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Wood age, rootstocks and cultivars drive the formation of productivity and fruit size in sweet cherry

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Abstract

To maintain the high yields and fruit quality necessary for profitability of sweet cherry production, it is important to consider precision crop load and canopy management techniques during limb renewal. The effects of branch section age, rootstock, and cultivar on spur and flower density and fruit quality have been discussed in previous studies, but most of them focus on a limited range of fruiting wood ages and scion-rootstock combinations. This study aims to analyse the processes of sweet cherry productivity and fruit size formation on a wide range of wood age to determine the limit after which branch preservation is not sustainable, and to evaluate the influence of rootstocks and cultivars on these parameters. The results indicate that wood age is one of the main drivers of productivity formation in cherry. The highest flower density was observed on 3-year-old branch sections – 324 flowers per linear m, due to high spur density, number of reproductive buds per spur and flowers per bud. Productivity on 2-year-old wood was also good (256 flowers per linear m), while a sharp decline in flower density was noted on 4- and 5-year-old wood. The largest fruits were formed on young branch sections, with a significant decline in fruit weight and diameter on 4- and 5-year-old sections. Rootstock vigour had a bigger effect on floral organ induction on 1-year-old shoots, than on spurs. Based on the results, it is advisable to regularly renew lateral branches older than 3 years to maintain high yield efficiency and fruit quality.

Keywords: sweet cherry, flower density, reproductive bud, wood age, rootstock

Introduction

Cultivation technology of tree fruit crops, including sweet cherry (*Prunus avium* L.), is constantly evolving with the implementation of vigour-controlling rootstocks, new training systems, and cultivar-based growing technologies. However, to maintain stable high yields and the fruit quality necessary for profitability of production, it is important to incorporate precision crop load and canopy management techniques into decision making. This includes considering the data on spur and flower number per tree after pruning, the number of flowers per spur and per bud, leaf population, and leaf to fruit ratio (Ayala and Lang 2017).

Sweet cherry forms reproductive buds on spurs, starting from 2-year-old sections of the branch, as well as non-spur buds in the basal part of 1-year-old shoots. As fruiting wood gets older, it gradually becomes blind and loses productivity (Kondratenko et al. 2021; Dzhubinov and Gandev 2016; Schaumberg and Gruppe 1985). However, a global switch to orchard architectures with very compact canopies that only utilise 1- and 2-year-old wood is not yet feasible for multiple reasons. In lower income countries where a large share of sweet cherry production is concentrated, high-density plantings are often not profitable or even possible to establish, due to high initial investment and maintenance costs (Kishchak et al. 2020; Manolova and Kolev 2013). In hotter arid regions, particularly in the face of global warming, the use of dwarfing rootstocks often leads to a decrease in yield and fruit quality (Bondarenko 2018; Gonçalves et al. 2006). Moreover, the formation of unmarketable double fruits can occur more frequently in compact trees with an altered canopy microclimate, as flower buds are more exposed to high temperatures and solar radiation (Southwick et al. 1991; Beppu and Kataoka 2011), while overly high temperatures during early summer may suppress flower formation altogether (Sønsteby and Heide 2019). Thus, cherry producers may have to utilize orchard architectures that preserve a wider range of wood age on the trees, and this should be taken into account when developing precision crop load management strategies.

Induction and development of generative buds and, later, fruit is driven by a large variety of factors, such as cultivar and rootstock genotype, ecological conditions, and agronomic practices in

the orchard (Koutinas et al. 2010). The influence of rootstocks on the flower induction, and, therefore, precocity and yield, has been studied extensively (Milić et al. 2019; Lang 2000; Edin et al. 1996). A large share of the research regarding sweet cherry floral organ formation is dedicated to framing various stages of reproductive bud development to specific dates and phenological phases of the trees (Fadón et al. 2015; Guimond et al. 1998), and to investigation of internal processes in the buds during dormancy (Götz and Chmielewski 2023; Fadón et al. 2019). Applied studies concerning more practical aspects of productivity formation in relation to wood age, have also been conducted. Wood age is reported to affect spur, bud and flower density (Kondratenko et al. 2021; Edin et al. 1996), fruit diameter, and soluble solids content (San Martino et al. 2014). In addition, these parameters are strongly influenced by the segment within a branch section of each age (Stanley 2016; Maguylo et al. 2004; Schaumberg and Gruppe 1985).

While the research on the topic is rather extensive, a lot of the studies focus on a limited range of fruiting wood ages and scion-rootstock combinations and are not always applicable to all ecological environments of cherry production. Therefore, the aim of this research is to analyse the processes of formation of sweet cherry productivity and fruit size on a wide range of wood age to determine the age limit after which preservation of the branch is not sustainable, and to evaluate the influence of the rootstocks and cultivars on these parameters, particularly in the regions with hotter arid climate.

Materials and Methods

Site description and weather conditions

The field experiment was conducted in 2021 in a sweet cherry orchard in Melitopol, south-eastern Ukraine (46°83'N, 35°35'E, 38 m a.s.l.). The soil of the site is southern chernozem (black soil) with loam texture. The region's climate is semi-arid, moderately continental. Based on long-term data, the average annual air temperature is 10.7 °C, and the average annual amount of precipitation is 481 mm. Monthly data on air temperature and precipitation are presented in Table S1

for the period from May 2020 (the presumed beginning of floral organ initiation) to June 2021 (the fruit harvest). In general, weather conditions during the study were fairly typical for the region, apart from the warmer autumn of 2020, when the mean monthly air temperature exceeded long-term data by 3.4 °C in September and by 4.4 °C – in October. In June 2021, the amount of precipitation was almost triple the norm, but most of the rainfall happened when the fruits were in relatively early stages of ripening and still retained green skin colour, so no rain-induced cracking occurred in the experimental orchard. The minimum temperature of minus 19.4 °C in January 2021 did not cause significant damage to floral organs. Conditions during flowering were also favourable and contributed to high fruit set.

Plant material and experimental design

The experimental orchard was planted in April 2015 with 1-year-old maiden trees without lateral branches, so productivity parameters were assessed for the yield in 7th leaf. The planting distance is 5 m between the rows and 3 m within the row. Trees were trained as central leader spindle-bush canopies and were grafted on clonal rootstocks Gisela 5, Gisela 6, and CAB 6P. These rootstocks were chosen because they demonstrate distinct vigour habits: Gisela 5 is classified as dwarfing, Gisela 6 – as semi-dwarfing, and CAB 6P – as medium vigour in most studies (Tersoglio and Setien 2016; Font i Forcada et al. 2017), as well as previous research in Southern Ukraine (Topov 2018). The cultivars ‘Krupnoplidna’ and ‘Melitopolska chorna’ were used. They are the main late ripening cultivars in commercial orchards in Ukraine and were bred in Melitopol Fruit Growing Research Station named after M.F. Sydorenko, Melitopol, Ukraine (Quero-García et al. 2017). ‘Krupnoplidna’ is characterised by more spreading canopies with wider crotch angles and higher shoot formation ability, while ‘Melitopolska chorna’ – by more compact upright canopies, with fewer shoots formed each year (Bondarenko 2019).

The experiment was arranged in a randomised block design and had 30 treatments with every possible combination of rootstock, cultivar, and age of the fruiting wood (1 to 5 years) being replicated 3 times with 3 trees in each replication. All studied parameters, therefore, had 3

replications. Wood age in terms of this study means the age of the section of the branch: 1-year-old wood is the extension shoot produced in the previous growing season (2020), 2-year-old wood is an extension shoot from 2 years ago (2019), etc.

Data collection

Two scaffold branches of similar size and crotch angle were selected in the lower part of the canopy on each tree. Spur density and the number of flower buds per spur were calculated during dormancy in February 2021 by measuring the length of the wood separately for each age section of the branch and counting the number of spurs and flower buds on it. The number of flowers per bud was assessed just before bud burst with a sample size of 50 buds per replication of each treatment. The number of flowers per linear m of wood was calculated as: Spur density \times Number of flower buds per spur \times Number of flowers per flower bud.

One-year-old shoots were excluded from flower density calculations since they form individual flower buds instead of spurs, and it is debatable whether flower density on them should be measured using shoot length before or after pruning. Instead, the number of flowers per each 1-year-old shoot was calculated using the following formula: Number of flower buds per shoot \times Number of flowers per flower bud. The number of flower buds on 1-year-old wood was assessed at the stage of BBCH 56 (flower pedicel elongation), when it was possible to unmistakably distinguish between vegetative and generative buds.

All field data were collected after the trees were pruned. Pruning was carried out in the first half of February. It consisted of heading cuts only, removing roughly 1/3 of the length of annual shoots, in order to preserve the maximum amount of flowers on the trees.

Fruit weight and diameter were determined at harvest (23 June 2021 for 'Melitopolska chorna', 25 June 2021 – for 'Krupnoplidna') with 50 fruits sampled per replication. Mean fruit weight was determined by weighing the sample on the electronic scales and division by the number of fruits in the sample (50). Each individual fruit in the sample was measured with the callipers, perpendicular to the suture, to determine their maximum equatorial diameter.

Data analysis

Statistical analysis of the results was performed using the software IBM SPSS Statistics 27. The research data were subjected to a three-way analysis of variance (two-way for the number of flower buds and flowers on 1-year-old shoots), followed by Tukey's post-hoc test at $p \leq 0.05$ in order to determine significant differences between the means. Pearson's correlation was used to determine dependencies between indices.

Results

Spur and flower bud density

Spur density significantly depended on wood age. The highest values of this index were observed on 2- and 3-year-old wood. As wood got older, spur density decreased by roughly two times at 4 years, and by 4 times – at 5 years (Table 1).

Table 1. Density of the spurs and flower buds per spur of seven-year-old sweet cherry trees grown in Melitopol, Ukraine, in 2021, depending on wood age, rootstock, and cultivar

Variant	Spur density, linear m ⁻¹	Flower buds per spur
Mean for Wood age		
2 years	15.6 ± 0.6 <i>a</i>	5.0 ± 0.3 <i>b</i>
3 years	17.1 ± 1.2 <i>a</i>	6.0 ± 0.1 <i>a</i>
4 years	7.6 ± 0.8 <i>b</i>	6.0 ± 0.2 <i>a</i>
5 years	3.5 ± 0.4 <i>c</i>	6.7 ± 0.3 <i>a</i>
<i>P value</i>	<0.001	<0.001
Mean for Rootstock		
Gisela 5	9.7 ± 1.2 <i>b</i>	6.2 ± 0.2 <i>a</i>
Gisela 6	11.2 ± 1.5 <i>a</i>	6.0 ± 0.2 <i>ab</i>
CAB 6P	11.9 ± 1.4 <i>a</i>	5.6 ± 0.3 <i>b</i>
<i>P value</i>	0.003	0.014
Mean for Cultivar		
Melitopolska chorna	12.9 ± 1.1 <i>a</i>	5.5 ± 0.2 <i>b</i>
Krupnoplidna	9.0 ± 1.0 <i>b</i>	6.3 ± 0.2 <i>a</i>
<i>P value</i>	<0.001	<0.001

Data presented as mean ± SE. Different letters within the same factor indicate significant difference between the mean values according to Tukey's test at $p \leq 0.05$

Between 0 and 10 flower buds were formed on each spur in the conditions of the trial. Spurs with 0 buds were found on 2- to 4-year-old sections of the branch, and spurs with 10 buds – on 3- to 5-year-old sections. Such extremes were observed in rather small quantities, and the majority of spurs

formed 4-8 flower buds, regardless of wood age. The lowest mean amount of flower buds per spur (5.0) was formed on 2-year-old wood. On older wood, this parameter increased by 20-34% on average for the studied cultivars and rootstocks. On 5-year-old wood, a tendency toward a further increase of the number of buds per spur was observed, but it was not statistically significant compared to 3- and 4-year-old wood.

Trees grafted on Gisela 5 rootstock, had 13-18% lower spur density, compared to Gisela 6 and CAB 6P, but formed a higher number of buds per each spur. Cultivar ‘Melitopolska chorna’, on average, formed 1.4 times more spurs per linear m of wood, but had 13% fewer flower buds per spur.

Number of flowers per flower bud

In the conditions of the experiment, the number of flowers per flower bud ranged between 1 and 5 and was significantly affected by the age of the wood, with the highest values observed on 2- to 4-year-old wood – 3.2-3.3 flowers per bud (Fig. 1A). This parameter was statistically lower on younger 1-year old wood and older 5-year-old wood – by 12% and 14%, respectively, on average for all studied rootstocks and cultivars. This decrease was more pronounced on 1-year old wood of the trees of the cultivar ‘Krupnoplidna’ compared to ‘Melitopolska chorna’ trees.

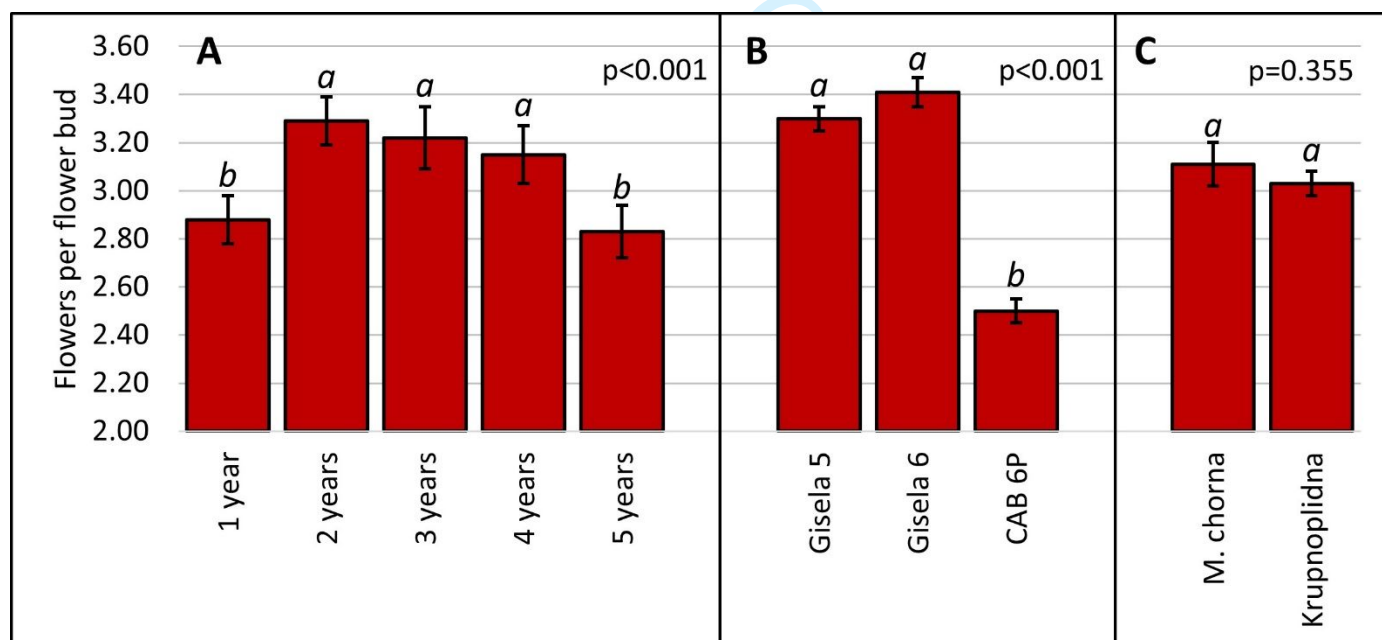


Figure 1. Mean number of flowers per flower bud of seven-year-old sweet cherry trees grown in Melitopol, Ukraine, in 2021, depending on wood age (A), rootstock (B), and cultivar (C). Data presented as mean \pm SE. Different letters within the same factor indicate significant difference

between the mean values according to Tukey's test at $p \leq 0.05$. Note that the scale doesn't start at zero

Trees grafted on a more vigorous CAB 6P rootstock, formed on average 2.5 flowers in each flower bud, which was 24-27% lower compared to the trees on more dwarfing Gisela 5 and Gisela 6 rootstocks (Fig. 1B). No significant differences were observed for this parameter between the studied cultivars (Fig. 1C).

Flower density

Using the data on spur density and number of generative buds per spur and flowers per flower bud, it is possible to calculate the flower density per linear meter of wood. A clear division based on the age of the wood was observed: on average, 256 flowers were formed on one linear m of 2-year-old wood; at 3 years, this index increased by 1.3 times (Fig. 2A). For older wood, flower density declined sharply: by 2.4 and 5.1 times respectively on 4- and 5-year-old wood, compared to the values of this parameter on 3-year-old wood. Both lower spur density and lower number of flowers per flower bud contributed to this decline.

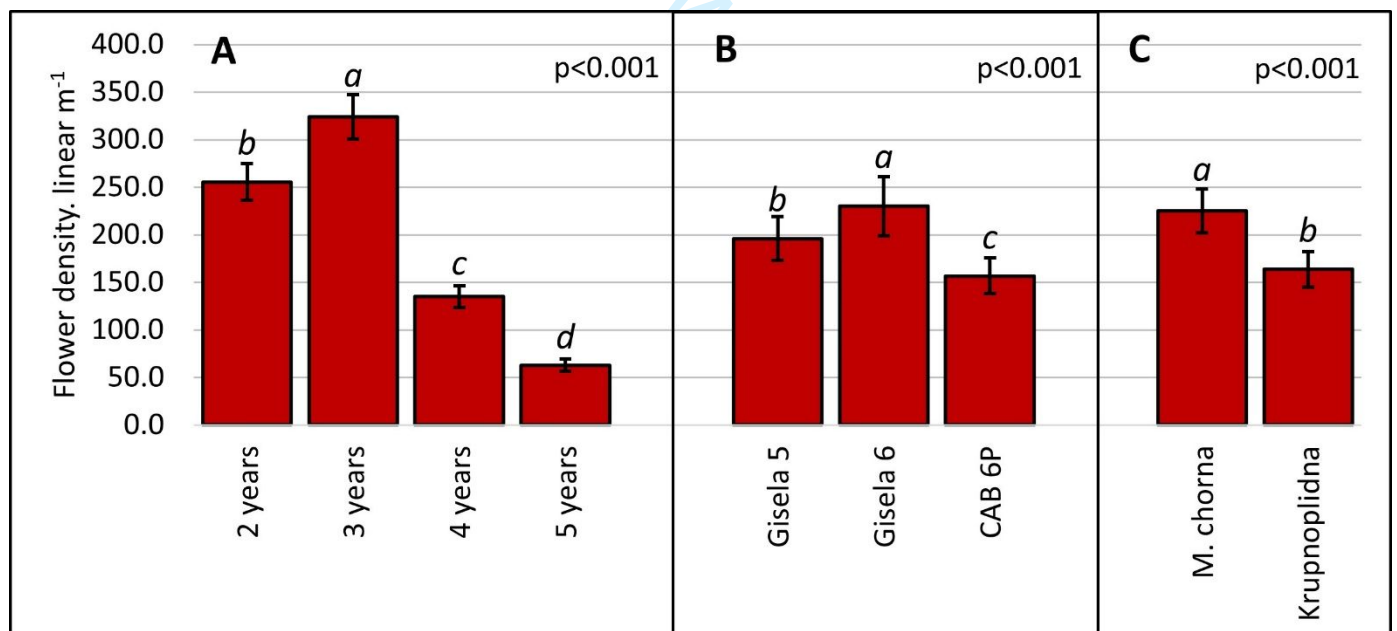


Figure 2. Flower density, linear m⁻¹, of seven-year-old sweet cherry trees grown in Melitopol, Ukraine, in 2021, depending on wood age (A), rootstock (B), and cultivar (C). Data presented as mean \pm SE. Different letters within the same factor indicate significant difference between the mean values according to Tukey's test at $p \leq 0.05$

Rootstock comparison showed that trees grafted on Gisela 6 had the highest flower density – 231 flower per linear m, which was 1.2 and 1.5 times higher than the trees on Gisela 5 and Gisela 6, respectively (Fig. 2B). ‘Melitopolska chorna’ trees formed 1.4 times more flowers per linear m of wood than ‘Krupnoplidna’ trees, mostly due to higher spur density (Fig. 2C).

Floral organ formation on 1-year-old shoots

On annual shoots, unlike older wood, individual flower buds are formed in the basal part of the shoot instead of on spurs. The number of flower buds per shoot correlated with rootstock vigour. The highest value (7.6 buds per shoot) was observed on the trees grafted on Gisela 5, the lowest-vigour rootstock in the experiment, while shoots on the trees grafted on the more vigorous Gisela 6 and CAB 6P rootstocks formed 20 and 43% fewer flower buds (Table 2). This tendency was even more evident when evaluating the number of flowers per shoot, where the difference between the trees on Gisela 5 and on CAB 6P was more than two-fold.

Table 2. Floral organ parameters of annual shoots of seven-year-old sweet cherry trees grown in Melitopol, Ukraine, in 2021, depending on rootstock and cultivar

Variant	Flower buds per 1-year-old shoot	Flowers per 1-year-old shoot
Mean for Rootstock		
Gisela 5	7.6 ± 0.7 <i>a</i>	23.8 ± 1.8 <i>a</i>
Gisela 6	6.1 ± 0.5 <i>b</i>	18.9 ± 0.8 <i>b</i>
CAB 6P	4.3 ± 0.5 <i>c</i>	10.2 ± 1.4 <i>c</i>
<i>P value</i>	<0.001	<0.001
Mean for Cultivar		
Melitopolska chorna	4.8 ± 0.4 <i>b</i>	14.9 ± 2.0 <i>b</i>
Krupnoplidna	7.2 ± 0.6 <i>a</i>	20.4 ± 2.1 <i>a</i>
<i>P value</i>	<0.001	<0.001

Data presented as mean ± SE. Different letters within the same factor indicate significant difference between the mean values according to Tukey’s test at $p \leq 0.05$

‘Krupnoplidna’ trees formed on average 1.5 times more generative buds and 1.4 times more flowers per 1-year-old shoot than ‘Melitopolska chorna’ trees.

Size of the fruits

The fruit set was high in 2021, ranging from 31 to 36%, with no significant differences between the variants of the experiment ($p = 0.600$ for the factor “Wood age”, $p = 0.131$ – for “Rootstock”, and

$p = 0.117$ – for “Cultivar”). All three studied factors significantly affected physical quality parameters of the sweet cherry fruits. As the age of the wood increased, the fruit size gradually decreased. The highest fruit weight and diameter were observed on 1-year-old wood: on average 7.8 g and 25.0 mm (Table 3). Fruits formed on 4-year old wood were already smaller compared to those on 1- and 2-year-old wood (significant according to Tukey’s test), but the biggest decline in fruit quality was noted on 5-year-old wood, where fruit weight was 19% lower, and fruit diameter was 8% lower.

Table 3. Fruit size parameters of seven-year-old sweet cherry trees grown in Melitopol, Ukraine, in 2021, depending on wood age, rootstock, and cultivar

Variant	Fruit weight, g	Fruit diameter, mm
Mean for Wood age		
1 year	7.8 ± 0.2 <i>a</i>	25.0 ± 0.2 <i>a</i>
2 years	7.4 ± 0.2 <i>b</i>	24.4 ± 0.2 <i>b</i>
3 years	7.3 ± 0.2 <i>bc</i>	24.2 ± 0.3 <i>bc</i>
4 years	7.1 ± 0.2 <i>c</i>	24.0 ± 0.3 <i>c</i>
5 years	6.3 ± 0.2 <i>d</i>	23.0 ± 0.3 <i>d</i>
<i>P value</i>	<0.001	<0.001
Mean for Rootstock		
Gisela 5	6.5 ± 0.1 <i>c</i>	23.2 ± 0.2 <i>c</i>
Gisela 6	6.9 ± 0.1 <i>b</i>	23.8 ± 0.2 <i>b</i>
CAB 6P	8.1 ± 0.1 <i>a</i>	25.3 ± 0.2 <i>a</i>
<i>P value</i>	<0.001	<0.001
Mean for Cultivar		
Melitopolska chorna	7.2 ± 0.1 <i>a</i>	23.8 ± 0.2 <i>b</i>
Krupnoplidna	7.1 ± 0.2 <i>a</i>	24.4 ± 0.2 <i>a</i>
<i>P value</i>	0.287	<0.001

Data presented as mean ± SE. Different letters within the same factor indicate significant difference between the mean values according to Tukey’s test at $p \leq 0.05$

Trees grafted on CAB 6P rootstock had higher fruit quality, exceeding other rootstocks by 18-24% in mean fruit weight and by 6-9% – in mean fruit diameter. There were no significant differences in fruit weight among the studied cultivars, but ‘Krupnoplidna’ trees formed fruits of larger diameter, which can be attributed to the round fruit shape, characteristic to this cultivar, compared to the heart-shaped fruits of ‘Melitopolska chorna’.

Discussion

The results show a complex effect of the studied factors on the formation of floral organs in sweet cherry. Scion-rootstock combinations demonstrated similar patterns of main productivity indices in relation to wood age.

A good preservation, within the range of seasonal differences, of spurs on 3-year-old sections of the branch and a decrease of spur density on older wood are also reported in other studies (Kondratenko et al. 2021; Edin et al. 1996). This decrease can be explained by the combination of the gradual death of spurs and their unintentional removal by pickers during harvest. The two-fold decline in spur density between 3- and 4-year-old wood in the present study is bigger than typically reported and, most likely, can be attributed to relatively young trees, as current 4-5-year-old wood was formed when trees were in 2nd-3rd leaf, and vegetative growth prevailed over spur formation.

The assumption that trees grafted on less vigorous rootstocks would have higher spur density because of shorter internodes, was not proven in our research. In fact, such trees tend to form a higher number of reproductive buds per 1-year-old shoot both in terms of absolute number and bud density per linear m (Milić et al. 2019), so bigger sections of wood become blind before spur induction. The same trend was observed in the present study, supported by an adverse correlation ($R^2 = -0.630$, $p < 0.01$) between the number of flower buds per 1-year-old shoot and spur density. Other studies also report rather inconsistent patterns regarding spur density on scion-rootstock combinations of varying vigour (Dziedzic et al. 2019; Tabakov et al. 2015).

Our results indicate that rootstock vigour has a larger influence on reproductive bud and flower formation on 1-year-old wood compared to spurs on older branch sections. This is consistent with other research, which reports a higher share of reproductive buds formed on shorter annual shoots (Alehina and Dolya 2012; Reginato et al. 2008), and should always be considered when choosing rootstock-scion combinations for specific training systems.

Little is known still about the mechanisms determining the number of flowers per reproductive bud. Our results, as well as other research, note the effect of rootstocks and cultivars on this parameter

(Dziedzic et al. 2019; Tabakov et al. 2015). In addition, in the present study, flower buds on 1-year-old shoots formed fewer flowers per bud, compared to spurs on 2- to 4-year-old sections of the branch. That supports results obtained in the study conducted in Turkey (Soysal et al. 2023). However, no difference between shoots and spurs in the number of flowers per bud was observed in other research (Đorđević et al. 2021; Alehina and Dolya 2012). One of the possible explanations for the lower number of flowers per bud can be later timing of flower bud induction on shoots compared to spurs (Koutinas et al. 2010). However, Guimond et al. (1998) did not observe visible differences in flower primordia development between buds on spurs and unpruned shoots, so this phenomenon warrants further research.

Our results suggest that 2- and 3-year-old branch sections have the highest flower density, and, thus, productivity potential, based on our results, while 4- and, especially, 5-year-old wood is much less productive. When making practical decisions about fruiting wood renewal in the orchard, not only the productivity of a branch section should be taken into account, but also the age of the limb, since renewal of branches older than 4 years may be challenging (Vaszily 2010). While high flower density may lead to overcropping and decline in fruit quality during the years with high fruit set, it is beneficial to base pruning decisions on factors such as bearing potential, ease of branch renewal, and canopy light interception improvement, and to apply a suitable thinning method for managing fruit quality (Measham et al. 2013; Whiting et al. 2006).

The influence of rootstock on fruit quality is well-documented in the scientific literature. Our results are in accordance with other studies, in which trees grafted on CAB 6P generically produced bigger fruits compared to trees grafted on less vigorous rootstocks, particularly when the experiments are conducted in hot arid regions (Font i Forcada et al. 2017; Landi et al. 2014). One of the possible explanations for this can be lower flower and fruit density of the trees grafted on CAB 6P rootstock compared to the trees on Gisela 5 and Gisela 6, leading to less carbohydrate competition. It should be noted that the correlation analysis showed only marginal negative relation between flower density

and fruit size on the whole tree level ($R^2 = -0.267$, $p = 0.028$). Therefore, flower density is not the only factor responsible for fruit size in relation to rootstocks.

No correlation between flower density of the individual branch section of a certain age and fruit size was observed ($R^2 = 0.043$, $p = 0.330$ for fruit weight; $R^2 = 0.013$, $p = 0.590$ for fruit diameter). In fact, both the lowest flower and fruit density and the lowest fruit size were noted on 5-year-old wood. Thus, a complex of other factors has contributed to the reduction of the weight and diameter of the fruits on the older wood, observed in this study. Older branch sections inherently positioned closer to the centre of the canopy and have lower levels of light interception. At the same time, photosynthetic productivity of sweet cherry leaves is 1.6-2.3 times higher at the periphery of the tree canopy compared to its centre (Bondarenko 2019), and 1.4-1.7 times higher for peach leaves (Alekseeva 1986). For apple, increasing light exposure levels progressively increased fruit weight (Robinson et al. 1983). From a certain wood age onwards, a decrease in leaf area and chlorophyll content is observed (Yang et al. 2019), and the leaf to fruit ratio is one of the most important drivers responsible for the fruit size (Usenik et al. 2010; Flore and Layne 1999; Facticeau et al. 1983). From the onset of stage III of fruit development, when the main increase in fruit mass happens for cherry, phloem gradually becomes the main contributor to the total vascular flow (Brüggenwirth et al. 2016). During this period, the fruits are the main sinks, receiving 87-96% of all photoassimilates (Ayala and Lang 2008), so adequate light interception, leaf area, and photosynthetic productivity are critical for fruit quality formation.

In addition, changes in fruit quality can be attributed to internal changes in older spurs, possibly due to the gradual deterioration of the vascular system, as well as a longer distance from other potential sources, such as extension shoot leaves. In a study conducted on pear, 3- to 7-year-old spurs, when defoliated, were unable to efficiently translocate assimilates from other parts of the tree, resulting in a roughly 30% decrease in fruit weight, but no such effect was observed on 1-year-old spurs (Teng et al. 1998). On cherry, during the years with high crop load, when leaf to fruit ratio is low and the competition for carbohydrates is high, such as the year of the present study, carbon

partitioning to the fruits located further from the source leaves is particularly weak, as 70-90% of carbon is received by the closest fruits (Ayala and Lang 2008). Also, as branches get older, the activity of enzymes, associated with fruit quality, progressively reduces (Yang et al. 2019).

Market price of sweet cherry is heavily influenced by fruit diameter; even slight size changes contribute significantly to crop profitability (Bondarenko 2018; Monney et al. 2009; Whiting et al. 2006). Intra-canopy variability in fruit size is inherent to fruit crops even within the same branch, cluster, and light environment (Whiting and Sallato 2022). In the present study, the difference between the smallest and the largest fruit on the same tree was 12 mm. Thus, it is important to be able to determine the wood age threshold, after which smaller less marketable fruits are more likely to be produced.

An important limitation of the present study is that wood age is assessed strictly as a factor. However, in the orchard, the proportions of branch sections of each wood age in the canopy structure are not equal, and it might be interesting to address this in future research by evaluating the number of reproductive organs formed on different age sections on a whole-tree level.

Conclusions

The results of the study indicate that wood age is one of the main drivers of productivity formation in sweet cherry. The highest flower density was observed on 3-year-old sections of the branch, with high spur density, number of reproductive buds per spur and flowers per bud contributing to that. 2-year-old wood also showed good productivity, while a sharp decline in flower density was noted on 4- and 5-year-old wood. The best quality fruits were formed on young sections of the branch, with a noticeable decline in fruit weight and diameter on 4- and 5-year-old sections. These trends were observed in all the studied scion-rootstock combinations. Rootstock vigour had a bigger influence on floral organ induction on 1-year-old shoots than on spurs. In summary, it is advisable to regularly renew lateral branches older than 3 years in order to maintain high yield efficiency and fruit quality.

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Competing interests

The authors declare there are no competing interests.

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Data availability

Data analysed during this study are available from the corresponding author upon reasonable request.

References

- Alehina, E., and Dolya, Y. 2012. Features of formation of productivity elements at sweet cherry varieties of NCRRIH&V selection. *Fruit growing and viticulture of South Russia* **16**(4): 22-29. Available from <https://journal.kubansad.ru/pdf/12/04/03.pdf>.
- Alekseeva, O. 1986. Radiation regime and photosynthetic productivity of peach leaves depending on the training systems and tree planting schemes. *Collection of scientific papers: physiological foundations of the productivity of fruit and berry crops* **46**: 59-61. Available from <http://elar.tsatu.edu.ua/handle/123456789/5389>.
- Ayala, M., and Lang, G.A. 2008. ¹³C-Photoassimilate partitioning in sweet cherry on dwarfing rootstocks during fruit development. *Acta Horticulturae* **795**: 625-632. doi: <https://doi.org/10.17660/ActaHortic.2008.795.97>.
- Ayala, M., and Lang, G. 2017. Morphology, Cropping Physiology and Canopy Training. *In Cherries: Botany, Production and Uses*. Edited by J. Quero-García, A. Lezzoni, J. Puławska, and G. Lang. CABI, Boston, MA, USA. pp. 269-304 doi: <https://doi.org/10.1079/9781780648378.0269>.
- Beppu, K., and Kataoka, I. 2011. Studies on pistil doubling and fruit set of sweet cherry in warm climate. *Journal of the Japanese Society for Horticultural Science* **80**(1): 1-13. doi: <https://doi.org/10.2503/jjshs1.80.1>.

Bondarenko, P. 2018. Comparative evaluation of the economic efficiency of cultivating the sweet cherry (*Cerasus avium* Moench.) orchards of different constructions in the Ukraine's Southern Steppe. *Sadivnytstvo (Horticulture)* **73**: 193-199. doi: <https://doi.org/10.35205/0558-1125-2018-73-193-199>.

Bondarenko, P. 2019. Physiological basics of sweet cherry productivity depending on rootstocks, interstems and plant density. *Open Agriculture* **4**(1): 267-274. doi: <https://doi.org/10.1515/opag-2019-0025>.

Brüggenwirth, M., Winkler, A., and Knoche, M. 2016. Xylem, phloem, and transpiration flows in developing sweet cherry fruit. *Trees* **30**: 1821–1830. doi: <https://doi.org/10.1007/s00468-016-1415-4>.

Dorđević, B., Đurović, D., Zec, G., and Boškov, Đ. 2021. The influence of rootstocks on the sensitivity of flower buds to frost and the main properties of the 'Carmen' sweet cherry cultivar. *Journal of Agricultural Sciences (Belgrade)* **66**(4): 351-358. doi: <https://doi.org/10.2298/JAS2104351D>.

Dzhuvinov, V., and Gandev, S. 2016. Evaluation of fruit bearing habit of apple, sweet cherry, walnut and strawberry cultivars in Bulgaria. *Acta Horticulturae* **1139**: 177-182. doi: <https://doi.org/10.17660/ActaHortic.2016.1139.31>.

Dziedzic, E., Bieniasz, M., and Kowalczyk, B. 2019. Morphological and physiological features of sweet cherry floral organ affecting the potential fruit crop in relation to the rootstock. *Scientia Horticulturae* **251**: 127-135. doi: <https://doi.org/10.1016/j.scienta.2019.03.013>.

Edin, M., Garcin, A., Lichou, J., and Jourdain, J. 1996. Influence of dwarfing cherry rootstocks on fruit production. *Acta Horticulturae* **410**: 239-246. doi: <https://doi.org/10.17660/ActaHortic.1996.410.35>.

Facteau, T.J., Chestnut, N.E., and Rowe, K.E. 1983. Relationship between fruit weight, firmness, and leaf/fruit ratio in Lambert and Bing sweet cherries. *Canadian Journal of Plant Science* **63**(3): 763-765. doi: <https://doi.org/10.4141/cjps83-096>.

Fadón, E., Herrero, M., and Rodrigo, J. 2015. Flower development in sweet cherry framed in the BBCH scale. *Scientia Horticulturae* **192**: 141-147. doi: <https://doi.org/10.1016/j.scienta.2015.05.027>.

Fadón, E., Herrero, M., and Rodrigo, J. 2019. Anther and pollen development in sweet cherry (*Prunus avium* L.) in relation to winter dormancy. *Protoplasma* **256**: 733-744. doi: <https://doi.org/10.1007/s00709-018-01332-4>.

Flore, J.A., and Layne, D.R. 1999. Photoassimilate production and distribution in cherry. *HortScience* **34**(6), 1015-1019. doi: <https://doi.org/10.21273/HORTSCI.34.6.1015>.

Font i Forcada, C., Pinochet, J., Gogorcena, Y., and Moreno, M. 2017. Effect of eight different rootstocks on agronomic and fruit quality parameters of two sweet cherry cultivars in Mediterranean conditions. *Acta Horticulturae* **1161**: 315-320. doi: <https://doi.org/10.17660/ActaHortic.2017.1161.51>.

Gonçalves, B., Moutinho-Pereira, J., Santos, A., Silva, A., Bacelar, E., Correia, C., and Rosa, E. 2006. Scion–rootstock interaction affects the physiology and fruit quality of sweet cherry. *Tree Physiology* **26**(1): 93-104. doi: <https://doi.org/10.1093/treephys/26.1.93>.

Götz, K.-P., and Chmielewski, F.-M. 2023. Metabolites that confirm induction and release of dormancy phases in sweet cherry buds. *Metabolites* **13**: 231. doi: <https://doi.org/10.3390/metabo13020231>.

Guimond, C., Andrews, P., and Lang, G. 1998. Scanning electron microscopy of floral initiation in sweet cherry. *Journal of the American Society for Horticultural Science* **123**(4): 509-512. doi: <https://doi.org/10.21273/JASHS.123.4.509>.

Kishchak, O., Grynyk, I., Barabash, L., and Kishchak, Y. 2020. Technological aspects of the creation of intensive plantations of cherries in Forest-Steppe of Ukraine. *Bulletin of Agricultural Science* **98**(3): 27-37. doi: <https://doi.org/10.31073/agrovisnyk202003-04>.

Kondratenko, P., Alekeeva, O., Senin, V., and Bondarenko, P. 2021. Yield formation of the sweet cherry (*Cerasus avium* L.) intensive orchards depending on interstem VSL 2 length in the

- Ukraine's Southern Steppe. *Sadivnytstvo (Horticulture)* **76**: 93-101. doi: <http://doi.org/10.35205/0558-1125-2021-76-93-101>.
- Koutinas, N., Pepelyankov, G., and Lichev, V. 2010. Flower induction and flower bud development in apple and sweet cherry. *Biotechnology & Biotechnological Equipment* **24**(1): 1549-1558. doi: <https://doi.org/10.2478/V10133-010-0003-9>.
- Landi, M., Massai, R., and Remorini, D. 2014. Effect of rootstock and manual floral bud thinning on organoleptical and nutraceutical properties of sweet cherry (*Prunus avium* L.) cv 'Lapins'. *Agrochimica* **58**(4): 335-351. doi: <http://dx.doi.org/10.12871/0021857201444>.
- Lang, G.A. 2000. Precocious, dwarfing, and productive – how will new cherry rootstocks impact the sweet cherry industry? *HortTechnology*, **10**(4): 719-725. doi: <https://doi.org/10.21273/HORTTECH.10.4.719>.
- Maguylo, K., Lang, G., and Perry, R. 2004. Rootstocks genotype affects flower distribution and density of 'Hedelfinger' sweet cherry and 'Montmorency' sour cherry. *Acta Horticulturae* **636**: 259-266. doi: <https://doi.org/10.17660/ActaHortic.2004.636.31>.
- Manolova, V., and Kolev, K. 2013. Economic results from growing of cherry in different levels of intensification. *Acta Horticulturae* **981**: 719-723. doi: <https://doi.org/10.17660/ActaHortic.2013.981.115>.
- Measham, P., Bound, S., Gracie, A., and Wilson, S. 2013. Crop load manipulation and fruit cracking in sweet cherry (*Prunus avium* L.). *Advances in Horticultural Science* **26**(1): 25-31. doi: <https://doi.org/10.13128/ahs-12749>.
- Milić, B., Kalajdžić, J., Keserović, Z., Magazin, N., Ognjanov, V., Miodragović, M., and Popara, G. 2019. Early performance of four sweet cherry cultivars grafted on Gisela 5 and Colt rootstocks in a high density growing system. *Acta Scientiarum Polonorum Hortorum Cultus* **18**(1): 99-108. doi: <https://doi.org/10.24326/asphc.2019.1.10>.
- Monney, P., Bravin, E., and Evéquo, N. 2009. Rootstock and crop load determine orchard profitability by sweet cherry. *Revue Suisse De Viticulture Arboriculture Horticulture* **41**(3): 167-174. Available from https://www.revuevitierbohorti.ch/wp-content/uploads/2009_03_f_738.pdf.
- Quero-García, J., Schuster, M., López-Ortega, G., and Charlot, G. 2017. Sweet cherry varieties and improvement. In *Cherries: Botany, Production and Uses*. Edited by J. Quero-García, A. Lezzoni, J. Puławska, and G. Lang. CABI, Boston, MA, USA pp. 60-94. doi: <https://doi.org/10.1079/9781780648378.0060>.
- Reginato, G., Robinson, T., and Yoon, T. 2008. Improving cherry fruit size of self-fertile cultivars in NY orchards. *New York Fruit Quarterly* **16**(3): 27-30. Available from <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=4b33eb4b613585cf4c9bd84429c188a8c44a8eca#page=27>.
- Robinson, T., Seeley, E., and Barritt, B. 1983. Effect of light environment and spur age on 'Delicious' apple fruit size and quality. *Journal of the American Society for Horticultural Science* **108**(5): 855-861. doi: <https://doi.org/10.21273/JASHS.108.5.855>.
- San Martino, L., Hochmaier, V., and Manavella, F. 2014. Sweet cherry (*Prunus avium* L.) fruit quality in relation to wood age and fruit position on the branch. *Acta Horticulturae* **1020**: 271-275. doi: <https://doi.org/10.17660/ActaHortic.2014.1020.39>.
- Schaumberg, G., and Gruppe, W. 1985. Growth and fruiting habit of *Prunus avium* cv. 'Hedelfinger' on clonal cherry hybrid rootstocks. *Acta Horticulturae* **169**: 227-234. doi: <https://doi.org/10.17660/ActaHortic.1985.169.31>.
- Sønsteby, A., and Heide, O. 2019. Temperature effects on growth and floral initiation in sweet cherry (*Prunus avium* L.). *Scientia Horticulturae* **257**: 108762. doi: <https://doi.org/10.1016/j.scienta.2019.108762>.
- Southwick, S., Shackel, K., Yeager, J., Asai, W., and Katakich, M. 1991. Over-tree sprinkling reduces abnormal shapes in 'Bing' sweet cherries. *California Agriculture* **45**(4): 24-26. Available from <https://calag.ucanr.edu/Archive/?article=ca.v045n04p24>.

Soysal, D., Doğan, D.E., Lizalo, A., Demirsoy, L., and Demirsoy, H. 2023. Rootstock affects the number of flowers in the floral bud in sweet cherries. *Erwerbs-Obstbau*. doi: <https://doi.org/10.1007/s10341-023-00852-5>.

Stanley, J. 2016. Factors affecting fruit set and fruit quality along branch units of different apricot cultivars. *New Zealand Journal of Crop and Horticultural Science* **44**(3): 171-191. doi: <https://doi.org/10.1080/01140671.2016.1161652>.

Tabakov, S., Kaymakanov, P., Yordanov, A., and Govedarov, G. 2015. Reproductive characteristics on two cherry cultivars, grafted on interstocks. *Agricultural Sciences* **7**(17): 79-86. Available from <https://www.cabdirect.org/cabdirect/FullTextPDF/2015/20153371468.pdf>.

Teng, Y., Tanabe, K., Tamura, F., and Itai, A. 1998. Effects of spur defoliation and girdling on fruit growth, fruit quality, and leaf and shoot carbohydrate levels on the spurs of different ages in 'Nijisseiki' pear. *Journal of the Japanese Society for Horticultural Science* **67**(5): 643-650. doi: <https://doi.org/10.2503/jjshs.67.643>.

Tersoglio, E., and Setien, N. 2016. Effect of Adara-M2624 combination and other seven rootstocks on canopy characteristics of two sweet cherry varieties. *AgriScientia* **33**(2): 113-125. doi: <https://doi.org/10.31047/1668.298x.v33.n2.16578>.

Topov, V. 2018. The influence of introduced rootstocks on the growth and development of young sweet cherry trees. Materials of the All-Ukrainian scientific and technical conference of TSATU students (dedicated to the 80th anniversary of the Zaporizhia region). TSATU, Melitopol Ukraine. p. 73. Available from <http://elar.tsatu.edu.ua/bitstream/123456789/6534/1/%d0%90%d0%a2%d0%95%20-77%d1%81%d1%82%d1%80-73.pdf>.

Usenik, V., Orazem, P., and Stampar, F. 2010. Low leaf to fruit ratio delays fruit maturity of 'Lapins' sweet cherry on Gisela 5. *Scientia Horticulturae* **126**(1): 33-36. doi: <https://doi.org/10.1016/j.scienta.2010.06.008>.

Vaszily, B. 2010. A study of processes active in regeneration of different sweet cherry varieties. *International Journal of Horticultural Science* **16**(1): 55-57. doi: <https://doi.org/10.31421/IJHS/16/1/864>.

Whiting, M., and Sallato, B. 2022. Intra-canopy variability in apple fruit quality is great. *Acta Horticulturae* **1346**: 821-828. doi: <https://doi.org/10.17660/ActaHortic.2022.1346.105>.

Whiting, M., Ophardt, D., and McPerson, J. 2006. Chemical blossom thinners vary in their effect on sweet cherry fruit set, yield, fruit quality, and crop value. *HortTechnology* **16**(1): 66-70. doi: <https://doi.org/10.21273/HORTTECH.16.1.0066>.

Yang, S., Mao, J., Zuo, C., Tian, F., Li, W., Dawuda, M., Ma, Z., Chen, B. 2019. Branch age and angle as crucial drivers of leaf photosynthetic performance and fruiting in high-density planting: A study case in spur-type apple "Vallee Spur" (*Malus domestica*). *Scientia Horticulturae* **246**: 898-906. doi: <https://doi.org/10.1016/j.scienta.2018.11.084>.