Scientia Horticulturae 332 (2024) 113250

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Research Paper

Quantifying Asian chestnut gall wasp (*Dryokosmus kuriphilus* Yasumatsu) impact on fruit yield and on tree growth using terrestrial LiDAR

Dimas Pereira-Obaya, Enoc Sanz-Ablanedo, Karen Brigitte Mejía-Correal, José Ramón Rodríguez-Pérez *

Grupo de Investigación en Geomática e Ingeniería Cartográfica (GEOINCA), Universidad de León, Avenida de Astorga sn, 24401-Ponferrada, León, Spain

ARTICLE INFO

Keywords:
Asian chestnut gall wasp
Infestation levels
LiDAR
Fruit yield
Tree growth, sweet chestnut

ABSTRACT

The Asian chestnut gall wasp is an invasive pest that causes ecological and economic losses in the management of the sweet chestnut (*Castanea sativa* Mill.). The pest therefore needs to be monitored in order to assess its impact on tree growth and fruit yield. As part of this work, we propose an infestation level classification based on the number of galls per branch. For two sweet chestnut orchards infested by the wasp, terrestrial light detection and ranging (LiDAR) data were used to calculate tree growth and fruit yield was quantified in terms of nuts and burrs. The tree growth and fruit yield variables were statistically analysed to determine the impact of different infestation levels on these variables, and differences between pairs of infestation levels were tested for significance. Negative correlations were found for the fruit yield variables with infestation indicators, while positive correlations were found for the tree growth variables. Significant differences were observed in fruit yield and tree growth variables associated with different infestation levels.

Introduction

Chestnut trees belonging to the genus Castanea sp. are widely distributed throughout the world, and in Europe, the sweet chestnut (*Castanea sativa* Mill.) has traditionally been managed to obtain wood and nuts (Conedera et al., 2004; Fernández-Cruz et al., 2022). Nowadays, however, the decrease in the distribution areas has enhanced the risk of diseases and plagues (Freitas et al., 2022). The chestnut tree plays an important ecological and economic role in southern Europe and also has potential in central Europe as a consequence of climate change (Conedera et al., 2021). It is therefore important to understand and monitor issues affecting chestnut orchards and stands, the most important of which, in recent years, is infestation by the Asian chestnut gall wasp (ACGW; *Dryokosmus kuriphilus* Yasumatsu).

Since it appeared in Italy in 2002, the ACGW has spread across Europe to become a plague (Amorim et al., 2022). In a one-year life cycle, the adult lays its eggs on recently formed buds of the chestnut tree, coinciding with the tree's most important vegetative development. Larval activity, which pauses during the winter, restarts in the spring with the formation of galls that interfere with proper shoot development, branch elongation (Branco et al., 2016), branch architecture, and the formation of lateral buds (Gehring et al., 2018). Other consequences, such as reduced tree growth and fruit yield, have also been reported. For instance, Castedo-Dorado et al. (2023) and Marcolin et al. (2021) reported, after analysing chestnut plots in Spain and Italy (over 5 and 10 years, respectively), that radial growth in infested trees was reduced, while Battisti et al. (2014) and Sartor et al. (2015) reported that fruit yields calculated using diameter at breast height (DBH) were lower when the infestation level increased.

Use of the parasitoid *Torymus sinensis* Kamijo as a biocontrol agent to reduce ACGW populations has had mixed success (Conedera et al., 2021; Ferracini et al., 2022; Gil-Tapetado et al., 2018), making it necessary to continue observing the pest and its consequences using innovative methods. Unmanned aerial vehicles (UAVs) equipped with spectral or light detection and ranging (LiDAR) sensors have been used to monitor vegetation, included chestnut trees. For instance, UAV RGB imagery has been used to estimate yield through automatic detection of burrs on images (Arakawa et al., 2023). LiDAR as used in precision agriculture generates 3D point clouds from surface-reflected radiation emitted and received by active sensors. Mobile laser scanner LiDAR has been used for crop monitoring tasks, and is especially suitable for estimating tree volume (Rivera et al., 2023) and for examining canopy structure in sweet chestnut coppices (Prada et al., 2022), although it has not yet been applied to chestnut orchards. Terrestrial or close-range LiDAR (based on

* Corresponding author.
E-mail address: jr.rodriguez@unileon.es (J.R. Rodríguez-Pérez).

https://doi.org/10.1016/j.scienta.2024.113250
Received 10 August 2023; Received in revised form 17 April 2024; Accepted 23 April 2024
Available online 27 April 2024

Table 1
Sweet chestnut orchard characteristics.

Plot	Number of trees	Row spacing (m)	Irrigation system	Chestnut variety
A	53	8. 5 × 8.5	Drip	Parede Roja
B	30	9. 0 × 9.0	Manual	Parede Roja

quantitative structure models) has been used to identify fruit and analyse branch architecture in a walnut orchard (Wang et al., 2023) and has been used to measure crown volume in olive orchards (Miranda-Fuentes et al., 2015).

In this context, we assessed how different ACGW infestation levels affect fruit yield and tree growth in two sweet chestnut orchards, and describe an alternative infestation classification to that of Gehring et al. (2020), i.e., based, not on the percentage of attacked buds, but on the number of galls present on branches. Our aims were to propose a new infestation classification, determine how ACGW infestation affects fruit yield and tree growth, and examine whether fruit yield and tree growth differ according to infestation level.

Material and methods

Study sample data and experimental design

This study took place in Robledo de las Traviesas in the El Bierzo region of north-western Spain. Two plots (A and B) of chestnut trees (*C. sativa* Mill.) were selected, with areas of 1.4 and 1.19 hectares, located 900 m above sea level (WGS 84 coordinates: 42° 42′ 28′’N; 6°26′ 13′’W and 42° 42′ 36′’N; 6° 26′ 9′’ W, respectively). The chestnut variety was Parede Roja, and all the trees had the same age (6 years) and were similar in size. As shown in Table 1, the two plots different grid spacings and different irrigation systems. From the 7 rows in Plot A and 3 rows in Plot B, and excluding trees with other health problems, 83 ACGW infested trees were selected.

ACGW infestation

Pest impact on branch architecture was analysed, in July 2022, during tree maximum vegetative development and coinciding with peak ACGW larval activity. This assessment was carried out using Gehring et al. (2018) as reference. The followed protocol has already been described by Pereira-Obaya et al. (2023), consists of choosing four branches from each of the selected 83 trees, and evaluating infestation in the part of the branch that had grown during the vegetative period, counting the number of new buds (N_B), the number of attacked buds (N_{AB}), and the number of galls (N_G). Although data was collected at the branch level, the parameter values were grouped in order to obtain representative infestation information at tree level. Therefore, from N_B, N_{AB}, and N_G, two infestation indicators were calculated that reflected the percentage of attacked buds (Gehring et al., 2018) and the number of galls per branch (Battisti et al., 2014):

$$\text{Infestation percentage} = \frac{\Sigma N_{AB}}{\Sigma N_B}\, x\ 100 \quad (1)$$

$$\text{Galls per branch} = \frac{\Sigma N_G}{4} \quad (2)$$

where ΣN_{AB} is the sum of attacked buds, ΣN_B is the sum of new buds, and ΣN_G is the number of galls in the four branches.

Tree growth: LiDAR data and dasymetric variables

Close-range LiDAR data were acquired using GeoSLAM ZEB Horizon (GeoSLAM Ltd., Nottingham, UK), equipped with 16 sensors that scan 300,000 points per second with accuracy of 1–3 cm within a 100-m range. Scans were carried out at three different stages of the vegetative cycle: before budding and the start of the growing stage (May 2022), during infestation assessment (July 2022), and during tree dormancy (January 2023).

Table 2
Equations used to calculate absolute and relative tree growth.

Variable	Equation
ΔH: Absolute growth in height (m)	$H_2 - H_1$
rΔH: Relative growth in height (m)	$\frac{\Delta H}{H_1}$
ΔA: Absolute growth of crown area (m^2)	$A_2 - A_1$
rΔA: Relative growth of crown area (m^2)	$\frac{\Delta A}{A_1}$
ΔV: Absolute growth in crown volume (m^3)	$V_2 - V_1$
rΔV: Relative growth in crown volume (m^3)	$\frac{\Delta V}{V_1}$

Table 3
Equations used to calculate normalized fruit yield variables.

Variable	Equation	Units
Nc: Number of nuts	$\frac{Nc}{A_J}$	n / m^2
Nb: Number of burrs	$\frac{Nb}{A_J}$	n / m^2
Wc: Weight of nuts	$\frac{Wc}{A_J}$	g / m^2
Wb: Weight of burrs	$\frac{Wb}{A_J}$	g / m^2

A_J: crown area (m^2) at the maximum vegetative development; n: number of nuts or number of burs.

LiDAR point clouds for each tree were processed in RStudio (v.4.2.1, R Core Team 2022), using the rLiDAR and rTLS packages to estimate dasymetric variables for each tree’s point cloud: height (H), as the maximum height value; crown area (A), calculated by fitting a 2D convex hull to the point cloud; and crown volume (V), calculated by modelling a 3D convex hull around the point cloud corresponding to the crown. Those variables enabled absolute growth and relative growth between the beginning and end of the vegetative cycle to be calculated using the six equations reflected in Table 2.

Fruit yield quantification

Yield was quantified in three field campaigns conducted in October and November 2022. Fully formed burrs were counted before harvesting, and, in two separate fieldwork operations during harvesting, the biomass yield of each tree was collected, weighed, and then divided into nuts and burrs. Four yield indicators were calculated: the number of nuts (Nc), weight of nuts (Wc), number of burrs (Nb), and weight of burrs (Wb). Since nuts are more numerous and nut quality is better in the outer crown, the values were normalized based on crown area, as shown in Table 3, where A_J is the estimated crown area at maximum vegetative development (July 2022).

Statistical analysis

Considering the two infestation indicators (infestation percentage and galls per branch), the three relative growth variables (rΔH, rΔA, rΔV), and the four yield variables (Nc, Wc, Nb, Wb), an exploratory data analysis was carried out to identify possible outliers and to understand sample response to ACGW infestation. The Shapiro-Wilk test was also applied to the yield and growth variables, confirming that the values were not normally distributed. The Pearson’s correlation method was applied to evaluate the relationship between the level of infestation and the fruit yield and tree growth variables.

Following the Gehring et al. (2020) classification, infestation levels

Table 4
Infestation of 83 trees according to infestation percentage and galls per branch.

	Infestation percentage	N	Galls per branch	N
Infestation levels	Low	7	Low	42
	Moderate	15	Moderate	33
	High	44	High	8
	Very High	17	–	–

were transformed into categorical data, defining four levels, i.e., low, moderate, high, and very high. Since no classification is available for galls per branch, we used Jenks natural breaks as a data clustering method (Coulson, 1987), resulting in three infestation levels, namely, low, moderate, and high. Grouping the sample by infestation levels, statistics were calculated for each variable. Significant differences ($p < 0.05$) between paired infestation levels were identified using the Mann-Whitney U test.

Statistical analyses were performed in the R language (v.4.2.1, R Core Team 2022).

Results

Infestation assessment

Table 4 summarizes ACGW infestation as assessed for the 83 sampled trees using infestation percentage and galls per branch as indicators. Infestation percentages at tree level were as follows: no single tree was unaffected, just over half the trees (44 of 83) were highly infested, 15 and 17 trees were moderately and very highly infested, respectively, and only 7 trees had a low infestation percentage. The number of galls per branch was low in half of the trees (42 of 83), moderate in 33 trees, and high in just 8 trees.

Tree growth

Fig. 1 depicts the tree growth variables (H, A, and V) on the LiDAR point cloud corresponding to one of the trees. Since LiDAR scans were carried out at three different times between May and January, calculating relative changes in these variables as rΔH, rΔA, and rΔV, respectively, indicated the growth of each tree. Table 5 shows the 83 trees grouped by infestation levels according to the infestation indicators (infestation percentage and galls per branch) and rΔH, rΔA, and

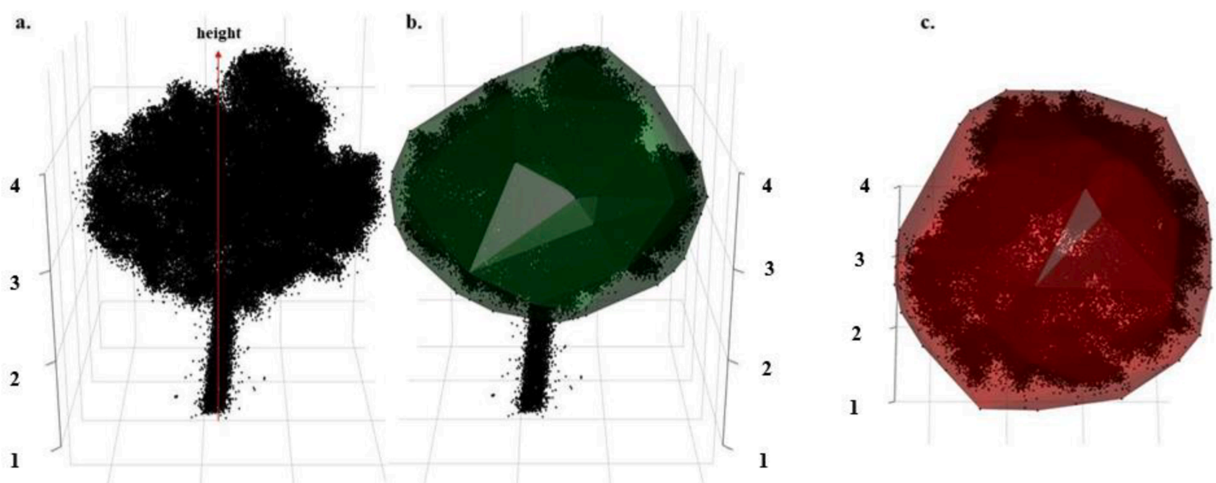

Fig. 1. Dasymetric variables displayed over a LiDAR tree point cloud. a. red arrow indicating height; b. green 3D convex hull enclosing crown area; and c. red 2D convex hull encompassing crown volume. Three all figures are represented in terms of meters (m).

Table 5
Relative tree growth statistics meters are shown grouped by infestation levels distinguishing between infestation percentage and galls per branch.

		Infestation percentage				Galls per branch			
		Very High	High	Moderate	Low		High	Moderate	Low
	N	17	44	15	7	N	8	33	42
rΔH	Mean	0.13	0.16	0.13	0.11	Mean	0.14	0.17	0.11
	Median	0.13	0.11	0.12	0.11	Median	0.12	0.12	0.1
	Min	0.05	0.03	−0.01	0.06	Min	0.07	0.03	−0.01
	Max	0.25	1.12	0.35	0.18	Max	0.25	1.12	0.35
	SD	0.06	0.18	0.11	0.04	SD	0.06	0.18	0.08
rΔA	Mean	0.4	0.32	0.34	0.27	Mean	0.46	0.34	0.3
	Median	0.36	0.29	0.29	0.26	Median	0.48	0.31	0.27
	Min	0.22	0.2	0.21	0.17	Min	0.27	0.2	0.17
	Max	0.61	0.73	0.69	0.47	Max	0.61	0.73	0.69
	SD	0.13	0.11	0.14	0.11	SD	0.15	0.12	0.11
rΔV	Mean	0.95	0.83	0.77	0.52	Mean	1.21	0.88	0.65
	Median	0.74	0.62	0.67	0.52	Median	1.15	0.68	0.55
	Min	0.48	0.29	0.27	0.29	Min	0.5	0.34	0.27
	Max	2.16	3.02	2.4	0.85	Max	2.16	3.02	2.4
	SD	0.51	0.59	0.55	0.22	SD	0.63	0.59	0.4

rΔH: relative growth in height (m); rΔA: relative growth of crown area (m^2); rΔV: relative growth in crown volume (m^3); N: number of trees; Min: minimum value; Max: maximum value; and SD: standard deviation.

Table 6
Fruit yield statistics by infestation levels distinguishing between infestation percentage and galls per branch.

		Infestation percentage					Galls per branch		
		Very High	High	Moderate	Low		High	Moderate	Low
	N	17	44	15	7	N	8	33	42
Nc	Mean	19	19	27	29	Mean	10	19	28
	Median	12	12	24	20	Median	7	20	23
	Min	0	0	0	11	Min	0	0	0
	Max	64	64	76	62	Max	35	49	76
	SD	20	20	20	19	SD	11	13	21
Wc	Mean	240.3	249.3	313.5	359.7	Mean	115.2	245.2	334.9
	Median	153.2	248.2	284.9	293.2	Median	89.3	256.6	284.9
	Min	0	0	0	127.57	Min	0	0	0
	Max	759.5	653.2	827.5	735.9	Max	338.4	653.2	827.5
	SD	242.1	179.5	221.4	215.1	SD	107.2	170.5	235.7
Nb	Mean	12	16	20	21	Mean	9	15	19
	Median	11	14	18	16	Median	8	14	16
	Min	0	0	3	11	Min	0	0	3
	Max	37	39	41	42	Max	21	39	42
	SD	9	9	10	11	SD	7	9	9
Wb	Mean	322.8	378.9	510.1	466.6	Mean	304.5	375.41	450.76
	Median	221.5	338.3	412.8	203.2	Median	254.9	334.4	346.8
	Min	0	0	0	172.51	Min	0	0	0
	Max	1497.1	1208.5	1225.1	1135.9	Max	942.5	1208.5	1497.1
	SD	346.1	263.8	353	408.4	SD	305.2	281	349.8

Nc: number of nuts (n/ m^2); Nb: number of burrs (n/ m^2); Wc: weight of nuts (g/m^2); Wb: weight of burrs (g/m^2); N: number of trees; Min: minimum value; Max: maximum value; and SD: standard deviation.

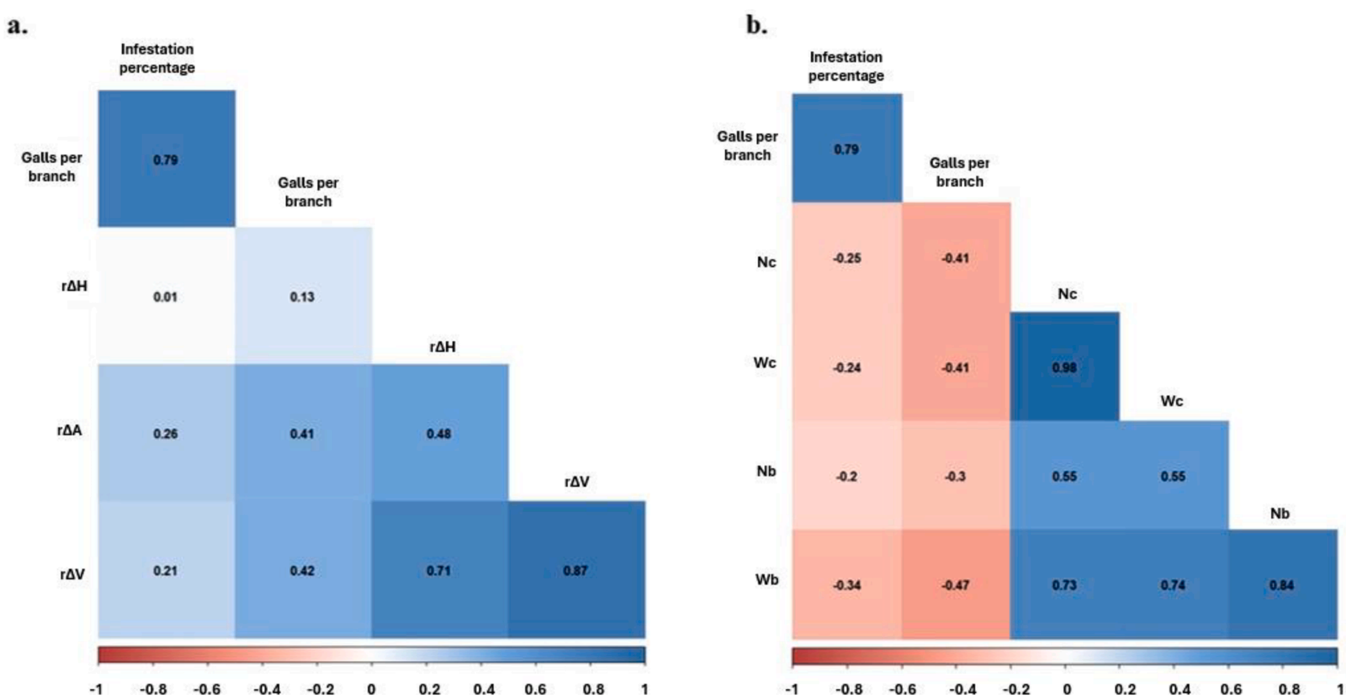

Fig. 2. Infestation percentage and galls per branch: correlations with tree growth (a) and fruit yield (b). rΔH: relative growth in height (m); rΔA: relative growth of crown area (m); rΔV: relative growth in crown volume (m); Nc: number of nuts (n/ m^2); Nb: number of burrs (n/ m^2); Wc: weight of nuts (g/m^2); Wb: weight of burrs (g/m^2).

rΔV values. Considering infestation percentages, low infestation levels presented smaller height increases than very high infestation levels, while height variations were similar for moderate and very high infestation levels. Crown area and crown volume growth increased as the infestation level increased, although considering the median, crown area growth was similar for moderate and high infestation levels. Regarding galls per branch, crown area and crown volume growths were greater as the infestation level increased. Considering median values, low infestation levels presented smaller growth rates than moderate and high infestation levels, which both reflected similar growth.

Fruit yield

During the harvesting season, fruit production variables were measured and converted into yields, normalized using crown area (m^2). Table 6 summarizes fruit yield variables, differentiated according to infestation percentage and galls per branch, and showing the same tendency for both infestation indicators, i.e., fruit yield decreased as the infestation level increased. However, for the infestation percentage, yields were greater for moderate infestation than for low infestation.

Table 7
Mann-Whitney U test results for infestation level pairs: infestation percentage.

Fruit yield			Tree growth		
Variable	Infestation level	p-value	Variable	Infestation level	p-value
Nc	Low-Moderate	0.8907	**rΔH**	Low-Moderate	0.8907
	Low-High	0.2129		Low-High	0.7991
	Low-Very High	0.1139		Low-Very High	0.4551
	Moderate-High	0.3126		Moderate-High	0.4529
	Moderate-Very High	0.1802		Moderate-Very High	0.5019
	High-Very High	0.5299		High-Very High	0.6845
Wc	Low-Moderate	0.6796	**rΔA**	Low-Moderate	0.1851
	Low-High	0.1843		Low-High	0.2741
	Low-Very High	0.1297		Low-Very High	**0.0337**
	Moderate-High	0.3746		Moderate-High	0.6983
	Moderate-Very High	0.2058		Moderate-Very High	0.1532
	High-Very High	0.5095		High-Very High	**0.0174**
Nb	Low-Moderate	0.8907	**rΔV**	Low-Moderate	0.4475
	Low-High	0.4516		Low-High	0.1170
	Low-Very High	0.0645		Low-Very High	**0.0160**
	Moderate-High	0.1460		Moderate-High	0.5753
	Moderate-Very High	**0.0177**		Moderate-Very High	0.0969
	High-Very High	0.0666		High-Very High	0.0868
Wb	Low-Moderate	0.6796			
	Low-High	0.8373			
	Low-Very High	0.4939			
	Moderate-High	0.1857			
	Moderate-Very High	0.0857			
	High-Very High	0.1616			

rΔH: relative growth in height (m); rΔA: relative growth of crown area (m); rΔV: relative growth in crown volume (m); Nc: number of nuts (n/ m^2); Nb: number of burrs (n/m^2); Wc: weight of nuts (g/m^2); Wb: weight of burrs (g/m^2). Bold indicates significant differences ($p < 0.05$).

Relationship between infestation level and yield and growth variables

As part of the exploratory data analysis, Pearson's correlation method was used to test whether tree growth and fruit yield depended on the infestation level (Fig. 2). The threshold intervals proposed by Schober et al. (2018) indicate that all the analysed pairs of variables showed weak (0.1–0.39) or moderate (0.40–0.69) correlations. For the infestation percentage indicator, rΔA (0.26) and rΔV (0.21) showed weak and positive correlations, while rΔH showed no correlation. For the galls per branch indicator, rΔA and rΔV showed moderate correlations (0.41 and 0.42, respectively). All four yield variables (Nc, Wc, Nb, and Wb) showed negative and low correlations with the infestation percentage indicator, while Nc, Wc, and Wb showed negative and moderate correlations with the galls per branch indicator. Nb showed the lowest correlation value (−0.3), Wb showed the highest correlation value (−0.47), and Nc and Wc had the same intermediate correlation value (−0.41).

Differences between ACGW infestation levels

The Mann-Whitney U test analysed whether there were significant differences between infestation pairs, using the indicators of infestation percentage and galls per branch. In the case of the infestation percentages (Table 7 and Fig. 3), only Nb, rΔA, and rΔV resulted significantly different, with the graph showing that differences between median values are not perceptible. As for galls per branch (Table 8 and Fig. 4), all the variables (Nc, Wc, Nb, Wb, rΔH, rΔA, and rΔV) showed

Table 8
Mann-Whitney U test results for infestation level pair: galls per branch.

Fruit yield			Tree growth		
Variable	Infestation level	p-value	Variable	Infestation level	p-value
Nc	Low-Moderate	0.2588	**rΔH**	Low-Moderate	**0.0377**
	Low-High	**0.0052**		Low-High	0.3385
	Moderate-High	**0.0260**		Moderate-High	0.5423
Wc	Low-Moderate	0.2743	**rΔA**	Low-Moderate	0.2336
	Low-High	**0.0039**		Low-High	**0.0019**
	Moderate-High	**0.0164**		Moderate-High	**0.0271**
Nb	Low-Moderate	0.5625	**rΔV**	Low-Moderate	**0.0400**
	Low-High	**0.0002**		Low-High	**0.0045**
	Moderate-High	**0.0007**		Moderate-High	0.1233
Wb	Low-Moderate	0.8008			
	Low-High	**0.0039**			
	Moderate-High	**0.0074**			

rΔH: relative growth in height (m); rΔA: relative growth of crown area (m); rΔV: relative growth in crown volume (m); Nc: number of nuts (n/ m^2); Nb: number of burrs (n/m^2); Wc: weight of nuts (g/m^2); Wb: weight of burrs (g/m^2). Bold indicates significant differences ($p < 0.05$).

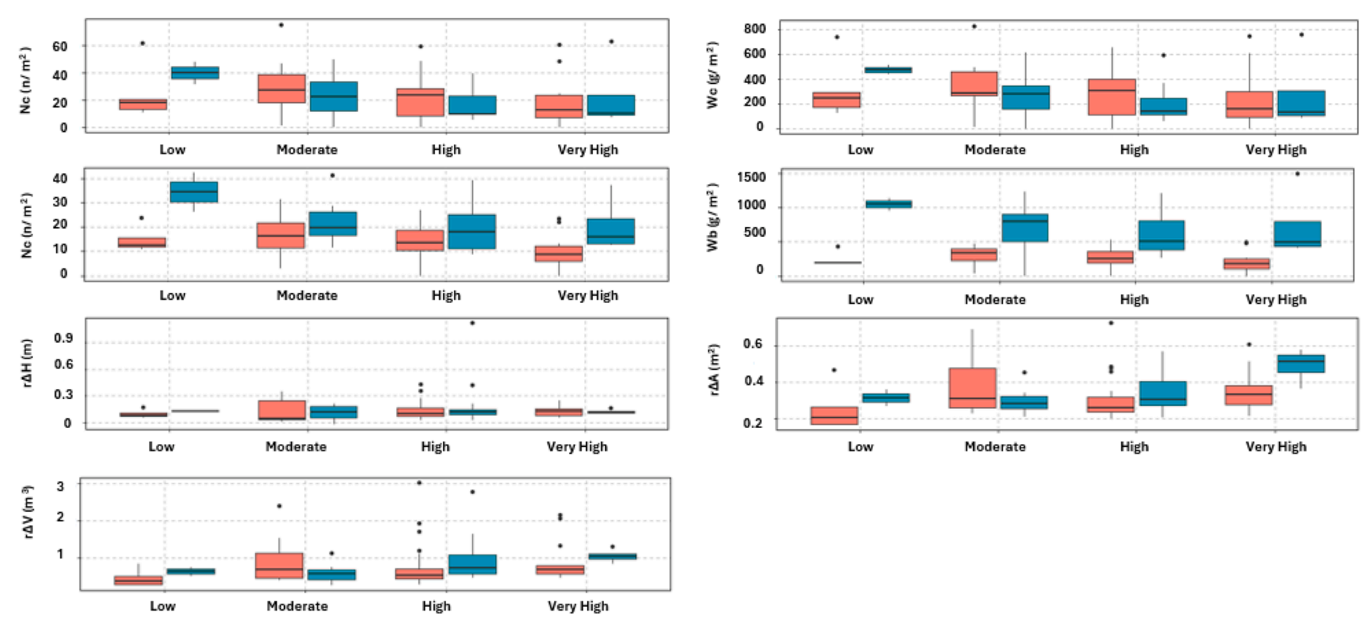

Fig. 3. Boxplots of infestation percentages for Plot A (red) and Plot B (blue). rΔH: relative growth in height (m); rΔA: relative growth of crown area (m); rΔV: relative growth in crown volume (m); Nc: number of nuts (n/ m^2); Nb: number of burrs (n/m^2); Wc: weight of nuts (g/m^2); Wb: weight of burrs (g/m^2).

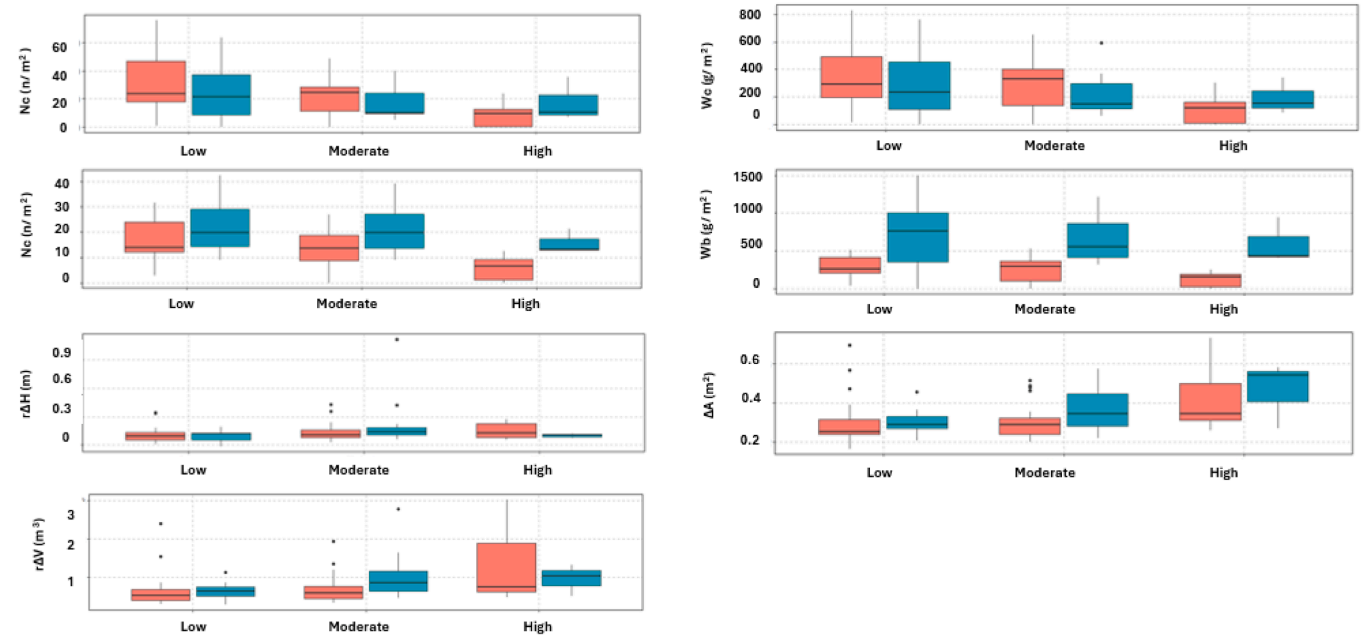

Fig. 4. Boxplots of galls per branch for Plot A (red) and Plot B (blue). rΔH: relative growth in height (m); rΔA: relative growth of crown area (m); rΔV: relative growth in crown volume (m); Nc: number of nuts (n/ m^2); Nb: number of burrs (n/m^2); Wc: weight of nuts (g/m^2); Wb: weight of burrs (g/m^2).

significant differences, mainly corresponding to the low-high and moderate-high infestation pairs, although rΔH and rΔV also showed significant differences for the low-moderate infestation pair.

Discussion

Considering both percentage infestation and galls per branch as indicators of infestation, correlation data confirm that fruit yield decreases as infestation increases, although the correlation was more robust when galls per branch was considered. These findings corroborate the graphical and numerical results reported by Battisti et al. (2014) and Sartor et al. (2015); in both cases, values were normalized using the DBH (cm^2), whereas in our study we used the crown area (m^2) instead to normalize values. This fact would confirm that crown area, where the burrs are mainly located (Wen et al., 2020), is a suitable dasymetric variable to discretize, calculate and compare fruit yields. In their study involving ten years of monitoring, Marcolin et al. (2021) concluded that radial growth was lower in trees that experienced more intense ACGW infestation in consecutive seasons. Castedo-Dorado et al. (2023), for five years of periodic measurements of DBH and tree height, also recorded lower radial growth rates in ACGW-infested trees; they drew the same conclusion regarding height increases, although in one of their plots the infested trees grew taller than the healthy trees. In terms of relative tree growth, our correlation data confirm that height, crown area, and crown volume increased with higher infestation levels.

Positive responses by trees against diseases, plagues, and other disturbances have been previously observed. Guillet and Bergström (2006) recorded compensatory growth when herbivores browsed in willow coppices, and despite the presence of gall-forming pests. Notwithstanding the fact that pests have negative effects on plant health, these consequences are reported to be null or even positive for woody plants, and no effects have been detected when galls form in the reproductive stage (Garcia et al., 2021). This is the case of the ACGW, as its eggs are laid in newly formed buds during the chestnut production season, and therefore seems to explain, not only the greater elongation rates for non-infested branches reported by Kato and Hijii (1997), but also our correlation findings for tree growth and fruit yield variables with the two different infestation indicators, i.e., infestation percentage and galls per branch.

Regarding significant differences between infestation level pairs, we found that only the number of burrs, crown area, and crown volume resulted significantly different for the infestation percentage indicator (although visually the differences between median values were not perceptible), whereas for the galls per branch, all the variables showed significant differences. Castedo-Dorado et al. (2023) reported significant differences between uninfested and infested trees in terms of height increases. We found that, with galls per branch, it was possible to significantly discriminate crown area and crown volume relative growth associated with different infestation levels (low, moderate, and high), and also that fruit yield variables were also significantly different on comparing infestation pairs.

It should be noted that the present work was carried out in two chestnut orchards and not in a chestnut coppice. None of the 83 trees in our study remained uninfested, in addition, only one season's growth was evaluated, and, since infestation levels from previous years were not taken into account, the effect of consecutive attacks could not be evaluated.

Conclusions

While classifications of Asian chestnut gall wasp (ACGW) infestation levels based on the percentage of attacked buds already exist, we propose a more easily applied alternative with a smaller number of classes that considers the number of galls per branch. This work can be considered a first step towards establishing a new infestation classification methodology.

Regarding fruit yield, our alternative approach points to significant differences, with higher infestation levels associated with lower yields, and therefore corroborating previous studies, even those using innovative techniques such as unmanned aerial vehicles (UAVs). While we found terrestrial light detection and ranging (LiDAR) to be an efficient means of estimating tree growth, few studies exist regarding how the ACGW as a gall-forming pest affects radial growth, so further research in sweet chestnut orchards and coppices is required to test close-range LiDAR for this kind of monitoring.

CRediT authorship contribution statement

Dimas Pereira-Obaya: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Enoc Sanz-Ablanedo:** Software, Investigation. **Karen Brigitte Mejía-Correal:** Writing – original draft, Investigation. **José Ramón Rodríguez-Pérez:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dimas Periera-Obaya reports financial support was provided by University of León.

Data availability

Data will be made available on request.

Funding

Dimas Pereira-Obaya gratefully acknowledges financial support provided by the European Social Fund, Operational Program of Castilla y León and of the Junta de Castilla y León, through the Consejería de Educación (grants for pre-doctoral research 2020). The research was supported by the company VITICAMPO, SL (grant id: 2021/00009/001; T132).

References

Amorim, A., Rodrigues, R., Nunes, L.J.R., Freitas, M., Moura, L., 2022. Dryocosmus kuriphilus Yasumatsu (Hymenoptera: cynipidae) in Minho (Northern Portugal): bioecology, native parasitoid communities and biological control with Torymus sinensis Kamijo (Hymenoptera: torymidae). Agronomy 12 (9). https://doi.org/10.3390/agronomy12092184. Article 9.

Arakawa, T., Tanaka, T.S.T., Kamio, S., 2023. Detection of on-tree chestnut fruits using deep learning and RGB unmanned aerial vehicle imagery for estimation of yield and fruit load. Agron. J. https://doi.org/10.1002/agj2.21330.

Battisti, A., Benvegnù, I., Colombari, F., Haack, R.A., 2014. Invasion by the chestnut gall wasp in Italy causes significant yield loss in Castanea sativa nut production. Agric. For. Entomol. 16 (1), 75–79. https://doi.org/10.1111/afe.12036.

Branco, M., Battisti, A., Mendel, Z., 2016. Foliage feeding invasive insects: defoliators and gall makers. Lieutier. In: En, T.D., Paine, & F. (Eds.), Insects and Diseases of Mediterranean Forest Systems. Springer International Publishing, pp. 211–238. https://doi.org/10.1007/978-3-319-24744-1_8.

Castedo-Dorado, F., Álvarez-Álvarez, P., Lombardero, M.J., 2023. The impact of the Asian chestnut gall wasp (Dryocosmus kuriphilus) on chestnut tree growth may be mediated by site resources. Front For. Glob. Change 5, 1095185. https://doi.org/10.3389/ffgc.2022.1095185.

Conedera, M., Krebs, P., Gehring, E., Wunder, J., Hülsmann, L., Abegg, M., Maringer, J., 2021. How future-proof is Sweet chestnut (Castanea sativa) in a global change context? For. Ecol. Manage. 494, 119320 https://doi.org/10.1016/j.foreco.2021.119320.

Conedera, M., Manetti, M.C., Giudici, F., Amorini, E., 2004. Distribution and economic potential of the Sweet chestnut (Castanea sativa Mill. Europe. Ecologia Mediterranea 30 (2), 179–193. https://doi.org/10.3406/ecmed.2004.1458.

Coulson, M.R., 1987. In The matter of class intervals for choropleth maps: with particular reference to the work of George F Jenks. Cartographica: Int. J. Geogr. Inf. Geovisualization 24, 16–39. https://doi.org/10.3138/U7X0-1836-5715-3546.

Fernández-Cruz, J., Míguez-Soto, B., Fernández-López, J., 2022. Origin of traditional sweet chestnut (Castanea sativa Mill.) varieties from the Northwest of the Iberian Peninsula. Tree Genet. Genomes 18 (5), 34. https://doi.org/10.1007/s11295-022-01564-9.

Ferracini, C., Pogolotti, C., Giacosa, S., Fontana, E.V., Rolle, L., Alma, A., 2022. Assessment of chestnut gall toughness: implications for a biocontrol agent. Insects 13 (12), 1095. https://doi.org/10.3390/insects13121095.

Freitas, T.R., Santos, J.A., Silva, A.P., Martins, J., Fraga, H., 2022. Climate change projections for bioclimatic distribution of Castanea sativa in Portugal. Agronomy 12 (5), 1137. https://doi.org/10.3390/agronomy12051137.

Garcia, A., Martinez, M., Diaz, I., Santamaria, M.E., 2021. The price of the induced defense against pests: a meta-analysis. Front. Plant Sci. 11, 615122 https://doi.org/10.3389/fpls.2020.615122.

Gehring, E., Bellosi, B., Quacchia, A., Conedera, M., 2018. Assessing the impact of Dryocosmus kuriphilus on the chestnut tree: branch architecture matters. J. Pest. Sci. (2004) 91 (1), 189–202. https://doi.org/10.1007/s10340-017-0857-9.

Gehring, E., Bellosi, B., Reynaud, N., Conedera, M., 2020. Chestnut tree damage evolution due to Dryocosmus kuriphilus attacks. J. Pest. Sci. 93 (1), 103–115. https://doi.org/10.1007/s10340-019-01146-0.

Gil-Tapetado, D., Gomez, J.F., Cabrero-Sanudo, F.J., Nieves-Aldrey, J.L., 2018. Distribution and dispersal of the invasive Asian chestnut gall wasp, Dryocosmus kuriphilus (Hymenoptera: cynipidae), across the heterogeneous landscape of the Iberian Peninsula. Eur. J. Entomol. 115, 575–586. https://doi.org/10.14411/eje.2018.055.

Guillet, C., Bergström, R., 2006. Compensatory growth of fast-growing willow (Salix) coppice in response to simulated large herbivore browsing. Oikos 113 (1), 33–42.

Kato, K., Hijii, N., 1997. Effects of gall formation by Dryocosmus kuriphilus Yasumatsu (Hym., Cynipidae) on the growth of chestnut trees. J. Appl. Entomol. 121 (1–5), 9–15. https://doi.org/10.1111/j.1439-0418.1997.tb01363.x.

Marcolin, E., Pividori, M., Colombari, F., Manetti, M.C., Pelleri, F., Conedera, M., Gehring, E., 2021. Impact of the Asian gall wasp Dryocosmus kuriphilus on the radial growth of the European chestnut Castanea sativa. J. Appl. Ecol. 58 (6), 1212–1224. https://doi.org/10.1111/1365-2664.13861. Scopus.

Miranda-Fuentes, A., Llorens, J., Gamarra-Diezma, J.L., Gil-Ribes, J.A., Gil, E., 2015. Towards an optimized method of olive tree crown volume measurement. Sensors 15 (2). https://doi.org/10.3390/s150203671. Article 2.

Pereira-Obaya, D., Castedo-Dorado, F., Sanz-Ablanedo, E., Mejía-Correal, K.B., Rodríguez-Pérez, J.R., 2023. Leaf trait hyperspectral characterization of Castanea sativa miller affected by Dryocosmus kuriphilus Yasumatsu. Agronomy 13 (3), 923. https://doi.org/10.3390/agronomy13030923.

Prada, M., Canga, E., Majada, J., Martínez-Alonso, C., 2022. Canopy characterization of sweet chestnut coppice in the north of spain from lidar data. Eur. J. For. Res. 141, 1–13. https://doi.org/10.1007/s10342-021-01436-2.

Rivera, G., Porras, R., Florencia, R., Sánchez-Solís, J.P., 2023. LiDAR applications in precision agriculture for cultivating crops: a review of recent advances. Compu. Electron. Agric. 207, 107737 https://doi.org/10.1016/j.compag.2023.107737.

Sartor, C., Dini, F., Torello Marinoni, D., Mellano, M.G., Beccaro, G.L., Alma, A., Quacchia, A., Botta, R., 2015. Impact of the Asian wasp Dryocosmus kuriphilus (Yasumatsu) on cultivated chestnut: yield loss and cultivar susceptibility. Sci. Hortic. 197, 454–460. https://doi.org/10.1016/j.scienta.2015.10.004.

Schober, P., Boer, C., Schwarte, L.A., 2018. Correlation coefficients: appropriate use and interpretation. Anesthesia Analgesia 126 (5), 1763. https://doi.org/10.1213/ANE.0000000000002864.

Wang, Y.-T., Bailey, B.N., Fu, K., Shackel, K., 2023. Topological and spatial analysis of within-tree fruiting characteristics for walnut trees. Sci. Hortic. 318, 112127 https://doi.org/10.1016/j.scienta.2023.112127.