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Original article

Mechanical pruning of European hazelnut: effects on yield and quality and potential to exploit its by-product

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Summary

Introduction – **Annual pruning of mature hazelnut orchards is commonly carried out by hand during the dormant phase of the plants and primarily it is limited to a few cuts aimed to removing dead, damaged, and bad oriented branches. Furthermore, due to the recent implementation of large hazelnut farms in various growing areas, new approaches to the mechanized pruning are highly required.** *Objectives* – **The aim of the study was to evaluate if two different mechanical pruning treatments affected yield and nut and kernel quality in European hazelnut.** *Material and methods* – **In 2014 a trial was established in central Italy on hazelnut cultivar 'Tonda Romana' through the application of two different pruning treatments carried out using a mechanical hedger applied to the tractor. The first treatment was done running lateral and top cuts of some plant rows (treatment A: 2 hedging and 1 topping), whereas the second one was carried out applying lateral cuts only (treatment B: 2 hedging). Mechanical treatments were compared with un-pruned plant rows subjected to the remove of dead branches when necessary (treatment C). Measurements were focused in determining the removed wood and in evaluating production, nut and kernel traits, and nut defects depending on the pruning treatments, over three years.** *Results and conclusion* – **The intensity of mechanical pruning has only slightly influenced the cumulative yield, whereas it has significantly increased the nut traits. Furthermore, treatment differences have arisen for the amount of wood mechanically cut, suggesting the use of this biomass leftover for energy purposes.**

Keywords
Corylus avellana L., mechanical hedger, hedging, topping, biennial bearing, cumulative yield

Significance of this study

What is already known on this subject?
- The recent expansion of hazelnut cultivation, which at this time is often affecting large farms, requires a review of hazelnut orchard management including annual pruning operations.

What are the new findings?
- The study carried out on mature hazelnut orchards has proven the medium-term sustainability of mechanical pruning applications on plants trained as shrubs.

What is the expected impact on horticulture?
- Mechanical pruning to be applied in the "new generation hazelnut orchards" represents the most promising innovation in the orchard management.

Introduction

European hazelnut (*Corylus avellana* L.) is a perennial crop cultivated on about 650,000 ha of the world's arable land and its in-shell nuts production is concentrated in few countries, namely Turkey (550,000 tons), Italy (110,000 tons), United States (34,000 tons), Georgia (32,000 tons), Azerbaijan (31,000 tons), and Spain (15,000 tons) (Boccacci et al., 2013; FAOSTAT, 2018). Recently, its cultivation has been established in new places including Chile, South Africa and Australia. In these new introducing areas it is often planted on large farms giving rise to a new generation of specialized production hazelnut districts (Fideghelli and De Salvador, 2009).

This temperate nut crop is a suckering plant tending to develop into multi-stemmed shrub, and its vegetative habit is often exploited for shaping the plants in commercial orchards, as in traditional Turkish and Italian areas of cultivation. Its shrub shape is highly appreciated by the grower that is able to gradually renew the plants eliminating the old stems to be replaced by selecting new lignified suckers. Although field evidence does not show significant yield differences among different growing systems (Tous et al., 1994), elsewhere, such as in Oregon (USA) and France, hazelnut plants are shaped at open V-shape and single trunk since this shaping facilitates cultural practices, mechanical harvesting and promotes more sunlight penetration into the orchard (Germain and Sarraquigne, 1997). In Italy, mature hazelnut orchards are trained to multi-stemmed shrubs at densities of 400–500 plants per hectare (Bignami et al., 2005a), and the new orchards are still largely hand-planted with three-four self-rooted suckers per hole. Moreover, in some areas there has recently been recorded an increase of new plantations with higher density (for instance 4.5 m × 3.0 m), planting single-trunk plants and using transplanting machines (Cristofori et al., 2017). These new high-density orchards might be mechanically pruned when mature.

In the past the orchard dynamic spacing has been also explored for hazelnut to attenuate its long juvenility period after planting as a consequence of an early competition between developing plants, and to enhance yield thanks to the doubled number of plants in the orchard during the first ten-twelve years of planting (Tous et al., 1994; Bignami et al., 2005a). Nevertheless, this planting system has not been applied at large because it is more expensive and for the risk of over-competition among contiguous plants. Only recently in Oregon (USA) a new dynamic spacing approach is noticed in managing the hazelnut orchards, combining cultivars with different vigor in alternate rows and cutting the most vigorous when the plant canopies of the contiguous rows begin to touch each other.

Pruning of mature plants is usually done by hand during wintertime and mainly consists in removing lignified suckers, dead wood and diseased or bad oriented branches (Cristofori et al., 2009). An uneven pruning, such as often occurs in the various producing areas, is the reason of the increase in canopy density and over the years the overlap of the branches stimulate the reduction of shoots vigor and reduce the light penetration inside the plant. The resulting physiological plant disorders stimulate the low yield, the kernel quality declines (Roversi and Mozzone, 2005) and the biennial bearing (Azarenko et al., 2005). Accordingly, annual pruning is highly recommended especially since some authors observed that hazelnut productivity is positively related to the develop of mixed one-year-old shoots, and a shoot length of 15–20 cm has been identified as ideal for a high incidence of fertile buds (Me et al., 1994).

Nevertheless, pruning is often neglected for its high labor requirement and time consuming since literature reports at least 15–18 labor hours per hectare for its execution in mature orchards (Franco and Pancino, 2009). The intensity of pruning operations in hazelnut also affects the amount of harvestable woody biomass, which needs to be removed from the orchard (Cristofori et al., 2009). Usually, the highest quantities of pruning wood are obtained from medium-high vigor plants over 20 years old. For these reasons, a new trend in mechanical pruning is introduced mainly for new large commercial orchards (Ellena et al., 2014; Ughini et al., 2014).

Even though there is still no long-period evidence that managing the orchard through mechanical pruning increases yield and nut quality (Silvestri et al., 2021), pruning operations are done faster and the shape of the plant results strongly modified among the rows, orientating the hazelnut orchard management towards higher levels of mechanization.

Furthermore, recently it has been demonstrated that hazelnut is a great source of biomass for energy uses (Di Giacinto et al., 2014) and its wood and shells are suitable to produce woodchips or pellets used in modern combustion devices. These byproducts can also be used as feedstock in downdraft air gasifiers in order to obtain syngas and biochar (Couto et al., 2013; Colantoni et al., 2016; Zambon et al., 2016). The harvesting and out-of-orchard transportation and the management of hazelnut byproducts for energy uses could strongly reduce the environmental impact on air quality in comparison to its current on-field burning that often occurs in commercial orchards (Zambon et al., 2019).

Hence, the aim of the trial was to investigate the effects on nut quantity and quality and to estimate the recyclable biomass in the medium-vigor cultivar 'Tonda Romana' subjected at two different mechanical pruning treatments, in order to define an appropriate technique for its application in mature orchards of this cultivar that is mainly grown in central Italy.

Materials and methods

Plant material

The mature hazelnut orchard under investigation was established in 1992 in a private farm located in central Italy (Viterbo province; lat. 42°16'N, long. 12°18'E, alt. 270 m). The seven-hectares commercial orchard was flat and grown with the medium vigor and semi-erect habit 'Tonda Romana' cultivar.

Every ten rows the main cultivar was alternated with one row of the compatible cultivar 'Nocchione' used as pollinizer in a ratio of 1:10, since the European hazelnut is a self-incompatible species.

The field was characterized by a medium loam soil, pH 6.6, with 2.0% organic matter. The plants were trained at multi-stemmed shrub and spaced 5.0 m × 4.0 m (orchard density 500 plants ha^{-1}).

The soil was managed with a natural green cover crop according to the rules of Fruits Integrated Production Systems (Regione Lazio, 2013) and annually was receiving the applications of the following quantities of main fertilizers: 90 kg ha^{-1} nitrogen, 60 kg ha^{-1} phosphorus and 90 kg ha^{-1} potassium. Irrigation supply through a sub-irrigation system was ensured during the summer seasons. The pests and diseases control was applied following the guidelines of the Integrated Pest Management (IPM) for hazelnut.

Trial setup

Mechanical pruning treatments were carried out in February 2014 before the beginning of bud break on mature plants with branches of two adjacent rows crossing each other. The experiment was conducted over three years (2014–2016). The trial was implemented using a mechanical hedger of the vineyard topper typology adapted to orchard and activated by a cab tractor (Figure 1). Two different mechanical pruning treatments were setup and compared with an un-pruned control.

Three contiguous rows of 90 plants each were pruned applying two side hedging and one topping (treatment A), meanwhile the following three contiguous ones were pruned applying two side hedging only (treatment B). Furthermore,

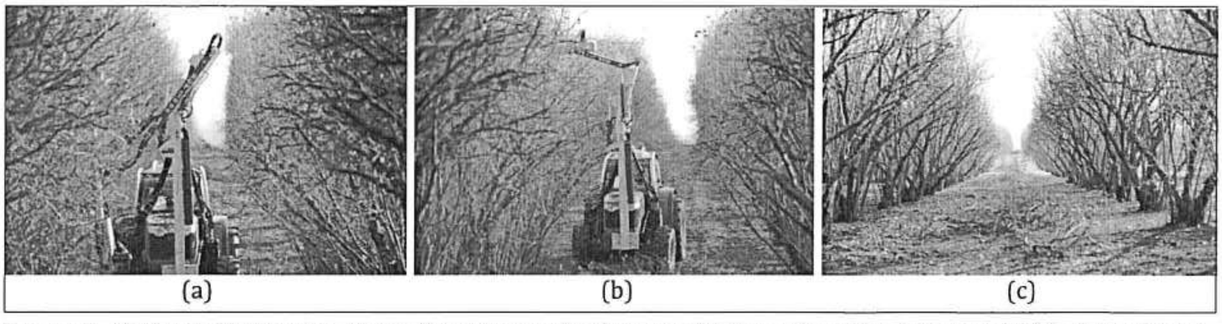
(a) (b) (c)

FIGURE 1. Mechanical hedger in action in the mature orchard grown with the main cv 'Tonda Romana': (a) hedging; (b) topping; (c) contiguous rows just after pruning. Dormant phase 2014.

three other contiguous rows were selected as un-pruned control and at the beginning of the trial only the dead branches were removed when necessary.

Mechanical pruning was applied only at the first year of the trial, whereas in the following two years all plants were carefully checked for cutting and removing any new dead branches. During mechanical pruning the intervention time were recorded using a chronometer for each continuous cutting operation on 90 plants (path of 360 m). In treatment A three cutting steps per row were recorded including two hedging, one per row side, and one topping, whereas in treatment B only two hedging steps per row were measured. The data were used to calculate the working speed during the two different mechanical cutting treatments and to estimate the intervention time per hectare, excluding the time lost for maneuvers, which in commercial orchards are variable according to their size, plantation density and slope.

After mechanical pruning the removed wood was measured using a digital hanging scale for field uses (Etekcity, model XY-2003). Eight replicates, each of five contiguous plants, were randomly selected only in the middle row of the two experimental plots mechanically pruned, for avoiding border effects. Moreover, the wood harvesting and weighing was made taking care to avoid to mix the pruned material from contiguous plants that were not included in the measurements. These collected data at the first year of the trial have allowed to estimate the expected amount of pruned wood per hectare in the two treatments. The dead branches manually removed throughout the experiment were excluded by this estimation.

Yield, nut and kernel traits and defected nut incidences

Total production, nut and kernel traits and defects, potentially affected by the two mechanical pruning treatments, were recorded over the period 2014–16.

Similarly for the removed wood, the production was measured considering four replicates, each of ten contiguous plants, randomly selected only in the middle row of the experimental plots, including the un-pruned control. At harvest time the nuts of each replication were grouped and mechanically harvested using a farmer's own self-propelled vacuum cleaner machine.

The collected nuts were further cleaned by hand, dried in the lab using a thermostatic heater according to the hazelnut market guidelines that requires a kernel moisture content not higher than 6% both for consumption and in-shell storage (OECD, 2011), and then weighted using a lab balance. Each lot of harvested nuts were properly stored at room temperature in the lab until subsequent analyses.

Two harvesting operations were applied to the trial over the three years, according to the cultivar aptitude that shows a ripening time three weeks long during which the nuts drop on the ground. Each year the first harvesting was carried out at the beginning of September and the second harvesting two weeks later.

The nut and kernel traits were characterized during the three years of investigation using representative nut samples selected from each treatment and year. A sample of 200 nuts per treatment was characterized yearly, according to the protocol proposed by Cristofori et al. (2008). The kernel/nut ratio (% kernel) for each nut sample was also calculated.

During the nut and kernel characterization the incidence of the main defects was recorded according to the protocol issued in the hazelnut breeding program in progress at the Oregon State University (USA) (Mehlenbacher et al., 1993).

Statistical analysis

Statistical analyses were carried out using InfoStat Professional v. 1.1 program. All parameters were subjected to analysis of variance (ANOVA). Differences were accepted as statistically significant when $P<0.01$. Tukey test was applied on dataset previously analyzed with ANOVA to identify significance among the samples. In order to compare the responses of the different pruning treatments and their interaction with the year of investigation, data were also analyzed by two-way ANOVA.

Results

Pruned wood and estimated working speed

Figure 2 describes the mean quantity of pruned wood per plant, obtained at the beginning of the trial applying the two mechanical pruning treatments. The mean weight of pruned wood per plant was more than 35% higher in treatment A, where two hedging, one per row side, and one topping were applied (5.42 kg tree^{-1}), in comparison to the treatment B managed with two mechanical hedging only (3.47 kg tree^{-1}).

The estimated pruned wood per hectare, considering a plantation density of 500 plants ha^{-1}, was 2.71 tons in treatment A and 1.74 tons in treatment B, respectively. These values were in accordance with the available literature on pruned wood estimations carried out for some Italian hazelnut districts (Di Giacinto et al., 2014).

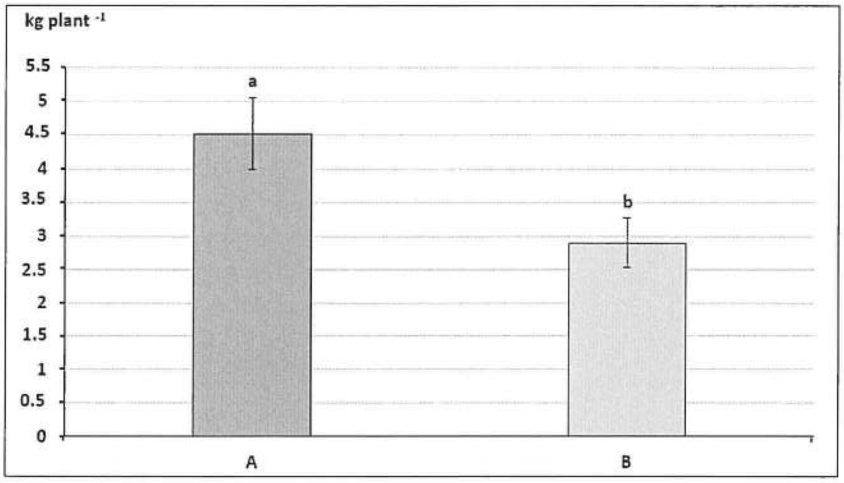

FIGURE 2. Quantity of wood removed through mechanical pruning applications at first year of the trial (treatment A: 2 hedging + 1 topping; treatment B: 2 hedging). Data are represented as mean ± standard deviation and different lowercase letters on the column indicate significant differences among pruning treatments (Tukey's test, $p<0.05$).

The working speed supported by the tractor that activated the mechanical hedger in the two different treatments was measured considering a standard total row length of 360 m (90 plants × 4 m distance among two contiguous plant) for each side pruning intervention or topping.

In treatment A (2 hedging + 1 topping) the tractor made a three-step cuts in each row, for a total distance travel of 1,080 m, while in treatment B (two hedging) were applied two-step cuts, for a total distance travel of 720 m for each treated row.

On average, the whole pruning of one row in treatment A required about 28 min of work, of which 9 min for topping, while for treatment B time requirement was about 20 min. It means that the estimated working speed was 2.2 km h^{-1} for hedging and 2.4 km h^{-1} for topping, respectively.

The estimated working speed did not consider the downtime for manoeuvres which should be taken into account for large and flat farm only, since working conditions could significantly change in irregular, small size and sloping orchards.

Production

The production of in-shell nuts recorded during the trial (Figure 3) was significantly affected by the pruning treatments and by the year of evaluation. On average, the first year of the trial showed the lower yield and the treatment A was highly penalized by the more severe mechanical pruning (hedging + topping). This treatment showed a total production of 1.88 ton ha^{-1}, versus an average yield of 2.50 ton ha^{-1} recorded for the un-pruned control, which was the higher production in the first year. Even in 2015 the un-pruned control showed the higher production (2.98 ton ha^{-1}) in comparison to those of plants mechanically treated (treatment A, 2.36 ton ha^{-1}; treatment B, 2.63 ton ha^{-1}), whereas in the third year of investigation the un-pruned control showed the lower production with values of 2.50 ton ha^{-1}, versus a mean production of 3.28 ton ha^{-1} recorded in treatment A, which was also the highest yearly production during the whole investigation. In 2016, also treatment B, where only hedging were applied, showed satisfying measured and estimated production (2.98 ton ha^{-1}).

The cumulative three-year production was of 7.51, 7.81 and 8.23 ton ha^{-1} in treatment A, treatment B and un-pruned control, respectively. On average the mechanical treatments showed only a slight yield reduction over the three-year investigation, in comparison to the un-pruned control, that on average produced only 240 kg ha^{-1} in-shell nuts per year more than treatment A, and a plus of 140 kg ha^{-1} per year in comparison to treatment B.

Furthermore, interesting results have emerged in terms of production stability of the treated plants. The un-pruned control confirmed through the period of investigation the tendency to the biennial bearing of the species (Azarenko et al., 2005), alternating heavy crop with low crop years and it was highly apparent in 2016. Conversely, the pruning treatments showed a constant increase of the yield over the years (Figure 3).

Nut and kernel traits and incidence of main defects

Nut and kernel traits were affected by pruning treatments, year, and their interaction, except for percent kernel (kernel/nut ratio) that has been affected by the pruning treatment only, as shown in Table 1. On average, these traits that affect the market uses of hazelnuts such as nut and kernel weight and kernel caliber, were similar for all treatments in the first year of investigation, contrariwise to those observed in 2015 and 2016, when the pruning treatments showed more filled nuts. Marked was also the increase of percent kernel determined excluding defected nuts, highlighting the relevance of this trait that directly influences the price of the in-shell nuts and thus the income of the grower.

In detail, the average values for the three-year investigation showed significant differences for percent kernel in the compared treatments, with values respectively of 1.5 and 1 point higher in treatment A (47.13%) and B (46.76%) when compared with those observed for the un-pruned control (45.76%). Another interesting trait was represented by the shell weight, since this by-product may be used for agronomic or energy purposes.

The average value of the shell weight was about 1.50 g representing about 53.5% of the whole in-shell nut. It means that over the three-year investigation the experimental plots achieved about 4.0, 4.2 and 4.4 ton ha^{-1} of shells in treatment A, B and C, respectively.

The shell incidence in the nut (percent shell) was influenced by the pruning system showing the higher values in the un-pruned control, and the mean values of this trait was in accordance with the literature for the cultivar 'Tonda Romana' (Cristofori et al., 2015).

Table 2 reports the incidence of defected nuts recorded during the nut and kernel characterization. The defects investigated were those mainly influenced by the pruning treatments, excluding defects under high genotype influence, such as double kernel (Mehlenbacher et al., 1993).

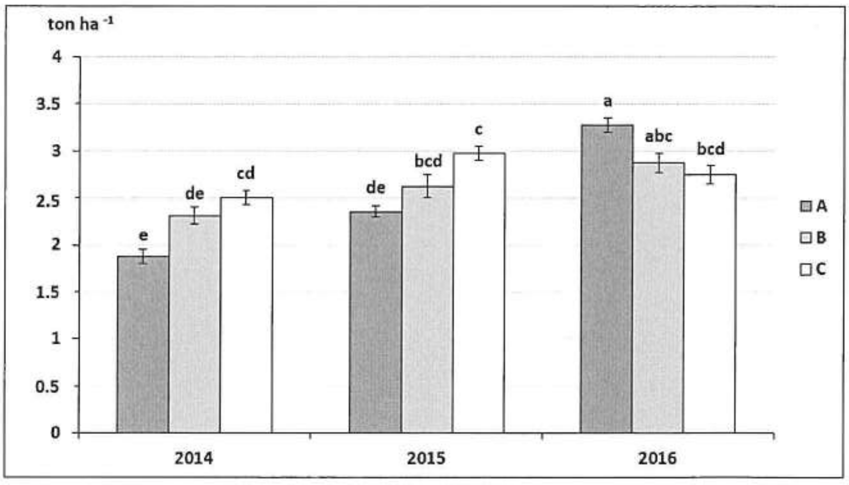

FIGURE 3. Total yield of cultivar 'Tonda Romana' subjected to different mechanical pruning interventions (treatment A: 2 hedging + 1 topping; treatment B: 2 hedging) and compared with untreated control (C). Average values include hazelnuts with defects. Data are represented as mean ± standard deviation. Different lowercase letters on the columns indicate significant differences among pruning treatments (Tukey's test, $p < 0.05$).

The pruning treatments highly affected the incidence of good nuts, that was stable over the three years for the un-pruned control (about 95%), meanwhile the good nuts increased in the second and third years of investigation in the treatments with incidences of almost 100% (treatment A, year 2015). The defects positively affected by mechanical pruning were the bug damage, the poor fill and the blank (empty nuts), on average showing a decrease of their incidence over the years. Contrariwise, the higher incidence of blank was observed for the un-pruned control in 2016, with values of 2%.

TABLE 1. Nut and kernel traits of cultivar 'Tonda Romana' subjected to different pruning applications (treatment A: 2 hedging + 1 topping; treatment B: 2 hedging; C: un-pruned control). Data are represented as mean ± standard deviation. Different lowercase letters on the columns indicate significant differences among pruning treatments (Tukey's test, p < 0.05).

Treatment	Year	Nut weight (g)	Kernel weight (g)	Shell weight (g)	Caliber (mm)	Kernel (%)
A	2014	2.87ab ± 0.42	1.34ab ± 0.20	1.52ab ± 0.25	16.02a ± 1.16	46.94 ± 2.78
B		2.84ab ± 0.55	1.31ab ± 0.27	1.52ab ± 0.35	15.75a ± 1.81	47.05 ± 3.65
C		2.88ab ± 0.37	1.34ab ± 0.22	1.55ab ± 0.21	15.98a ± 1.26	46.90 ± 2.75
A	2015	2.86ab ± 0.43	1.34ab ± 0.20	1.52ab ± 0.25	16.00a ± 1.16	47.02 ± 2.67
B		2.84ab ± 0.55	1.32ab ± 0.27	1.52ab ± 0.35	15.75a ± 1.81	47.30 ± 3.73
C		2.29d ± 0.41	1.01 d ± 0.26	1.27c ± 0.21	13.27c ± 1.74	44.92 ± 4.32
A	2016	2.56cd ± 0.51	1.22bc ± 0.27	1.39bc ± 0.24	15.44b ± 1.41	46.31 ± 4.26
B		3.02a ± 0.51	1.42a ± 0.28	1.60a ± 0.25	15.79a ± 1.82	47.04 ± 2.61
C		2.61bc ± 0.51	1.14cd ± 0.34	1.46ab ± 0.23	14.38bc ± 2.02	45.12 ± 4.01
Average treatment	2014	2.86a ± 0.45	1.33a ± 0.23	1.53a ± 0.27	15.92a ± 1.43	46.97 ± 3.04
	2015	2.66b ± 0.53	1.22b ± 0.28	1.44b ± 0.30	15.01b ± 2.01	46.41 ± 3.77
	2016	2.73b ± 0.55	1.26b ± 0.32	1.48ab ± 0.25	14.69b ± 1.95	46.16 ± 3.76
A	Average year	2.76b ± 0.47	1.30a ± 0.23	1.48b ± 0.26	15.44a ± 1.48	46.76a ± 3.28
B		2.90a ± 0.54	1.35a ± 0.28	1.55a ± 0.32	15.79a ± 1.80	47.13a ± 3.35
C		2.59c ± 0.49	1.16b ± 0.31	1.43b ± 0.24	14.38b ± 2.05	45.65b ± 3.84
Source of variation						
Treatment		***	***	***	***	***
Year		***	***	***	***	n.s.
Treatment * Year		***	***	***	***	n.s.

TABLE 2. Incidence of main nut defects revealed on cultivar 'Tonda Romana' subjected to different pruning applications (treatment A: 2 hedging + 1 topping; treatment B: 2 hedging; C: un-pruned control). Data are represented as mean ± standard deviation. Different lowercase letters on the columns indicate significant differences among pruning treatments (Tukey's test, p < 0.05).

Treatment	Year	Good (%)	Bug damage (%)	Poor fill (%)	Brown tip (%)	Blank (%)
A	2014	95.0	2.5	1.5	0.0	1.5 b
	2015	99.0	0.5	0.0	0.0	0.5 ab
	2016	98.5	0.0	0.5	1.0	0.0 a
B	2014	96.5	2.0	1.5	0.0	0.0 a
	2015	98.0	0.0	0.0	0.0	1.5 b
	2016	97.5	1.5	0.0	1.0	0.0 a
Control	2014	95.0	2.5	1.5	0.0	0.5 ab
	2015	96.5	2.0	1.0	0.0	0.5 ab
	2016	95.0	2.0	0.0	1.0	2.0 b
Average treatment	2014	95.5	2.3	1.5 b	0.0 a	0.7
	2015	97.8	0.8	0.3 a	0.2 ab	0.8
	2016	97.0	1.2	0.2 a	1.0 b	0.7
A	Average year	97.3	1.0	0.7	0.3	0.7
B		97.3	1.2	0.5	0.5	0.5
Control		95.7	2.2	0.8	0.3	1.0
Source of variation						
Treatment		n.s.	n.s.	n.s.	n.s.	n.s.
Year		n.s.	n.s.	***	***	n.s.
Treatment * Year		n.s.	n.s.	n.s.	n.s.	***

Discussion

The findings obtained in this experiment are of two main types: agronomic and energetic. The wood removed by mechanical pruning was a suitable amount to be harvested as recyclable biomass, even excluding from the trial estimations the dead stems of the mature plants that may appear during the plant life cycle and that need being removed by hand. The recorded values were according to those observed by other authors in the same area through manual pruning approaches (Cristofori et al., 2009; Bignami et al., 2005b) and carried out with greater time and work consuming (Franco and Pancino, 2009).

Colantoni et al. (2016) demonstrated that hazelnut wood, similarly to the shells, has an average calorific value about 15 $\mathrm{MJ\ ha^{-1}}$, and this means that 2.5–3.0 kg of hazelnut wood corresponds to one liter of diesel oil. Hazelnut wood is characterized by low volumetric mass density (650 $\mathrm{kg\ m^{-3}}$) and considering that one hectare of mature hazelnut orchard produces an amount of pruned wood able to generate energy as 500 kg of diesel oil, it reinforces the opportunity to use this by-product for energy purposes. Moreover, recently it has been demonstrated that applying proper treatments, hazelnut wood may be an excellent source for producing biochar (Zambon et al., 2016).

Referring to the working time measured in the trial for mechanical pruning applications, on average, two hedging and one topping as proposed in treatment A required about 2 hours 35 minutes per ha of effective work, while applying the two hedging only (treatment B) the work requirement was reduced to about 1 hour 50 minutes per ha. Based on these observations, the operation was very fast in comparison to manual pruning which has been proven to require about 15–18 hours per ha per year for pruning mature hazelnut orchards grown in multi-stemmed shrub in central Italy (Franco and Pancino, 2009).

Some agronomical benefits have emerged mainly when hedging and topping were combined. Firstly, the restored inter-row access (hedging) and the reduction of plant height (topping) has been obtained, producing a shading reduction in the inner portion of the plants and facilitating the transit of the tractor during the other seasonal mechanized operations.

Secondly, the treatment has gradually induced a change in the physiological behavior of the plant. Under the effect of a more uniform and lengthening distribution of the light in the inner portion of the plant crown during the growing season, mainly in spring, the plants promoted the flower induction. In the two following years after pruning applications the treated plants showed a high incidence of vigorous shoots well distributed within the tree crown and a high incidence of fertile buds, confirmed by the increasing trend in production over the years.

As expected, a first year of low production was recorded in coincidence with mechanical pruning applications, as well as it has been recently observed for other fruit crops such as walnut, pecan and mandarin (Ninot et al., 2005; Wells, 2018; Mesejoa et al., 2020).

Instead, the un-pruned plants were exposed to a high and permanent shading in their inner and basal portion, as shown in Figure 4. Similarly to what is observed in other works carried out in commercial hazelnut orchards in central Italy (Cristofori et al., 2009), at the beginning of May the light infiltration at the base of the un-pruned control is very low because the canopies of the crossed branches of contiguous plants become a relevant obstacle to the light penetration. It has been demonstrated such as insufficient light penetration and continuous canopies shading cause a reduction in nut size, number and quality (Hampson et al., 1996). Furthermore, the shading long-term influence provokes biennial bearing (Azarenko et al., 2005), and tends to concentrate the presence of high-quality nuts only in the apical portion of the plant (Pannico et al., 2017).

Nut and kernel traits are useful qualitative parameters both to discriminate cultivars and to orientate the use of hazelnuts for in-shell or kernel market. Hazelnuts for kernel market are shelled in proper factories producing great quantities of shells, and this by-product may be allocated for energy and horticultural uses. In our trial a significant amount of shells were produced ranging on average between 1.45 to 1.33 $\mathrm{tons\ ha^{-1}\ y^{-1}}$ (un-pruned control and treatment A, respectively). This by-product is often destined to produce thermal energy for heating residential and industrial spaces thanks to its economy and easy management and storage (Senol and Zenk, 2020). Shells can also be used for mulching in agriculture, since they are promoting soil moisture conservation and during their decomposition do not cause changes in soil pH. Groundcover with chopped shells has been proven very useful for soil health preventing weeds and as source of


(a) (b) (c)

FIGURE 4. Overview of unpruned control (a) and treated plots after mechanical pruning applications: (b) two hedging and one topping; (c) two hedging. Growing season 2015.

micronutrients during their decay (Bender Özenç and Özenç, 2009). Furthermore, the shells undergoing to thermal hydrolysis processes with acidified water produce hemicelluloses or short-polymerized sugars with high nutritional interest (Surek and Buyukkileci, 2017).

As shown in Table 2, the mechanical pruning applications have strongly affected the incidence of defected nuts, mainly reducing the bug damages, since the new shape of the plants, more similar to the hedges than shrubs, probably has improved the effectiveness of the agrochemical treatments for pests and diseases control.

Conclusion

The outputs of this work confirmed the sustainability of mechanical pruning applications in mature hazelnut orchards when oriented to their long-term management. In general, ecophysiological response of the plant to hedging and topping depends on several factors, and heavy pruning is usually followed by a substantial drop in yield for one or two years, depending upon the condition of the plants and by the following cultural practices applied to the orchard. To alleviate the initial nut losses, different approaches in mechanical pruning may be applied. For instance, in medium-large farms the grower could generate a pruned plots rotation, cutting only on a portion of orchards each year to dilute the application and thus to alleviate the initial production losses.

Some growers use mechanical hedging to renovate overgrown orchards, such as this is a rapid, economical way to remove large amounts of wood, and the regrowth often is so rapid that the space between plants created by hedging is filled after two seasons.

The trial has confirmed the high impact of mechanical pruning in reducing labor costs, for instance such as already observed for vineyard (Kurtural et al., 2019). The treatment generated only a tolerable negative yield impact during the same growing season of the pruning application, meanwhile starting from the second year after pruning the yield increased consistently.

Mechanical pruning applications may promote hazelnut as a great source of biomass for energetic uses. Anyway, the supply chain organization is fundamental: suitable machinery for harvest and chipping are necessary. The local farmer cooperatives could represent a valid tool to promote the energetic uses of these by-products, currently often burned by the grower on the edge of the orchard. Furthermore, these aggregations may promote the harvesting, transport, storage and processing chain together with other agricultural districts that in the same area release other pruning residues suitable for producing agro-pellet and biochar (Rajabi Hamedani et al., 2019).

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