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Nut and kernel growth and shell hardening in eighteen hazelnut cultivars (*Corylus avellana* L.)

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Abstract

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Growth and development of nuts and kernels were measured in 18 hazelnut (*Corylus avellana* L.) cultivars from cluster appearance until nut maturity and drop. At harvest, shell thickness and force to penetrate the shell were determined and related to the incidence of nut weevil damage. The force to penetrate the shells started to increase when nuts reached 80–90% of their final size, and continued until kernel full size. During nut growth, shell hardness and kernel size were highly correlated (R^2 = 0.921). At maturity, values of force ranged from 46.7 to 185.7 N. Values of nut weevil damage ranged from 0.6 to 24.4%. At harvest, the force to penetrate the shells was highly correlated with the shell thickness (r = 0.945) and negatively correlated with the nut weevil damage (r = –0.564). Late onset of nut development was associated with a high percentage of nut weevil damage (R = 0.638). These information can be used to model nut development and provide important tools for planning orchard management activities.

Keywords: European hazelnut; fruit growth curve; force of shell penetration; shell thickness; nut weevil damage

Hazelnut (*Corylus avellana* L.) is one of the most important tree nut crops with a yearly production of about 872,000 t of in-shell nuts with a cultivated area of approximately 604,000 ha (average 2008–2012, FAOSTAT 2014). Over 80% of hazelnut world production is supplied by Turkey (70%) and Italy (11%) with additional production in the United States of America, Georgia and Azerbaijan, and significant new planting in Chile (Fideghelli, De Salvador 2009).

The biology of hazelnut shows some peculiar characteristics. The species is monoecious, self-incompatible and mostly dichogamous; blooming occurs during winter and a period of 4 months elapses between pollination and fertilization. Following fertilization, nut growth follows a sigmoidal curve (Thompson 1967) as in walnut and pecan (Westwood 1993).

Knowledge of the timing of nut and kernel development is important for orchard management, especially irrigation. A lack of water during nut growth results in reduced nut size, while during kernel growth it leads to poorly filled nuts and shriveled kernels (Mehlenbacher et al. 1993). Kernel quality is reduced and it is more difficult to remove the pellicle after roasting (Germain, Sarraquigne 2004). Water availability during kernel growth can also influence the presence of blanks (nuts lacking kernels) (Solar, Stampar 2011; Milošević, Milošević 2012).

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Nut and kernel development has been studied in few cultivars and under different climatic conditions: cv. Tonda Gentile delle Langhe (Roversi 1973) and cv. Tonda Gentile Romana (Tombesi et al. 1983) in Italy; cv. Barcelona in Willamette Valley, Oregon, USA (Thompson 1979) and in France (Germain 1983); cv. Butler in Portugal (Silva et al. 2001) and cvs Tombul and Palaz in Turkey (Beyhan, Marangoz 2007).

Shell characteristics at harvest, such as thickness, force to break the shell and other morphological traits (number of cell layers, thickness of cell walls, shape and dimensions of sclereids; presence and density of hairs), were described for some cultivars and related with the susceptibility to nut weevil *Curculio nucum* L. (Coleoptera: Curculionidae) (Caramiello et al. 2000).

Nut growth as well as shell hardening was also studied in relation to susceptibility to the nut weevil. The sequence of shell hardening during nut growth was described for six hazelnut cultivars during the time when ovipositing weevil females were present (Guidone et al. 2007) and this preliminary study demonstrated that hazelnut cultivar susceptibility is related to the timing of nut growth and shell hardening.

Therefore, the aims of this study were: (i) to describe the timing of nut and kernel growth, including shell hardening, in 18 hazelnut cultivars grown in the same environmental and orchard management conditions; (ii) to describe fruit characteristics at harvest including shell thickness and force to penetrate the shell; (iii) to evaluate the presence of blanks and nut weevil damage at harvest; (iv) to correlate the timing of nut development and fruit characteristics at harvest with the frequency of blanks and nut weevil damage.

MATERIAL AND METHODS

Plant material. In 2008, investigations were carried out on 18 hazelnut cultivars of different origins (Table 1) in the hazelnut collection in Cravanzana

Table 1. Hazelnut cultivars investigated, areas of origin and nut development time

Cultivar	Code	Area of origin	5–15% of nut volume (date)	Nut growth class
Alcover	AL	Spain	June 23	3
Camponica	CA	Italy	June 12	2
Casina	CS	Spain	June 23	3
Closca Molla	CM	Spain	June 23	3
Cosford	CO	England	July 4	4
Culplà	CU	Spain	June 23	3
Daria	DA	Italy	June 12	2
Du Chilly	DC	England	June 23	3
Ghirara	GH	Italy	June 3	1
Gunslebert	GU	Germany	June 23	3
Jean's	JE	Unknown	June 23	3
Merveille de Bollwiller (syn Hall's Giant)	MB	France	June 23	3
Mortarella	MO	Italy	June 12	2
Negret	NE	Spain	June 23	3
Nocchione	NO	Italy	June 12	2
Pauetet	PA	Spain	June 23	3
Tonda Gentile delle Langhe	TGdL	Italy	June 3	1
Tonda di Giffoni	TG	Italy	June 12	2

nut growth class: 1 – very early, 4 – late

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(Piedmont region, Northwest Italy; 44°34'N, 8°07'E, 550 m a.s.l.), an area intensively and traditionally cropped with hazelnut. The orchard was planted in 1982 with a plant spacing of 4 × 4 m and bush training system; each cultivar was represented by three adjacent plants. To evaluate the incidence of nut weevil damage at harvest, no pesticide treatments were applied during the trial.

Nut and kernel growth, shell hardness. To assess nut and kernel growth as well as the hardness of the shell during nut development, 15 nuts per cultivar were collected directly from the plants approximately every 10 days from June 3 to September 9. In the laboratory, nut characteristics were assessed in the following order: nut dimensions, force to penetrate the shell and then kernel dimensions after breaking the shell.

Nut and kernel length (L), width (W) and depth (D) were measured using a caliper (VWR i819-0013; VWR, Radnor, USA) with an accuracy of 0.01 mm. The nut and kernel volumes were then calculated using the ellipsoid formula (Valentini et al. 2006). Nut measurements started when nut width was at least 5 mm (about 80–120 mm^3 in volume). Before this stage it was extremely difficult to separate the husk from the nut. Kernel measurements started with the length of the embryo reached 2 mm, because generally only one of the two ovules develops after fertilization while the second one aborts and remains about 1 mm in length (Thompson 1979).

For instrumental requirements, hardness measurements started when nut width was 8–10 mm (about 200–300 mm^3 in volume). Nut samples were analysed using a Universal Testing Machine TA.HD® Texture Analyser (Stable Micro System, Godalming, Surrey, UK). The max. force (N) required to puncture the shell in the median zone of the nut (Guidone et al. 2007) was recorded using the Texture Expert® software provided with the instrument. The puncture test was performed with a 50 kg load cell using a P/N needle probe at 1 mm/s constant speed. The nut was placed in a HDP/90 perforated platform. The force-time curve was acquired as a graph at 500 Hz.

The time of nut growth of hazelnut cultivars was classified from 1 (very early) to 4 (late) based on the date at which the nuts reached 5–15% of their total volume.

Nut and kernel characteristics at harvest. At harvest, the nuts from each plant were manually harvested from the ground. Nut samples of each cultivar were collected and analysed in the same way as those collected during nut growth (nut and kernel dimensions, force to penetrate the shell). The roundness index of the nut (RI) was calculated using the formula $RI = (W + D)/2L$ (Fregoni, Zioni 1962). In addition, shell thickness of 10 nuts from each of three replicate plants per variety was measured in the median zone of the nut using a caliper with an accuracy of 0.01 mm.

Three random samples of 100 nuts for each cultivar were then inspected in laboratory for presence of blanks and nuts damaged by *C. nucum.* Nuts were firstly separated in two groups: intact nuts and nuts showing the emergence hole of mature weevil larvae. Afterwards all intact nuts were cracked by hand and checked for the presence of weevil larvae or absence of kernel (blank).

Statistical analysis. Data recorded at harvest were analysed by ANOVA and the Duncan's Multiple Range test using the software SPSS Statistics 20.0 (IBM, New York, USA). Pearson correlation coefficients (r) were calculated to correlate: nut and shell characteristics at harvest (nut and kernel volumes, shell thickness and force required to penetrate shell), time of nut development (time required to reach 5–15% of final nut volume, expressed as days from June 1), percentage of nut weevil damage and percentage of blanks.

RESULTS AND DISCUSSION

Nut and kernel growth, shell hardening

Nuts and kernels of all the cultivars grew following a sigmoidal curve (Fig. 1) as shown by other authors (Thompson 1967; Roversi 1973; Germain 1983; Tombesi et al. 1983; Silva et al. 2001; Beyhan, Marangoz 2007). The fruit (ovary) needed 4 to 5 weeks to complete growth and attain full size; the development of the kernel started when the nut had almost reached full size and kernel growth continued for approximately 5 to 6 weeks until it attained its full size.

Hazelnut cultivars were divided into four classes in relation to the beginning of nut development (Table 1). Hazelnut varieties showed a wide range of nut development times since the latest cultivars developed about a month later than the earliest ones (Table 2). Cvs Tonda Gentile delle Langhe (TGdL) and Ghirara had very early nut growth which started in early June (class 1), reach-

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Table 2. Mean values (±SE) of nut and kernel volume (mm³) measured in 2008 (n = 15)

Cultivar		June 3	June 12	June 23	July 4	July 15	July 25	August 6	August 18	August 28	September 9
AL	NV		1,16.6 ± 18.0	308.6 ± 36.6	2,400.0 ± 105.6	2,442.0 ± 184.4	2,736.0 ± 119.1	2,689.6 ± 77.2	2,467.1 ± 66.0	2,522.0 ± 59.6	2,923.5 ± 96.6
	KV				4.5 ± 0.6	131.2 ± 47.0	628.6 ± 102.2	1,157.8 ± 66.7	1,257.5 ± 51.0	1,477.2 ± 41.7	1,625.4 ± 48.5
CA	NV	79.5 ± 12.3	198.3 ± 19.3	1,305.8 ± 269.7	3,036.3 ± 286.9	3,340.9 ± 376.0	3,665.9 ± 161.1	3,763.9 ± 187.9	4,202.5 ± 239.3	4,243.9 ± 200.5	
	KV			1.4 ± 0.2	33.1 ± 7.4	115.0 ± 27.7	814.8 ± 166.5	1,423.4 ± 283.6	2,008.1 ± 134.5	2,048.4 ± 97.7	
CS	NV		84.3 ± 33.9	265.0 ± 33.7	946.4 ± 89.4	2,309.6 ± 122.0	2,393.3 ± 112.2	2,468.6 ± 79.3	2,496.0 ± 132.6	2,470.3 ± 99.7	2,724.8 ± 77.4
	KV				1.0 ± 0.3	25.9 ± 8.3	93.5 ± 23.0	540.9 ± 58.8	1,264.8 ± 99.0	1,314.1 ± 63.9	1,577.8 ± 61.0
CM	NV			202.4 ± 35.1	1,828.7 ± 200.9	3,004.5 ± 245.0	3,318.2 ± 172.3	3,074.6 ± 177.9	3,366.2 ± 228.7	3,046.4 ± 187.4	3,577.6 ± 177.8
	KV				1.8 ± 0.3	21.4 ± 5.0	126.0 ± 44.5	310.3 ± 72.7	1,603.9 ± 89.0	1,678.4 ± 131.1	1,730.8 ± 130.6
CO	NV				195.5 ± 64.4	846.3 ± 133.1	2,453.5 ± 385.8	3,466.1 ± 124.0	3,397.1 ± 122.5	3,385.4 ± 176.0	3,578.4 ± 114.3
	KV					1.1 ± 0.2	25.5 ± 7.4	157.8 ± 54.8	889.3 ± 134.0	1,813.1 ± 65.3	1,841.5 ± 117.1
CU	NV		105.2 ± 22.0	342.5 ± 64.2	1,524.8 ± 278.5	3,284.5 ± 115.6	3,167.6 ± 73.3	3,107.8 ± 71.6	3,472.9 ± 127.5	3,444.3 ± 42.2	3,557.5 ± 78.8
	KV				1.0 ± 0.3	18.9 ± 5.0	87.2 ± 16.9	1,038.3 ± 78.5	1,703.8 ± 86.0	1,911.9 ± 41.3	1,885.9 ± 44.9
DA	NV	78.5 ± 8.7	151.0 ± 20.2	1,065.2 ± 116.5	2,736.1 ± 191.8	3,029.1 ± 144.9	2,927.8 ± 105.5	3,082.4 ± 158.9	3,221.3 ± 102.5	3,231.3 ± 84.5	
	KV				5.2 ± 1.4	57.1 ± 25.5	518.5 ± 169.5	924.9 ± 128.6	1,680.5 ± 57.8	1,733.9 ± 66.9	
DC	NV			158.8 ± 38.7	1,142.3 ± 212.3	2,759.7 ± 375.7	3,740.0 ± 278.4	3,986.1 ± 115.4	3,951.2 ± 183.1	3,962.4 ± 156.5	4,279.3 ± 108.4
	KV				1.4 ± 0.2	24.7 ± 12.0	265.0 ± 48.0	1,216.6 ± 186.9	1,626.2 ± 122.5	1,786.9 ± 117.8	1,909.2 ± 106.4
GH	NV	123.8 ± 26.1	571.0 ± 71.4	1,464.0 ± 138.1	2,485.8 ± 99.0	2,143.3 ± 126.5	2,424.9 ± 116.1	2,304.2 ± 157.8	2,899.6 ± 198.3	2,824.9 ± 149.9	
	KV			2.3 ± 0.5	60.8 ± 10.3	616.8 ± 114.6	1097.7 ± 85.9	1,102.4 ± 118.9	1,366.4 ± 72.0	1,339.0 ± 72.2	
GU	NV			185.5 ± 23.8	1,684.3 ± 178.8	3,377.8 ± 120.2	3,443.4 ± 175.1	3,446.6 ± 143.2	3,882.7 ± 76.9	3,894.1 ± 113.2	3,917.8 ± 90.1
	KV				1.5 ± 0.2	32.2 ± 6.6	62.1 ± 16.1	250.6 ± 56.0	1,316.4 ± 150.4	1,613.5 ± 63.7	1,653.1 ± 154.1
JE	NV		204.3 ± 41.6	471.3 ± 41.3	2,685.3 ± 307.6	2,878.6 ± 162.3	2,720.0 ± 233.8	3,056.5 ± 155.6	2,912.4 ± 131.9	3,154.9 ± 171.6	3,267.9 ± 159.3
	KV				10.1 ± 3.5	67.8 ± 21.6	460.7 ± 53.3	1,208.4 ± 165.0	1,490.5 ± 82.3	1,484.8 ± 68.9	1,483.0 ± 47.4
MB	NV		136.7 ± 32.7	757.9 ± 96.2	2,639. 1 ± 271.6	5,004.5 ± 320.7	5,541.2 ± 143.7	5,623.1 ± 280.2	5,633.9 ± 175.9	5,946.5 ± 248.0	
	KV				6.4 ± 1.3	39.3 ± 12.9	379.6 ± 65.3	2,167.5 ± 181.6	2,434.5 ± 79.4	2,976.1 ± 140.6	
MO	NV	76.2 ± 12.5	246.3 ± 42.9	1,856.5 ± 143.3	2,485.3 ± 284.5	2,647.6 ± 143.4	2,784.1 ± 144.7	2,885.9 ± 97.5	3,190.3 ± 137.9	3,242.0 ± 71.2	
	KV			1.0 ± 0.1	16.3 ± 4.3	479.8 ± 50.6	762.8 ± 117.0	1,318.1 ± 60.9	1,601.2 ± 70.0	1,539.0 ± 77.1	
	KV			2.3 ± 0.5	41.2 ± 11.8	281.3 ± 90.6	1,219.7 ± 71.8	1,734.3 ± 168.7	1,852.9 ± 72.0	1,949.1 ± 89.2	

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Table 2 to be continued

Cultivar		June 3	June 12	June 23	July 4	July 15	July 25	August 6	August 18	August 28	September 9
NE	NV		117.0 ± 13.5	237.1 ± 25.8	1,783.0 ± 223.2	2,715.9 ± 108.9	3,059.8 ± 84.2	2,997.4 ± 85.3	3,130.1 ± 46.4	3,006.4 ± 66.3	2,936.7 ± 120.6
	KV				1.1 ± 0.1	9.6 ± 2.5	121.0 ± 38.3	1,057.7 ± 97.5	1,528.9 ± 51.3	1,471.3 ± 28.4	1,486.1 ± 63.88
NO	NV		208.8 ± 37.8	1,413.3 ± 110.4	3,143.7 ± 377.3	3,851.6 ± 150.4	3,823.5 ± 152.2	3,637.1 ± 132.1	3,827.0 ± 266.9	3,687.0 ± 120.3	4,175.6 ± 104.8
	KV			1.0 ± 0.2	8.8 ± 4.1	104.0 ± 13.4	304.7 ± 37.2	1,155.2 ± 71.2	1,429.7 ± 123.3	1,426.3 ± 71.7	1,767.7 ± 64.3
PA	NV		67.8 ± 7.5	329.7 ± 40.9	1,888.0 ± 174.7	2,150.9 ± 51.4	2,347.3 ± 75.6	2,288.4 ± 143.3	2,573.5 ± 89.5	2,474.3 ± 114.1	2,689.6 ± 75.8
	KV				5.3 ± 3.0	58.2 ± 13.1	307.5 ± 36.0	617.3 ± 113.0	1,056.7 ± 65.5	1,232.2 ± 45.6	1,448.2 ± 46.8
TGL	NV	162.7 ± 17.9	903.5 ± 105.8	2,770.3 ± 227.4	2,869.4 ± 121.9	3,035.8 ± 111.9	3,077.8 ± 140.7	3,059.0 ± 158.6	3,196.1 ± 109.7		
	KV			2.5 ± 0.5	44.7 ± 7.4	793.7 ± 144.7	1,078.1 ± 158.3	1,483.0 ± 66.1	1,602.2 ± 62.3		
TG	NV	85.8 ± 6.3	247.9 ± 37.0	2,113.8 ± 155.2	3,754.3 ± 194.9	3,478.6 ± 209.7	3,733.2 ± 177.9	4,105.5 ± 140.0	4,018.1 ± 121.9	3,917.6 ± 149.0	
	KV			2.3 ± 0.5	41.2 ± 11.8	281.3 ± 90.6	1,219.7 ± 71.8	1,734.3 ± 168.7	1,852.9 ± 72.0	1,949.1 ± 89.2	

NV – nut volume; KV – kernel volume; *n* – number of observed nuts

ing 20% in mid-June and about 90% of its final volume on July 4 (Table 2); the kernel started to grow on June 23. Data concerning the time of nut and kernel development in TGdL confirmed those previously observed by Roversi (1973) and Me et al. (1989). A second group of cultivars that includes cultivars native to southern Italy (Camponica, Mortarella, Nocchione, Tonda di Giffoni) and Daria, a cultivar selected in Italy from the crossing TGdL × Cosford (Botta et al. 1997), began nut growth in mid-June, reaching over 30% of its final volume on June 23 and over 70% at the beginning of July (class 2). A third group included cvs Du Chilly, Gunslebert, Jean's, Merveille de Bollwiller and all Spanish cultivars (Alcover, Casina, Closca Molla, Culplà, Negret, Pauetet). In this group, nuts began to develop in the second ten-day period of June reaching almost full size (over 80%) on July 15, while kernels started to grow at the beginning of July (class 3). The latest cultivar was Cosford, in which nut development started only at the beginning of July and ended in late July while the kernel started to grow in mid-July (class 4). The influence of the genetic origin of the cultivars on development date is evident (Table 1). In fact, all Italian cultivars were categorised in classes 1 and 2, and all the Spanish cultivars and most of those native to central and northern Europe in class 3. The latest developing cv. Cosford (class 4) has an English origin.

The sequence of shell hardening for each cultivar is shown (Table 3). At the beginning of growth, the shell was greenish and soft for all cultivars, with values of penetration force ranging from 3.0 to 6.0 N. The values of force increased only when nuts reached at least 80% of their final size, and grew rapidly and constantly until kernels reached their full size. Indeed, shell hardening and kernel development were strictly correlated ($y = 14.554x^{0.407}$; $R^2 = 0.921$; Fig. 2) and follows the same timing of kernel growth (Fig. 1) as observed by Guidone et al. (2007) in six cultivars in a shorter time window. Hazelnut cultivars followed a similar growth curve but showed different values of penetration force since the onset of nut development until the end of growth (Table 3).

Physical properties of nuts at harvest

The hardness of the shell and the thickness of the shell at harvest showed significant differences among cultivars (Table 4). At maturity, values of the

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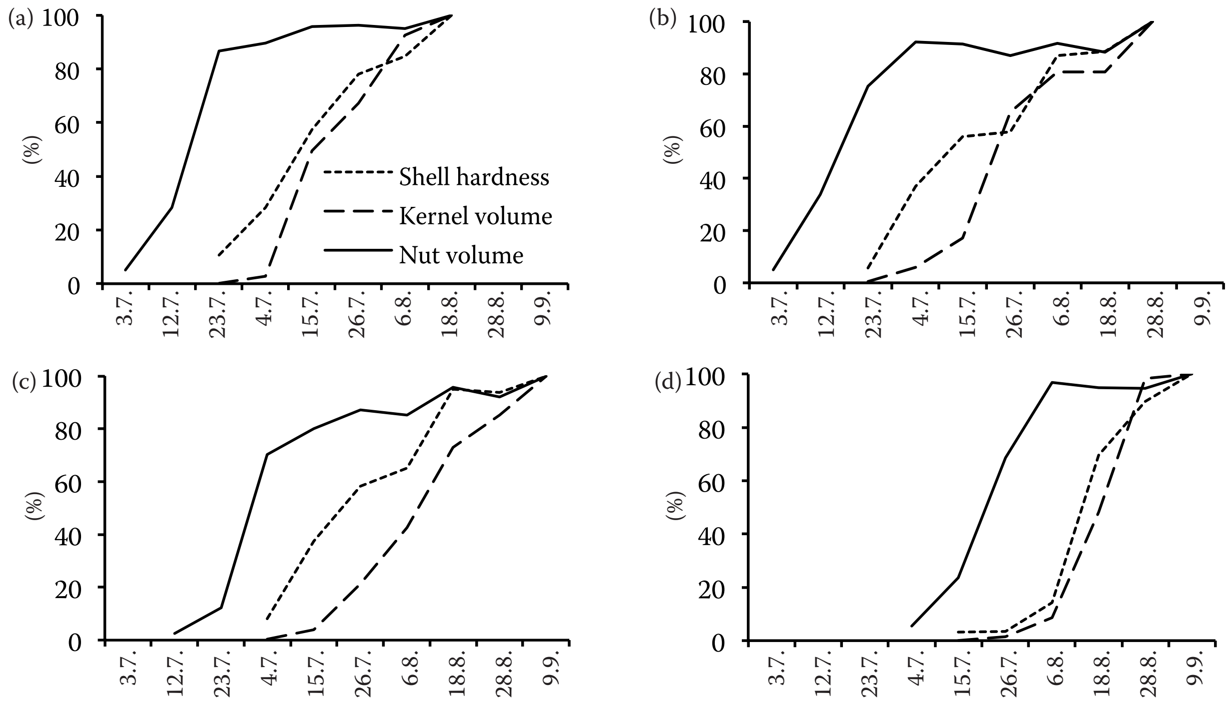

Fig. 1. Curves of growth of nut and kernel (expressed as percentage of the final volume) and of shell hardening (expressed as percentage of final force to penetrate the shell) of cvs (a) Tonda Gentile delle Langhe (TGdL), (b) Nocchione, (c) Pauetet, and (d) Cosford, representative of the 4 classes of nut growth

penetration force ranged from 185.7 N in cv. Nocchione to 46.7 N in cv. Closca molla. The Spanish cv. Closca molla is appropriately named, as in Catalan "closca molla" means soft shell.

The thickest shells were in cv. Nocchione (2.07 mm), as previously observed by Solar and Stampar (2011) and Milošević and Milošević (2012). The thinnest shells were in cvs Closca molla and Cosford (0.84 mm). TGdL had a medium thickness shell as confirmed by Solar and Stampar (2011) and Valentini et al. (2014). This confirms that the thickness of the shell is a stable trait (Valentini et al. 2014) and that each cultivar has a particular structure of the shell (Caramiello et al. 2000).

At harvest, the characteristics of the shell were not related to nut size, but the values of penetration force were highly and positively correlated with shell thickness ($y = 101.13x - 29.442$, $R^2 = 0.895$, $r = 0.945$, Table 5, Fig. 3). This may indicate that shell hardness increases proportionately with shell thickness during nut growth. The thickness of the shell was also negatively correlated to late nut development ($r = -0.524$, Table 5).

The cultivars differed also for final nut dimensions (Table 4). Cvs Camponica, Closca molla, Merveille de Bollwiller, Nocchione, Tonda di Giffoni and TGdL had nut calibre larger than 20 mm and roundish shape ($RI > 0.89$). The other cultivars had nuts with nut calibre ranging from 16.69 mm (cv. Casina) to 19.72 mm (cv. Culplà). The highest and the lowest values of kernel calibre were found in cv. Merveille de Bollwiller (17.09 mm), and in cv. Cosford (12.79 mm), respectively. Moreover, final nut volume was highly correlated with final kernel volume ($r = 0.924$, Table 5).

Weevil damage and presence of blanks

The hazelnut cultivars differed in susceptibility to *C. nucum* attacks in agreement with previous research (Piskornik 1992, 1994; Caramiello et al. 2000; Gantner 2005; Wojciechowicz-Zytko 2005; Guidone et al. 2007; Solar, Stampar 2011). The mean percentages of nuts damaged were significantly different, ranging from 0.6% for cv. Merveille de Bollwiller to 24.4% for cv. Cosford (Table 4). In cvs Camponica, Merveille de Bollwiller, Nocchione, Tonda di Giffoni and TGdL damage was very low (lower than 3.5%), while in the

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Table 3. Mean values (±SE) of force required to puncture the shells (N) of 18 cultivars in 2008 (n = 15)

Cultivar	June 12	June 23	July 4	July 15	July 25	August 6	August 18	August 28	September 9
AL		5.6 ± 0.2	4.8 ± 0.3	28.2 ± 4.7	39.2 ± 3.5	45.4 ± 2.7	61.9 ± 3.2	57.2 ± 3.4	64.7 ± 3.5
CA	4.4 ± 0.2	5.2 ± 0.1	22.5 ± 3.0	25.1 ± 4.9	37.6 ± 3.1	50.5 ± 7.9	70.7 ± 4.4	81.1 ± 5.7	
CS		5.4 ± 0.2	4.5 ± 0.1	12.4 ± 1.3	21.9 ± 3.4	31.3 ± 2.6	58.3 ± 4.4	67.0 ± 3.5	69.6 ± 3.0
CM			4.3 ± 0.1	6.9 ± 1.3	11.8 ± 3.2	13.3 ± 2.3	47.5 ± 2.1	47.5 ± 2.3	49.7 ± 1.2
CO				1.5 ± 0.1	1.7 ± 0.5	6.8 ± 1.6	33.4 ± 3.6	43.1 ± 4.0	48.0 ± 4.4
CU		5.4 ± 0.1	4.2 ± 0.1	21.1 ± 3.2	38.7 ± 3.8	57.6 ± 2.8	95.9 ± 3.6	95.7 ± 4.1	94.0 ± 3.8
DA		5.3 ± 0.2	9.6 ± 2.1	27.6 ± 4.2	36.4 ± 6.1	55.0 ± 2.6	56.2 ± 5.8	63.9 ± 7.9	
DC			4.9 ± 0.3	10.4 ± 4.0	46.9 ± 5.1	66.0 ± 5.3	103.8 ± 4.8	108.9 ± 6.1	114.0 ± 3.9
GH	3.1 ± 0.4	5.0 ± 0.2	44.8 ± 4.7	90.9 ± 4.6	91.6 ± 3.9	93.4 ± 6.6	112.7 ± 10.0	115.3 ± 7.4	
GU			5.4 ± 0.2	17.1 ± 3.3	21.3 ± 3.0	32.5 ± 3.8	51.6 ± 3.4	65.1 ± 4.8	64.8 ± 3.0
JE		5.2 ± 0.2	6.9 ± 0.8	30.3 ± 4.4	65.1 ± 5.0	58.7 ± 6.0	90.8 ± 4.4	93.5 ± 5.8	99.3 ± 4.6
MB		5.1 ± 0.2	5.2 ± 0.1	26.6 ± 4.5	51.1 ± 6.4	78.0 ± 10.1	111.9 ± 5.1	113.2 ± 7.5	
MO	5.4 ± 0.2	3.9 ± 0.1	16.2 ± 3.5	70.8 ± 5.1	74.5 ± 4.0	77.9 ± 3.8	94.5 ± 5.8	94.6 ± 7.0	
NE		6.1 ± 0.2	4.8 ± 0.2	16.0 ± 2.9	42.9 ± 4.5	65.8 ± 4.4	78.8 ± 3.3	79.0 ± 4.8	88.8 ± 3.4
NO		5.3 ± 0.2	10.4 ± 2.9	68.6 ± 5.0	103.8 ± 3.6	107.3 ± 7.4	161.4 ± 14.1	164.7 ± 8.2	185.7 ± 7.7
PA		3.6 ± 0.1	6.4 ± 1.1	29.9 ± 3.4	46.4 ± 2.6	51.8 ± 5.8	75.6 ± 3.1	74.6 ± 3.8	79.6 ± 3.9
TGL	3.5 ± 0.4	10.4 ± 2.7	28.0 ± 5.0	56.5 ± 4.8	76.8 ± 5.8	83.4 ± 6.9	98.4 ± 4.3		
TG	5.2 ± 0.2	4.9 ± 0.2	24.2 ± 2.6	69.1 ± 9.2	78.3 ± 4.4	79.7 ± 5.0	94.7 ± 6.7	97.1 ± 6.5	

other cultivars it ranged from 6.2% to 13.9%, and was highest in cv. Cosford (24.4%). Cvs Daria and TGdL showed values of damage similar to those previously observed in the same area (Guidone et al. 2007), as well as cv. Merveille de Bollwiller had low damage and cv. Cosford had high damage, as reported by Piskornik (1994).

The orchard was located in an area intensively cultivated with hazelnut, surrounded by woods where wild hazelnuts are abundant and with high weevil pressure. In these conditions, only a few cultivars can be grown without insecticide treatments (Camponica, Merveille de Bollwiller, Nocchione, Tonda di Giffoni, and TGdL), while for the other cultivars economic yield losses due to nut weevil are not acceptable and insecticide treatments are required.

The shell thickness and the force to penetrate shell at harvest were negatively correlated to the percentages of nut weevil damage (r = –0.544 and –0.564). On the contrary, late nut development was associated with more weevil damage (r = 0.638) (Table 5).

Although, the influence of the thickness of the shell on the damage rate by *C. nucum* was hypothesized (Caramiello et al. 2000) but not confirmed in a more recent investigation (Guidone et al. 2007), in this research, thickness and hardness of the shell and timing of nut development were correlated with the damage by nut weevil, indicating that both factors can affect susceptibility to this pest (Table 5).

The mean percentages of blanks were significantly different among cultivars; the lowest values

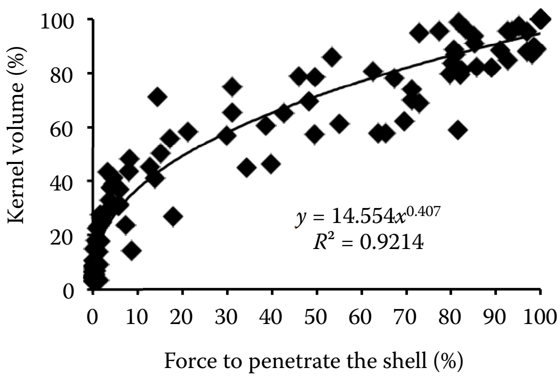

Fig. 2. Correlation between kernel volume (expressed as percentage of final volume) and force to penetrate the shell (expressed as percentage of final force) during nut growth

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Table 4. Nut and kernel traits, and percentages of nuts damaged by *Curculio nucum* and blanks at harvest in 18 cultivars in 2008 (mean value ± SE)

Cultivar	Shell thickness (mm)	Force to penetrate shell (N)	Nut calibre (width, mm)	Kernel calibre (width, mm)	Damaged by weevil (%)	Blanks (%)
AL	0.89 ± 0.03^{gh}	62.86 ± 3.45^{hi}	18.10 ± 0.26^{fgh}	14.76 ± 0.22^{cdefg}	11.30 ± 0.46^{bcd}	4.97 ± 0.51^{e}
CA	1.29 ± 0.02^{cd}	95.28 ± 5.66^{bcd}	20.55± 0.41^{bcd}	16.12 ± 0.52^{abc}	2.62 ± 0.36^{fg}	12.80 ± 0.78^{cde}
CS	0.99 ± 0.02^{fgh}	64.03 ± 2.87^{ghi}	16.69 ± 0.26^{h}	13.01 ± 0.22^{il}	13.93 ± 0.46^{b}	14.25 ± 2.44^{cde}
CM	0.84 ± 0.01^{h}	46.75 ± 1.31^{i}	20.66 ± 0.49^{bcd}	15.63 ± 0.37^{bcde}	6.21 ± 1.05^{ef}	22.64 ± 2.00^{abc}
CO	0.84 ± 0.01^{h}	50.05 ±2.55^{i}	17.23 ± 0.23^{gh}	12.79 ± 0.23^{l}	24.44 ± 0.73^{a}	14.29 ± 3.00^{cde}
CU	1.21 ± 0.02^{de}	88.51 ± 4.90^{bcdef}	19.72 ± 0.33^{de}	15.89 ± 0.29^{abcd}	7.92 ± 0.23^{ef}	3.82 ± 0.98^{e}
DA	0.87 ± 0.01^{h}	71.16 ± 3.67^{efghi}	19.35 ± 0.32^{def}	14.98 ± 0.32^{cdef}	11.18 ± 0.64^{bcd}	10.59 ± 0.41^{de}
DC	1.28 ± 0.03^{cd}	129.94 ± 5.35^{b}	18.57 ± 0.20^{efg}	13.30 ± 0.39^{hil}	6.79 ± 1.10^{d}	16.47 ± 5.26^{bcd}
GH	1.57 ± 0.08^{b}	109.87 ± 7.15^{bc}	19.32 ± 0.42^{def}	14.93 ± 0.24^{cdef}	8.66 ± 0.77^{cde}	25.37 ± 1.24^{ab}
GU	1.07 ± 0.05^{ef}	67.50 ± 4.65^{fghi}	17.15 ± 0.21^{gh}	13.73 ± 0.48^{fghil}	13.47 ± 1.94^{b}	11.11 ± 2.49^{de}
JE	1.44 ± 0.01^{bc}	112.06 ± 6.95^{bc}	17.72 ± 0.42^{gh}	13.55 ± 0.32^{ghil}	6.20 ± 1.17^{ef}	8.86 ± 1.70^{de}
MB	1.52 ± 0.02^{b}	125.92 ± 11.75^{b}	22.27 ± 0.43^{a}	17.09 ± 0.35^{a}	0.59 ± 0.15^{g}	10.93 ± 0.93^{de}
MO	1.32 ± 0.02^{cd}	99.83 ± 6.09^{bcd}	17.10 ± 0.61^{gh}	14.40 ± 0.28^{efghi}	12.77 ± 1.74^{bc}	16.08 ± 3.01^{bcd}
NE	1.10 ± 0.04^{ef}	93.71 ± 4.08^{cde}	17.65 ± 0.32^{gh}	13.23 ± 0.32^{il}	8.74 ± 0.16^{cde}	12.60 ± 1.88^{cde}
NO	2.07 ± 0.10^{a}	185.72 ± 13.00^{a}	21.82 ± 0.33^{ab}	15.87 ± 0.36^{abcd}	3.14 ± 0.03^{fg}	4.31 ± 1.22^{e}
PA	1.04 ± 0.04^{fg}	80.23 ± 2.58^{cdefg}	17.49 ± 0.24^{gh}	13.91 ± 0.19^{fghil}	12.09 ± 2.46^{bcd}	15.77 ± 2.87^{bcd}
TGL	1.21 ± 0.04^{de}	92.62 ± 5.76^{bcde}	20.17 ± 0.32^{cd}	14.65 ± 0.28^{defgh}	0.99 ± 0.49^{g}	30.91 ± 4.51^{a}
TG	1.22 ± 0.03^{de}	94.01 ± 7.32^{bcd}	21.36 ± 0.47^{abc}	16.96 ± 0.43^{ab}	1.23 ± 0.38^{g}	17.81 ± 1.46^{bcd}

means within a column followed by the same letter are not significantly different ($P \leq 0.01$; Duncan's Multiple Range test)

were found in cvs Alcover, Culplà and Nocchione (< 5%) while the highest ones were found in cvs Closca Molla, Ghirara and TGdL (>20%). Studies conducted in other growing areas showed differences in cultivar susceptibility to blanks indicating some genetic control of this defect (Mehlenbacher et al. 1993), which may also be related to particular environmental conditions (Solar, Stampar 2011). The involvement of nut weevil in the production of blanks and aborted nuts was also hypothesized by several authors in relation to the adult feeding activity on female flowers and developing nuts (Tabamaĭshvili 1988; Paparatti 1990; Pucci 1992) or as consequence of the transmission of pathogens that follows insect feeding (Akça, Tuncer 2005). However, in our research, percentages of blanks at harvest were not correlated with any other recorded parameter, including nut weevil damage at harvest.

Knowledge of nut development and shell hardening times is valuable information that can be used to model nut development and provide important tools for planning orchard management activities, including irrigation, fertilization and pest control. Time of nut growth and shell hardening should be considered in breeding for increased tolerance or avoidance of pests and water stress.

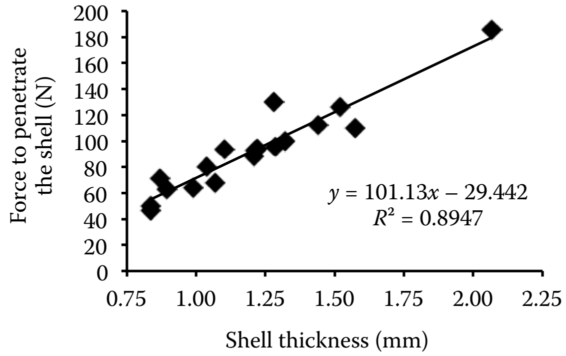

Fig. 3. Correlation between nut shell thickness and force required to penetrate the shell at harvest

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Table 5. Pearson correlation coefficients (*r*) between fruit characteristics at harvest (nut and kernel volume; shell thickness and force to penetrate the shell), timing of nut growth (expressed as days from June 1), percentage of nuts damaged by *Curculio nucum* and blanks at harvest

		1	2	3	4	5	6	7
1	nut volume	1						
2	kernel volume	0.924**	1					
3	shell thickness	0.299	0.052	1				
4	force to penetrate the shell	0.361	0.106	0.945**	1			
5	timing of nut growth	–0.149	–0.128	–0.524*	–0.450	1		
6	weevil damage (%)	–0.415	–0.329	–0.544*	–0.564*	0.638**	1	
7	blanks (%)	–0.168	–0.137	–0.136	–0.195	–0.313	–0.144	1

*, **significant at 0.05 and 0.01 *P* levels, respectively

References

Akça I., Tuncer C. (2005): Biological control and morphological studies on nut weevil (*Curculio nucum* L. Col., Curculionidae). Acta Horticulturae (ISHS), 686: 413–419.

Beyhan N., Marangoz D. (2007): An investigation of the relationship between reproductive growth and yield loss in hazelnut. Scientia Horticulturae, 113: 208–215.

Botta R., Gianotti C., Me G. (1997): Kernel quality in hazelnut cultivars and selections analyzed for sugars, lipids and fatty acid composition. Acta Horticulturae (ISHS), 445: 319–326.

Caramiello R., Me G., Radicati L. (2000): Structure and characteristics of the hazelnut shell in different cultivars and their agronomic and industrial influence. Acta Horticulturae (ISHS), 517: 195–208.

FAOSTAT (2014): Agriculture data. Available at http://faostat3.fao.org/home/index.html (accessed November 24, 2014)

Fideghelli C., De Salvador F.R. (2009): World hazelnut situation and perspectives. Acta Horticulturae (ISHS), 845: 39–51.

Fregoni M., Zioni E. (1962): Caratteristiche morfologiche, merceologiche e chimico-industriali dei frutti di alcune cultivar di nocciolo della Liguria. In: Atti Convegno internazionale sul nocciolo, Alba, Italy: 125–156.

Gantner M. (2005): Susceptibility of large-fruited hazel cultivars grown in Poland to major pests and their crop productivity. Acta Horticulturae (ISHS), 686: 377–384.

Germain E. (1983): Physiology of reproduction in filbert (*Corylus avellana* L.): Flowering and fruiting. In: Atti del convegno internazionale sul nocciolo, Avellino, Italy: 47–60.

Germain E., Sarraquigne J.P. (2004): Le noisetier. Paris, Editions CTIFL.

Guidone L., Valentini N., Rolle L., Me G., Tavella L. (2007): Early nut development as a resistance factor to the attacks of *Curculio nucum* (Coleoptera: Curculionidae). Annals of Applied Biology, 150: 323–329.

Me G., Emanuel E., Botta R., Vallania R. (1989): Embryo development in 'Tonda Gentile delle Langhe' hazelnut. Hortscience, 24: 122–125.

Mehlenbacher S.A., Smith D.C., Brenner L.K. (1993): Variance components and heritability of nut and kernel defects in hazelnut. Plant Breeding, 110: 144–152.

Milošević T., Milošević N. (2012): Cluster drop phenomenon in hazelnut (*Corylus avellana*). Impact on productivity, nut traits and leaf nutrients content. Scientia Horticulturae, 148: 131–137.

Paparatti B. (1990): *Balaninus nucum* L. (Coleoptera: Curculionidae). Catture di adulti ed analisi dell'infestazione condotte nell'areale del Lago di Vico (Viterbo) nel biennio 1989–90. Frustula Entomologica, 13: 93–112.

Piskornik Z. (1992): Observation on the resistance of hazelnut (*Corylus avellana* L.) to the hazelnut weevil (*Curculio nucum* L., Coleoptera, Curculionidae). Acta Horticulturae (ISHS), 317: 163–170.

Piskornik Z. (1994): Relationship between the resistance of hazelnut cultivars to the hazelnut weevil and the content of sugars, amino acids, and phenols in the endocarp tissue of growing nuts. Acta Horticulturae (ISHS), 351: 617–624.

Pucci C. (1992): Studies on population dynamics of *Balaninus nucum* L. (Col., Curculionidae) noxious to the hazel (*Corylus avellana* L.) in Northern Latium (Central Italy). Journal of Applied Entomology, 114: 5–16.

Roversi A. (1973): Rilievi sull'accrescimento e sull'accumulo in grasso dei frutti di *Corylus avellana* L. (cv Tonda Gentile delle Langhe). Annali della Facoltà di Agraria. Milano, Università Cattolica del Sacro Cuore, , 13: 318–338.

Silva A.P., Santos A., Rosa E. (2001): Nut growth and development in Butler hazelnut. Acta Horticulturae (ISHS), 556: 377–384.

Solar A., Stampar F. (2011): Characterization of selected hazelnut cultivars: phenology, growing and yielding capacity, market quality and nutraceutical value. Journal of the Science of Food and Agriculture, 91: 1205–1212.

doi: 10.17221/327/2014-HORTSCI

Tabamaishvili L.E. (1988): The nut weevil and its control. Subtropicheskie Kul'tury, 5: 128–131.

Thompson M.M. (1967): Role of pollination in nut development. Proceedings Nut Growers Society Oregon and Washington, 53: 31–36.

Thompson M.M. (1979): Growth and development of the pistillate flower and nut in Barcelona filbert. Journal of American Society Horticulture Science, 104: 427–432.

Tombesi A., Cartechini A., Preziosi P. (1983): Formation and development of the vegetative and reproductive organs of the filbert tree. In: Atti del convegno internazionale sul nocciolo, Avellino, Italy: 533–538.

Valentini N., Rolle L., Stevigny C., Zeppa G. (2006): Mechanical behaviour of hazelnuts used for table consumption under compression loading. Journal of the Science of Food and Agriculture, 86: 1257–1262.

Valentini N., Calizzano F., Boccacci P., Botta R. (2014): Investigation on clonal variants within the hazelnut (*Corylus avellana* L.) cultivar 'Tonda Gentile delle Langhe'. Scientia Horticulturae, 165: 303–310.

Westwood M.N. (1993): Temperate-zone Pomology. Physiology and Culture. Portland, Timber Press.

Wojciechowicz-Zytko E. (2005): Infestation of hazel nuts by hazelnut weevil (*Curculio nucum* L., Coleoptera, Curculionidae) in Poland. Journal of Plant Protection Research, 45: 59–61.

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