A is cross sectional area, calculated using equation 5.

Experiment 2: Flexural test of grapevine wood branches (Fig. 2B). In the flexural test, different dimensions from each wood branch sample were collected: 3 measurements of the minimum diameter and 3 measurements of the maximum diameter in the sections of each sample (approximates a circular section), 2 diameter measurements at the midpoint of the branch where the load is exerted (one in the direction of the applied load and another one in the perpendicular direction to the applied load), the total sample length, the curvature and the number of knots (if the sample had them).

For the infested branches, the number of adult exit holes per surface area and presence or absence of galleries appearing on both ends of the sample were also measured. The flexural strength (fm,0) of the samples was calculated according to the European Standard EN 14251:2003, the previous equations 3-5 and the following equation number 6:

$$fm,0 = \frac{\mathrm{M_Z}}{\mathrm{W_Z}} = \left(\frac{\mathrm{M_Z}}{\mathrm{I}}\right)\tau \qquad (6)$$

where, fm,0: compression strength (flexural) (MPa); MZ: bending moment (N·mm); WZ: resistant module (mm^3); r: radio (mm). Both compression and flexural strength results are showed in MPa ($N \cdot mm^{-2}$), removing the variation diameter size effect and being able the comparison between specimens with similar, but not exactly the same, diameter size.

Experiment 3: Simulation of harvest weight by variety. The harvest weight of grapes by variety on branches and trunks of wood vine varieties was simulated with CYPE Engineers version 2018.f software (CYPE, 1983, Alicante, Spain). Trunks (T) and branches (B) were considered vertically and horizontally respectively (to mimic the compression strength and the downward bending experimented in the field). Harvest weights of 2.50 kg for 'Prieto Picudo' (León 2018), 2.70 kg for 'Tempranillo' (Ribera del Duero 2018) and 3.0 kg for 'Cabernet-Sauvignon' (Ribera del Duero 2018) were considered for each variety. Harvest weights in each variety were applied as a uniform load ($N \cdot m^{-1}$) on both arms of the simulated structure (2.0 m). With the average turning radius (equation number 6, in mm), the transversal sectional area (equation number 8, in mm^2) and the resistance modulus (equation number 6, in mm^3), the axial stress (equation number 5) was calculated in the trunk and the maximum bending moment in the branches (Fig. 3).

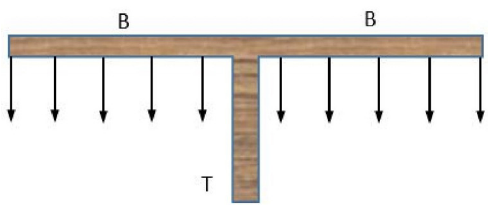

Fig. 3 Typical scheme of loads in a "vid en espaldera". T: trunk (0.7 m), B: branches (1.0 m). The vectors shown are representative of the loads experimented due to the harvest weight of grapes.

Statistical analysis: Statistical analyses were performed using the SPSS version 21 software (IBM, 1968, NY, USA). Means parameters evaluated (on trunks and branches) were normally distributed, presented homocedasticity and were subjected to an analysis of variance ANOVA (Fisher's LSD, considered significant at $p \leq 0.05$) to evaluate the mechanical properties of uninfested and infested wood.

Results

The moisture content obtained in wet samples was 59.5 % in 'Tempranillo', 54.2 % in 'Cabernet-Sauvignon' and 56.7 % in 'Prieto Picudo'.

Experiment 1: Compression test of grapevine wood trunks. 'Tempranillo' wood, both from uninfested and infested samples, showed the highest resistance under compressive strength, being significantly greater than the rest of the varieties (F = 5.686; d.f. = 2,9; P = 0.025 for uninfested samples and, F = 5.140; d.f. = 2,9; P = 0.032 for infested samples). This occurred despite 'Tempranillo' also showing the greater value of mechanical slenderness, which would predispose those specimens to be weaker, taking into account its shape. Uninfested and infested samples achieved a mean of 11.27 MPa and 6.63 MPa, respectively, which was due to the presence of holes in the infested wood. The amount of exit holes per surface area may be one of the reasons why 'Tempranillo' (634.35 cm^2 of exit holes) observed higher compression strength than the other varieties (1993.17 cm^2 for 'Cabernet-Sauvignon' and 709.20 cm^2 for 'Prieto Picudo'), but not the only one, since for uninfected samples, without holes, 'Tempranillo' remained the strongest variety. 'Cabernet-Sauvignon' showed the weaker uninfected wood trunks (a mean of 7.70 MPa), however it achieved the highest failure load values (for both uninfested and infested samples, with a mean of 75.33 kN and 46.20 kN, respectively) due to having a higher thicknesses in the transversal section area (with a mean of 9,970.80 mm^2 and 1,1401.30 mm^2, respectively), which was significantly higher (F = 33.599; d.f. = 2,9; P ≤ 0.001 for uninfested samples and, F = 6.364; d.f. = 2,9; P = 0.019 for infested samples) than the rest of the varieties evaluated.

When the same wood varieties were compared (between uninfested and infested), all uninfested samples were able to withstand significantly higher failure load (F = 6.169; d.f. = 1,11; P = 0.018 in 'Tempranillo', F = 10.968; d.f. = 1,5; P = 0.021 in 'Cabernet-Sauvignon' and F = 5.342; d.f. = 1,2; P = 0.032 in 'Prieto Picudo') values than their respective samples infested by *X. arvicola* larvae (Tab. 2). In the same way, all the infested specimens for each variety exhibited a significantly lower resistance (in terms of compressive strength, MPa) than their respective uninfested samples (F = 6.399; d.f. = 1,11; P = 0.014 in 'Tempranillo', F = 5.544; d.f. = 1,5; P = 0.045 in 'Cabernet-Sauvignon' and F =16.598; d.f. = 1,2; P = 0.050 in 'Prieto Picudo'; Tab. 2).

The mean number of knots present in the different varieties of trunks evaluated ranged with a mean between 3.86 and 5.00 for uninfested wood, and with a mean between 3.50 and 4.67 for infested wood). Thus, there being no significant differences in relation to the number of knots when these varieties were compared between them and with other varieties, according their condition (uninfested or infested). The average of exit holes per lateral surface observed in the different varieties varied from 1.25 in the 'Cabernet-Sauvignon' variety to the 2.17 presented by the 'Tempranillo' variety, but there were no significant differences among them (Tab. 2).

Experiment 2: Flexural test of grapevine wood branches. The normal tension applied on branches showed that 'Cabernet-Sauvignon' supported the highest flexural strength, which was significantly greater ($F = 7.540$; d.f. = 2,9; $P = 0.050$ for uninfested samples and, $F = 8.010$; d.f. = 2,7; $P = 0.048$ for infested samples) than in the rest of varieties, whether the sample was uninfested (a mean of 57.75 MPa) or infested (a mean of 32.16 MPa). 'Cabernet-Sauvignon' wood (both uninfected and infested) was the variety that managed to withstand the higher magnitudes at failure load values (with a mean of 9.05 kN and 4.95 kN, respectively), due to having the highest thicknesses in the transversal section area among the uninfested wood (a mean of 2097.70 mm^2) and one of the highest among the infested wood (a mean of 1469.49 mm^2). In addition, infested wood of 'Cabernet-Sauvignon' was the variety exhibiting the least amount of exit holes. Generally, all the infested samples showed a decrease in the flexural strength when the surface of exit holes increased. All uninfested samples for each variety were able to withstand a higher failure load ($F = 8.401$; d.f. = 1,11; $P = 0.036$ in 'Tempranillo', $F = 5.024$; d.f. = 1,2; $P = 0.028$ in 'Cabernet-Sauvignon' and $F = 7.202$; d.f. = 1,3; $P = 0.019$ in 'Prieto Picudo') and strength values ($F = 6.706$; d.f. = 1,11; $P = 0.043$ in 'Tempranillo', $F = 9.149$; d.f. = 1,2; $P = 0.028$ in 'Cabernet-Sauvignon' and $F = 5.301$; d.f.=1,3; $P = 0.0046$ in 'Prieto Picudo'), which showed them to have a significantly greater resistance than their respective infested samples (Tab. 3).

Finally, 'Cabernet-Sauvignon' variety reached the maximum bending moment on uninfested (a mean of 690,333.33 N·mm^{-1}) and infested samples (a mean of 255,750.00 N·mm^{-1}), which was significantly higher ($F = 5.111$; d.f. = 2,9; $P = 0.043$) than that of the remaining varieties. When the varieties were compared between them, all uninfested samples reached a significantly higher maximum bending moment ($F = 7.115$; d.f. = 1,11; $P = 0.027$ in 'Tempranillo', $F = 9.204$; d.f. = 1,2; $P = 0.044$ in 'Cabernet-Sauvignon' and, $F = 6.781$; d.f. = 1,3; $P = 0.028$ in 'Prieto Picudo') than their respective infested samples (Tab. 3).

The number of knots in the wood varieties evaluated ranged between a mean of 5.50 to 8.00 for uninfested wood and a mean of 5.33 to 8.50 for infested wood. In addition, among the infested wood samples, 'Cabernet-Sauvignon' and 'Prieto Picudo' showed a significantly higher number of knots ($F = 8.201$; d.f. = 2,7; $P = 0.028$) than 'Tempranillo'.

Experiment 3: Simulation of harvest weight by variety. According to the geometric and load diagram displayed on Fig. 2 and using the commercial program CYPE Ingenieros v.2018.f, a structural modeling was carried out on the different varieties for weights of total grapes between 2.5 and 3 kg per plant and variety, according to what is established in the material and methods section. From the modelling, the maximum bending moment supported by

Table 2

Parameters evaluated of the different *V. vinifera* varieties in the compression test of wood trunks

Grapevine wood variety	n	Failure load (kN)	Cross sectional area (mm^2)	Compression strength (MPa)	Mechanical slenderness	Number of knots	Shaped exit holes per surface of lateral area (#/cm^2)	Larval galleries (presence/absence)
				Uninfested wood				
Tempranillo	7	28.01 ± 4.45bA	2555.40 ± 449.75cA	11.27 ± 0.66aA	21.60 ± 2.65aA	3.86 ± 0.26aA	-	Absence
Cabernet-Sauvignon	5	75.33 ± 9.01aA	9970.80 ± 1003.42aA	7.70 ± 1.20bA	13.26 ± 1.02bA	4.00 ± 0.57aA	-	Absence
Prieto Picudo	4	31.80 ± 8.90bA	3975.40 ± 732.40bA	7.85 ± 0.79bA	15.22 ± 3.44bA	5.00 ± 1.00aA	-	Absence
				Infested wood				
Tempranillo	6	19.76 ± 3.63bB	4152.50 ± 1164.35bA	6.63 ± 1.55aB	17.55 ± 2.28aA	4.67 ± 0.76aA	2.17 ± 0.50a (634.35 cm^2)	Presence
Cabernet-Sauvignon	4	46.20 ± 3.82aB	11401.30 ± 2164.58aA	4.45 ± 0.80abB	12.30 ± 1.00bA	3.75 ± 0.85aA	1.25 ± 0.95a (1993.17 cm^2)	Presence
Prieto Picudo	4	15.05 ± 2.65bB	4476.10 ± 214.27bA	3.39 ± 0.75bB	15.69 ± 3.20abA	3.50 ± 0.55aA	2.00 ± 0.95a (709.20 cm^2)	Presence

n: number of samples; Different lowercase letters indicate a significant difference among varieties for uninfested and infested wood respectively. Different capital letter indicate a significant difference between uninfested and infested wood in the same wood variety.

Table 3

Parameters evaluated of the different *V. vinifera* varieties in the flexural test of wood branches

Grapevine wood variety	n	Failure Load (kN)	Cross sectional area (mm^2)	Flexural strength (MPa)	Maximum bending moment ($N\cdot mm^{-1}$)	Number of knots	Shaped exit holes per surface of lateral area (#/cm^2)	Shaped larval galleries (presence/absence)
				Uninfested Wood				
Tempranillo	7	4.81 ± 0.83bA	1537.67 ± 159.70aA	40.64 ± 4.68bA	331000.00 ± 46523.75cA	6.57 ± 0.64aA	-	Absence
Cabernet-Sauvignon	4	9.05 ± 1.85aA	2097.79 ± 721.57aA	57.75 ± 7.30aA	690333.33 ± 42666.66aA	8.00 ± 1.52aA	-	Absence
Prieto Picudo	5	5.76 ± 1.56bA	1777.85 ± 402.99aA	41.28 ± 7.51bA	425722.22 ± 39276.44bA	5.50 ± 1.50aA	-	Absence
				Infested wood				
Tempranillo	6	3.31 ± 0.70bB	1297.21 ± 149.59aB	30.29 ± 4.74abB	231166.66 ±49122.75abB	5.33 ± 0.84bA	1.17 ± 0.47a (525.87 cm^2)	Presence
Cabernet-Sauvignon	4	4.95 ± 0.17aB	1469.49 ± 190.09aB	32.16 ± 4.99aB	255750.00 ± 12916.66aB	8.00 ± 0.50aA	0.50 ± 0.50a (421.25 cm^2)	Presence
Prieto Picudo	4	2.25 ± 0.95bB	1602.62 ± 160.12aA	20.25 ± 5.46bB	182166.66 ± 63833.33bB	8.50 ± 1.50aA	1.00 ± 0.00a (695.43 cm^2)	Presence

n: number of samples; different lowercase letters indicate a significant difference among varieties for uninfested and infested wood respectively. Different capital letter indicate a significant difference between uninfested and infested wood in the same wood variety.

branches (B) and the axial load of maximum compression in trunk (T) were obtained at maximum values of 10,000 ($N\cdot mm^{-1}$) and 100 N, respectively. Then, the comparison between the maximum value of the bending stress obtained in the computer modeling (10000 $N\cdot mm^{-1}$) with the maxima shown in Tab. 3 (maximum bending moment - $N\cdot mm^{-1}$), allowed the determination of the safety coefficients for breakage (*i.e.* the ratio between the break moment and the moment supported) of all varieties which oscillated between 69 for the uninfested 'Cabernet-Sauvignon' and 18 for the infested 'Prieto Picudo'. This shows that the wood damage by the infestation of *X. arvicola* larvae initially does not pose a risk to the grapevine, since the safety ratio is very wide. However, it can be appreciated that for the different condition within each variety the aforementioned ratio decreases significantly, from 33 to 23 in 'Tempranillo', from 69 to 26 in 'Cabernet-Sauvignon' and from 43 to 18 in 'Prieto Picudo' (from uninfested to infested wood). Thus, the infestation by *X. arvicola* was responsible for a decrease in the breakage ratios of 30.0 %, 62.0 % and 58.0 % respectively for 'Tempranillo', 'Cabernet-Sauvignon' and 'Prieto Picudo', which represents an important reduction in the structural capacities of the infested branches.

Discussion

All the experiments carried out show that the infestation by *X. arvicola* larvae produces numerous damages in the parenchymal tissue of the infested wood which a very important decrease in its resistance (from 30.0 to 62.0 % according to the variety) due to the changes in the mechanical properties of the trunks and branches affected. Based on these results, it cannot be ruled out, that in an extreme situation, the damage caused by *X. arvicola* larvae can produce a break in the branches of the vines (by bending), as it has also occurred in other woody species (McClure 1991, Stadler *et al.* 2005). In fact, this cerambyd species has been observed in *P. spinosa* trees causing the weakening of the affected trees and/or the death or breakage of the affected branches for several years (Biurrun *et al.* 2007).

While the negative effects of invasive insects on native plants are well documented, the mechanisms behind these effects are often poorly understood (Soltis *et al.* 2014). The factors for which a lower resistance is observed in the varieties affected by *X. arvicola* larvae could be traced back to:

1. the indirect damage caused by the propagation of wood diseases that kill the vascular tissues of the plant; and
2. the direct damage produced by the reduction of vascular tissue, which was ingested by larvae.

1. Insects and pathogens are known to affect the mechanical properties of other woody species, as it has been described in the genera *Pinus* spp. (Kurkela *et al.* 2005, Drenkhan *et al.* 2006), *Pseudotsuga* spp. (Hansen *et al.* 2000) and *Larix* spp. (Krause and Raffa 1992). Other authors (Ocete *et al.* 2002, García-Benavides *et al.* 2013) have described that the action of *X. arvicola* larvae inside the wood favors the propagation of different diseases of wood fungi (described in the introduction) that lead to the death of the plant vascular tissue. This fungal attack occurs mainly in 'Tempranillo' and

'Cabernet-Sauvignon', which are two of the main varieties of the Spanish vineyards and have been studied in this work.

The varieties affected by these diseases accumulate a greater amount of dead wood that predisposes the plant to a greater fragility, which leads to a progressive death of the affected areas, as described by Hauer *et al.* (2008) in other woody species. Similarly, authors such as Kane (2008) and Detters *et al.* (2008) have also reported that an accumulation of dead wood by the attack of pathogens on branches or trunks predisposes woody species to damage or breakage when they are subjected to external agents (snow, wind, static charges).

2. Ingestion of vascular tissue by insect larvae also affects the mechanical properties of woody species. *X. arvicola* larvae feeding alters the mechanical properties of branches of grapevine wood, with evidence of decreased flexibility in the infested wood varieties (maximun bending moment). The changes in the woody tissues are most pronounced following a continuous infestation by these larvae, and it is due to the destruction of the xylem tissue inside the grapevine wood, which affects the production and harvesting of the grapevine. Overall, branches breakage due to the mechanical factors may reduce plant fitness as a result of both biomass and meristem loss, as it has been reported in the biomechanics effects on *Tsuga canadensis* Carriére (Pinales: Pinaceae) produced by *Adelges tsugae* Annand (Hemiptera: Adelgidae) (Soltis *et al.* 2014). Spatz and Bruechert (2000) have described that several years of strong gusts of wind can cause mechanical instability in those woody species that have suffered previous damage.

Regarding the knots in the varieties evaluated, their presence do not condition the resistance exerted by the wood fibers of the samples, since there are no significant differences between the number of knots presents of uninfested and infested varieties. For infested wood, the number of exit holes was also considered and the findings in 'Tempranillo' (2.17 and 1.17 holes in the trunks and branches, respectively) confirm those obtained by Moreno (2005), who described this variety as one of the most sensitive to be attacked by *X. arvicola*. It should also be noted that this variety on wood trunks (for both infested and uninfested samples) showed the highest values in the mechanical slenderness, which means that its structural integrity could be seen as more compromised (*i.e.* more prone to break, whether it is infested or not) due to the unfavorable shape of the specimens. Nevertheless, the values of mechanical slenderness were not significantly different when the different varieties were compared according to their affection. High values of mechanical slenderness have been shown to increase the chances of breakage in trees affected by the EAB, *A. planipennis*, as described by Persad and Tobin (2015) and Persad *et al.* (2013).

Regardless of the transversal section area, trunks and branches infested supported lower values of strength respect to their uninfested wood counterpart samples. Thus, these trunks and branches could become more sensitive to mechanical external factors such as strong winds, as it happens in other woody species (Soltis *et al.* 2014), the weight of the grape harvest, and the vibration exerted by the harvesting machines in those vineyards that employ this technique.

In conclusion, this work represents the first documented research to study the alterations on the mechanical properties of wood originated by *X. arvicola* larvae. The infestation of the wood by the wood-borer larvae produces numerous damages in the parenchymal tissue and causes a very important decrease in its resistance (from 30.0 to 62.0 % according to the variety) due to the changes in the mechanical properties of the trunks and branches affected. The affected samples endured a lower strength and normal tension on trunks and branches, regardless of the transversal section area, or a decrease in the safety coefficients for breakage (*i.e* the ratio between the break moment and the moment supported). 'Tempranillo' was the most resistant variety on wood trunks despite its unfavorable shape (*i.e.* high mechanical slenderness), which would predispose that variety to be significantly weaker to withstand efforts. 'Cabernet-Sauvignon' was the most resistant variety on wood branches, where all infested varieties showed a lower bending moment than that of the unifested branches. In terms of the knots, it was possible to disregard their effect on the resistance exerted by the samples. Based on the obtained results, it cannot be ruled out that, in an extreme situation, the damage caused by larvae can produce a break (by bending) in the branches of grapevines over time. Moreover, the grapevine attacked by larvae could be more sensitive to mechanical external factors in the vineyards such as strong winds, the harvest weight and, the vibration exerted by harvesting machines in those vineyards affected that employ this technique.

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Erratum

On page 105 of the manuscript:

Analysis of the mechanical properties of wood attacked by *Xylotrechus arvicola* (Coleoptera: Cerambycidae) larvae, and its influence on the structural properties of the plant

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The editors apologise for this error.