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THE GROWTH ACTIVITY AND PRODUCTIVITY OF APPLE TREES DEPENDING ON THE FORM OF THE CROWN AND THE TIME OF PRUNING

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ABSTRACT

The apple tree is the most common fruit crop in the temperate climate zone. Modern intensive fruit cultivation involves the use of new, highly productive cultivars and cultivation technologies, thanks to the creation of small crown shapes with an increased number of trees per hectare. Reducing planting patterns and creating more dense plantation systems can significantly improve their yields. However, the limiting factor that can reduce tree productivity and deteriorate fruit quality is the degree of crown illumination. Ensuring even access of sunlight to all parts of the crown is the main task in the formation and pruning trees. The study aimed to determine the effect of crown pruning at BBCH 0 (winter) and BBCH 74 (early summer) and various types of crown formation on the growth activity and productivity of 'Fuji' and 'Honeycrisp' apple trees. A significant decrease (20%) in the number of newly formed shoots in the form of the French axis crown compared to the ballerina and slender spindle crowns was found. However, their length and total growth were significantly higher. The formation of the ballerina crown (with the removal of overgrown wood in the 25 cm zone on the central conductor above the lower tier of semi-cross-branched branches) contributed to a decrease in shoot length and total growth. The introduction of crown pruning in the summer also improved crown illumination – shoot length decreased by 17% and total growth by 12%. Specific productivity per bole cross-section and total shoot length was the highest in ballerina crown trees, followed by trees with a slender spindle crown, and trees pruned in winter and summer.

Key words: apple tree, form of crown, ballerina, slender spindle, French axis, pruning time, specific productivity

INTRODUCTION

The productivity of garden crops depends on the amount of light energy intercepted. In single-row plantings of intensive apple orchards with the creation of a fruit wall, the maximum light interception is about 60%. According to Palmer et al. (1992), the relatively low level of light interception remains the main limitation for increasing the orchard's productivity. This limitation is determined by planning the direction of the rows and the shape of the crown (Tustin et al. 2022).

According to Tustin (2022), the solution to this problem in the further intensification of horticulture should be aimed at the use of small, narrow crowns, which can increase the biological potential of fruit trees as a result of better illumination of the middle of the fruit tree canopy. According to Breen et al. (2020), a high level of illumination inside the crown is the key to achieving optimal yield and high fruit quality. The main determining factors are the planting scheme, crown shape, and tree height (Lordan et al. 2018), which are closely correlated with the level of illumination (Musacchi & Serra 2018).

According to Grappadelli and Lakso (2007) and Jackson (1989), this can be achieved through high tree density and low-volume crown shapes. As a result, many different low-volume crown forms have been developed that expose most of the foliage to intense light. It allows the orchard to be adapted to robotic processes while increasing light interception to increase yields. Examples of such innovative

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systems are "Bibaum", "UFO", "Planar Cordon", and "Double-Guyot" (Bortolotti et al. 2022).

The formation and subsequent pruning of tree crowns ensure the creation of a specific crown architecture that facilitates its care and maximizes the absorption of solar energy by all its parts. Therefore, according to Reig et al. (2019), the choice of crown shape is crucial for increasing yields and, as a result, the profitability of the orchard. By properly selecting the shape of the crown, it is possible to obtain annual and even fruit yield throughout the crown (de Wit 2008; Melnyk 2012; Melnyk & Melekhova 2012).

The ratio of vegetative and generative processes determines the quantity and quality of the yield. They compete with each other and, according to studies by Balandier et al. (2000) and Mohammadi et al. (2013), fruit production can be optimized for moderate vegetative growth activity. After all, excessive tree growth vigor reduces the intensity of generative bud formation and fruit setting and can reduce the fruit quality (Ashraf & Ashraf 2014). According to Zhang et al. (2016), this depends on the crown's shape and the location of its structural elements in space.

Tree pruning significantly affects the crop load on trees (Robinson et al. 2016). In their research, Zamani et al. (2006) found that summer pruning is one of the most effective ways to control tree growth and stimulate the generative buds.

Crown pruning during the growth season inhibits vegetative growth (Kweon & Sagong 2022), and according to de Almeida and Fioravanço (2018) and Gościło (2013), increases the fruit yield in the following year. However, according to Bound and Summers (2001), summer pruning reduces the content of dry soluble substances in fruits.

Summer pruning is the primary agricultural measure that increases the penetration and distribution of light in the crown (Buler & Mika 2009). It has a positive effect on fruit size and quality. However, the timing, intensity of pruning, and fruit load must be taken into account (Wertheim 2005). Another positive effect of summer pruning is growth regulation (Platon & Zagrai 1997). Since summer pruning involves the removal of weak shoots and leaves with low photosynthetic activity and high respiration rate, it has a positive effect on the leaf-to-fruit ratio and carbohydrate distribution, thus regulating the yield load and improving fruit quality (Tahir et al. 2008). The study by Li et al. (2003a) shows that the potential impact of reduced crown photosynthesis after summer pruning depends on the balance of supply and demand for carbohydrates. In addition, crown transpiration decreases in proportion to the intensity of pruning (Li et al. 2003b).

As a result of pruning, the side branches are systematically replaced, but the lower branches that produce a large number of fruits remain constant. It can be a limiting factor in a spindle-shaped crown, as with the closure of the crowns of neighboring trees, these branches are quickly shaded, and the quality of the fruit deteriorates (Dallabetta et al. 2014). A partial increase in the productivity of these branches can be achieved by shortening annual growths (Mohammadi et al. 2013). Still, with sufficient illumination of the lower tier of branches, the quality of the fruit will improve.

The study aimed to determine the effect of pruning time and forming different crown shapes on the productivity of apple trees in an irrigated apple orchard in the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study of the formation type and timing of pruning of small-sized crowns of apple trees began in the spring of 2019 in the experimental garden of the Uman National University of Horticulture (48°46′06″N, 30°14′27″E). The orchard was planted in the spring of 2015 with medium-sized 'Fuji' and vigorous 'Honeycrisp' cultivars grafted onto a dwarf rootstock M.9 T337. The planting scheme was 4 × 1 m, and the soil type is black soil sod-podzolic. The system of soil maintenance in the inter-rows is sod-humus, herbicide steam in the near-stem strip, and the irrigation system is drip. The weather and climatic conditions during the experiment were typical for the region (Table 1).

Table 1. Average monthly weather conditions during the experiment (2019–2022 years)

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Rainfall (mm)	47	44	39	48	55	87	87	59	43	33	43	48
Air temperature (°C)	−5.7	−4.2	0.4	8.5	14.6	17.6	19	18.2	13.6	7.6	2.1	−2.4

Relative air humidity (%)	86	85	82	68	64	66	67	68	73	80	87	88

The effect of two variables was studied –crown shape and the pruning timing. The trees were pruned in two terms: in winter – BBCH 0 (scale by Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) and twice during the growing season: in winter and summer, after the June ovary shedding – II decade of June, BBCH 74, and crown type: slender spindle, ballerina (with the removal of overgrown wood on the central conductor, in the 25 cm zone above the tier of semi-complex branches) and French axis (Fig. 1).

Phytometric records were made according to generally accepted recommendations and research methods. According to Kondratenko and Bagel (1999), growth parameters were recorded at the end of the growing season. The bole diameter increase was recorded as the difference of values between adjacent years measured with a caliper at a bole height of 30 cm from the soil level. The length and number of annual shoots longer than 5 cm were taken after the end of growth from the annual ring to the top of the shoot growth cone. The total length of the shoots was calculated by multiplying the average length of the shoots by their total number on the tree.

Experimental design and data analysis

The factors were three crown shapes and two pruning times with four replications of five trees in replicates in plantations of two cultivars – 'Fuji' and 'Honeycrisp'. The placement of options is a randomized block design. The data are based on annual averages and standard deviation. All data were analyzed by two-way analysis of variance (ANOVA) using Statistica 10. Means were compared separately using Tukey's mean comparison test ($p = 0.05$) for each cultivar. The graphs show the average long-term values of the variables in the overall experiment and standard deviation. The direct correlation in the overall experiment was determined by comparing the average annual values.

RESULTS AND DISCUSSION

The intensity of lateral growth of apple trees 'Fuji' and 'Honeycrisp' cultivars during the experiment was significantly different, with a predominance in favor of the latter (Table 2). The introduction of various crown shapes and their pruning in winter and during the growing season also influenced the intensity of growth of the stem diameter.

In particular, as a result of winter pruning of the French axis crown of 'Honeycrisp' trees, the most intensive thickening of the stem was found up to 7.2 mm per year, which was almost twice as high as the value of the indicator as a result of double pruning of the ballerina crown of 'Fuji' trees (3.8 mm).

The activity of lateral growth of the bole (Fig. 2A) during four years of research did not differ significantly but significantly depended on the cultivar, with a 44% prevalence of 'Honeycrisp' over 'Fuji'.

More active lateral growth of the stem was promoted by the crown formation of the French axis, regardless of the term of pruning (6 mm). In comparison, the formation of the ballerina crown significantly slowed down this process, with an annual average of 5.1 mm. The crown formation of the slender spindle occupied an intermediate position. Pruning the crown of trees twice during the growing season (BBCH 0 and 74) contributed to a 10% slowdown in the intensity of stem thickening.

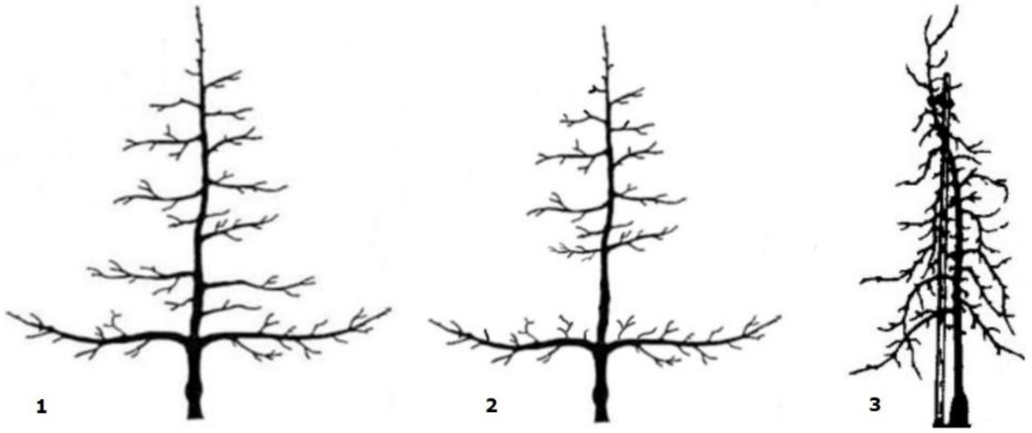

Figure 1. Crown formation: slender spindle (1), ballerina (2), and French axis (3)

Table 2. Parameters of vegetative growth of apple trees depending on the form of the crown and the term of pruning (averaged data for 2019–2022 years)

Crown form	Term of pruning	Stem diameter increase (mm)	Number of shoots (pcs. per tree)	Shoot length (cm)	Total shoot length (m per tree)
‘Fuji’					
Slender spindle	winter (control)	4.8 ± 0.1* ab	49 ± 3 ab	22.1 ± 1.8 c	10.6 ± 0.3 ab
	winter and summer	4.1 ± 0.1 cd	54 ± 5 a	16.0 ± 1.1 de	8.6 ± 0.8 bc
French axis	winter	5.2 ± 0.2 a	36 ± 3 c	28.8 ± 2.7 a	10.3 ± 0.8 ab
	winter and summer	4.6 ± 0.2 abc	41 ± 2 bc	27.2 ± 2.6 ab	11.0 ± 0.3 a
Ballerina	winter	4.4 ± 0.2 bcd	49 ± 3 ab	20.3 ± 1.3 bcd	9.9 ± 0.8 abc
	winter and summer	3.8 ± 0.2 d	54 ± 5 a	14.7 ± 0.7 e	7.9 ± 0.8 c
‘Honeycrisp’					
Slender spindle	winter (control)	6.5 ± 0.2 bc	45 ± 2 ab	28.8 ± 0.9 ab	12.8 ± 0.8 a
	winter and summer	6.1 ± 0.1 c	44 ± 2 ab	26.4 ± 0.8 b	11.3 ± 0.3 a
French axis	winter	7.2 ± 0.1 a	39 ± 2 b	32.1 ± 2.0 a	12.4 ± 0.3 a
	winter and summer	6.9 ± 0.1 ab	39 ± 2 b	29.3 ± 1.4 ab	11.4 ± 0.4 a
Ballerina	winter	6.5 ± 0.1 bc	43 ± 1 ab	25.0 ± 1.6 b	10.7 ± 0.7 ab
	winter and summer	5.8 ± 0.2 c	50 ± 5 a	17.3 ± 0.8 c	8.6 ± 1.0 b

*The average values (mean ± SD) of indicators marked with the same letter do not differ according to the Tukey test (p = 0.05); The analysis was performed for each cultivar separately

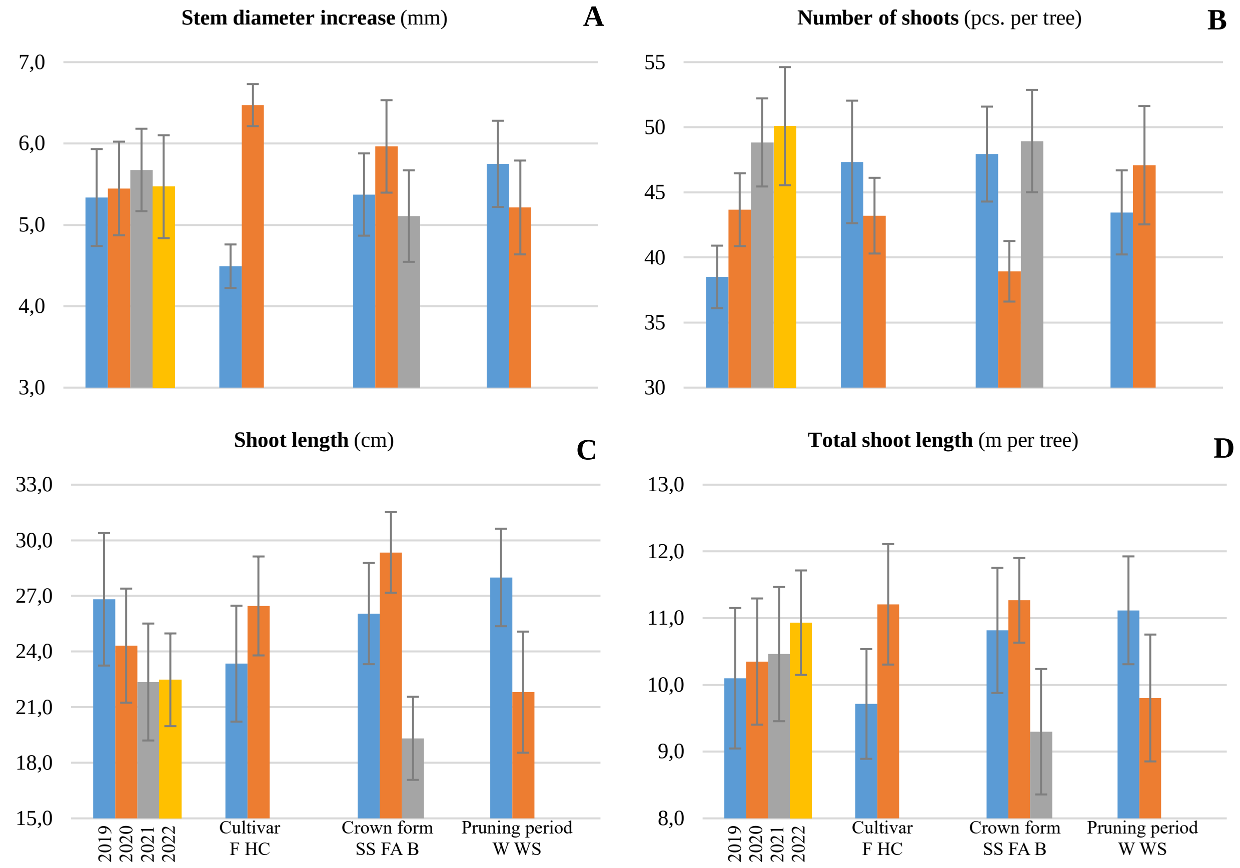

Figure 2. Average growth of stem diameter (A), number of shoots (B), shoot length (C) and total shoot length (D) of apple trees in 2019–2022 depending on the crown shape and pruning time

Note: cultivars: ‘Fuji’ (F), ‘Honeycrisp’ (HC); crown form: slender spindle (SS), French axis (FA), ballerina (B); pruning period: winter (W), winter and summer (WS)

The correlation between the increase in bole diameter and shoot length (r = +0.74) and the inverse relationship with the number of shoots (r = −0.66) was found.

The experiment revealed a significant effect of the studied agricultural practices on the growth activity of apple trees. In general, the most active shoot formation, in response to the introduced pruning methods and timing, was found in ‘Fuji’ trees with two-time pruning of the crown of the slender spindle and ballerina – 54 newly formed shoots per tree. For comparison, winter pruning of the French axis crown resulted in the formation of only 36 shoots (Table 2). According to the ANOVA, during the experiment and the annual consistent growth and development of plants, there was a tendency to gradually increase the number of newly formed shoots by 11–12% compared to the previous season (Fig. 2B). The shoot-forming ability of ‘Fuji’ trees significantly exceeded the value of ‘Honeycrisp’ – 47 pcs. per tree vs. 43 pcs. per tree, respectively. The formation and subsequent pruning of the French axis crown contributed to a significant weakening of the growth activity of the studied trees. They provided a quarter reduction in the number of annual shoots compared to other crown forms that were studied. There was no significant difference in the indicator’s value in the variants with the formation of the crown of a slender spindle and ballerina. However, a 6% increase in the number of shoots was achieved with tree crown pruning twice during the growing season, in winter and summer, in the plantations of both cultivars.

A strong correlation between the number of shoots was found with the total leaf area (r = +0.86), tree fruit load (r = +0.81), and yield (r = +0.82) and an inverse relationship with shoot length (r = −0.93).

An important qualitative characteristic of the crown architecture of fruit trees is the length of annual shoots. The formation of the crown by the French axis and its subsequent pruning during the dormant period activated the growth force of shoots. It provided their greatest length in both studied cultivars. On the other hand, two-time pruning of trees in the shape of the ballerina crown significantly reduced the growth force of the plantations, forming shoots of 14.7–17.3 cm (Table 2). During the research period, with the annual increase in the number of shoots, their length decreased (Fig. 2C) from an average value of 26.8 cm at the beginning of the experiment to 22.5 cm at the time of its completion (16%). The peculiarities of ‘Honeycrisp’ provided a 26% predominance of shoot length compared to the corresponding indicator of ‘Fuji’. Also, the increase in shoot growth force was facilitated by introducing the French axis crown shape. In the experiment, it amounted to an average of 29.3 cm, one quarter more than that obtained by slender spindle formation and twice as much as ballerina crown formation, which recorded the lowest values of the studied indicator. Also, the repeated pruning of trees in the early summer period contributed to a significant restraint of shoot growth. Thus, two-time pruning of trees in winter and early summer decreased the length of shoots by 4.5 cm (17%).

The correlation between shoot length and total shoot length (r = +0.92) and the number of leaves was found (r = +0.92), and inverse relationships with crown volume, tree fruit load, yield (r = −0.81), and number of fruits (r = −0.87) were found.

The total shoot length (Fig. 2D) in the experiment increased with the age of the orchards and significantly depended on the cultivar. In the ‘Honeycrisp’ trees, the indicator’s value was 15% higher than the ‘Fuji’. As a result of the formation of the French axis crown and the activation of growth processes, the total shoot length increased to 11.3 $m \cdot d^{-1}$. In contrast, with an increase in yield and a decrease in shoot length, the ballerina crowns’ total shoot length decreased to 9.3 m per tree. Total shoot length was correlated with shoot length (r = +0.92) and yield (r = −0.63).

Specific productivity per cross-sectional area of the stem prevailed in the plantations of the ‘Fuji’, with the maximum value of the indicator as a result of double pruning of the ballerina crown shape – 0.68 $kg \cdot cm^{-2}$. As a result of a decrease in the level of yield and activation of growth processes of trees of the ‘Honeycrisp’ (Table 3), when forming the French axis crown and its subsequent pruning in winter, the lowest value of this indicator was obtained at the level of 0.17 $kg \cdot cm^{-2}$. In general, in the experiment, the value of specific productivity per cross-sectional area of the bole during the research period decreased due to the activation of growth processes in older trees (Fig. 3A). The increase in specific productivity per bole cross-sectional area contributed to an increase in the yield level of the characteristic cultivar during the formation of the ballerina crown, as a result of double pruning of trees.

The value of specific productivity on the total shoot length among the research variants significantly prevailed due to the double pruning of the ballerina crown of both studied cultivars (Table 3). According to the ANOVA, the trees of the 'Honeycrisp' were characterized by more active vegetative growth, which resulted in a 15% decrease in the values of the indicator (Fig. 3B). However, as a result of the predominance of fruiting and overgrowth processes, a significant increase in specific productivity per total shoot length was obtained in trees with a ballerina crown, which was 127% higher than the value of the French axis crown and 44% higher than the slender spindle crown. Also, on average, the increase in specific productivity by the total shoot length by 0.4 kg·m^{-1} was facilitated by the implementation of two-time pruning of trees in winter and summer. The correlation of specific productivity on the total shoot length with the level of yield (r = 0.92), the number of fruits (r = 0.84), and the inverse with the total shoot length (r = −0.86) was obtained.

Table 3. Specific productivity of apple trees depending on the shape of the crown and the term of pruning (averaged data for 2019–2022 years)

Crown form	Term of pruning	Specific productivity per bole cross-sectional area (kg·cm^{-2})	Specific productivity per total shoot length (kg·m^{-1})
		'Fuji'	
Slender spindle	winter (control)	0.40 ± 0.03 cd	0.95 ± 0.06 c
	winter and summer	0.51 ± 0.04 bc	1.44 ± 0.13 b
French axis	winter	0.26 ± 0.02 e	0.72 ± 0.10 c
	winter and summer	0.33 ± 0.01 de	0.79 ± 0.12 c
Ballerina	winter	0.57 ± 0.05 ab	1.42 ± 0.09 b
	winter and summer	0.68 ± 0.04 a	2.03 ± 0.19 a
		'Honeycrisp'	
Slender spindle	winter	0.31 ± 0.03 bc	0.84 ± 0.05 bc
	winter and summer	0.40 ± 0.03 ab	1.18 ± 0.04 ab
French axis	winter	0.17 ± 0.02 d	0.54 ± 0.08 c
	winter and summer	0.24 ± 0.01 cd	0.75 ± 0.08 bc
Ballerina	winter	0.35 ± 0.03 ab	1.13 ± 0.07 b
	winter and summer	0.43 ± 0.05 a	1.78 ± 0.24 a

The average values (mean ± SD) of indicators marked with the same letter do not differ according to the Tukey test (p = 0.05); The analysis was performed for each cultivar separately

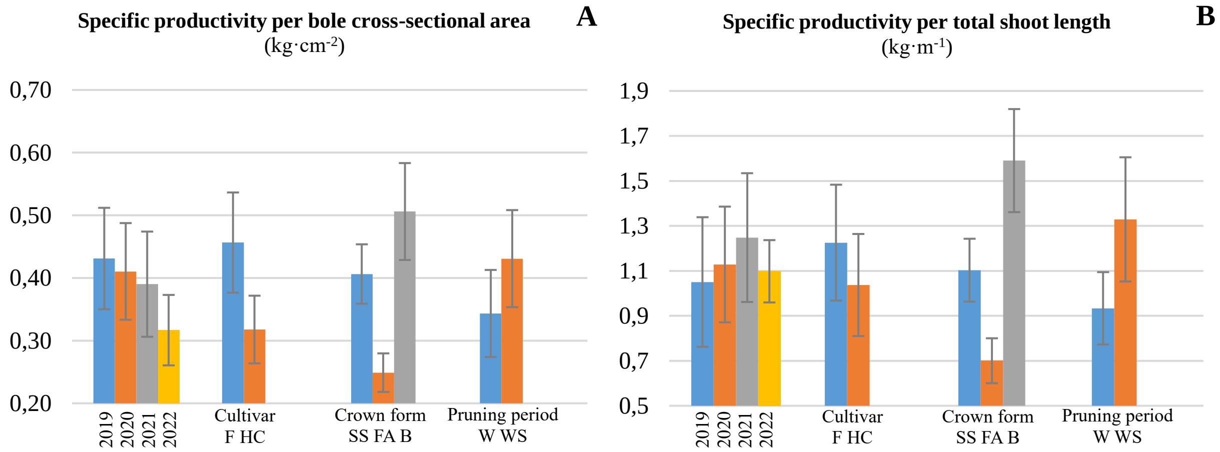

Figure. 3. Averaged data of specific productivity per cross-sectional area of the stem (A) and specific productivity per total shoot length (B) of apple trees for 2019–2022 depending on the shape of the crown and the term of pruning

Note: see Fig. 1

The results of the study indicate a significant weakening of the vegetative growth of the crown as a result of summer pruning, which confirms the research by Golovatyy (2012) and Chaploutskyi et al. (2023). A similar dependence was obtained in the studies of Chaploutskyy and Melnik (2015) on 'Golden Delicious' and 'Jonagold' cultivars, according to which pruning of the crowns in the early summer period causes an 11% decrease in the girth of the stem, the number of shoots by 15, shoot length by 12, and by 24% of their total length. Similar results were obtained by Melnik and Kravtsova (2019) with the 'Gala' and 'Jonagold' cultivars. Mészáros et al. (2017) reported increased specific productivity per stem cross-sectional area and total shoot length as a result of summer pruning.

Further research can involve expanding the range of cultivars, timing of crown pruning, and determining the optimal planting scheme, which will ultimately ensure higher plantation productivity.

CONCLUSIONS

The study showed a significant impact of pruning on the growth and productivity of apple trees. Forming the crown of the French axis increases the stem diameter by 11%, but when this agricultural measure is performed in the summer, the stem thickening is slowed down.

The number of shoots in the French axis crown was 20% smaller compared to the ballerina and slender spindle, but their length and total growth were significantly greater. The formation of the ballerina crown contributed to reducing the shoot length, which improved the crown illumination. Pruning in summer decreases the shoot length by 17% and their total growth by 12%.

The ballerina crown provided the maximum value of specific productivity per stem cross-sectional area and total shoot length. Summer pruning also facilitates a positive specific productivity effect.

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