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THINNING STRATEGIES FOR THE POSSIBLE ROBOTIZATION OF COLUMNAR APPLE ORCHARDS

Luděk Laňar[1], Klára Scháňková[1], Lukáš Nývlt[1]

[1] Department of Technology, Research and Breeding Institute of Pomology Holovousy Ltd., Holovousy 129, 508 01 Holovousy, Czech Republic

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Abstract

Columnar apple varieties, which have a genetically determined slender growth pattern, are seen as a possible solution for simplifying and unifying the structure of orchard canopies. This makes them well-suited for the upcoming robotization. However, columnar varieties usually have very strong tendency to alternate bearing. We investigated the possible thinning strategies for columnar apples to avoid this tendency, maintain high production, and facilitate future robotization. Several treatments were designed in young orchard of the columnar apple variety ‘Redspring’/M26. Three different main strategies that could be partly or fully carried out by robots were tested. First, we only removed flower clusters. Second, flower clusters removal was combined with subsequent fruitlet thinning leaving only the king fruit. The third strategy involved removing flower clusters, followed by removing fruitlets to reach the target crop load. In all strategies, the thinning level was set at 2, 3, or 4 units per 10 cm of central axis height. The results indicate that all strategies leading to a crop load 2–2.5 fruits per 10 cm of central axis height seems ideal for maintaining high, quality, and stable production. A strategy that thins to 2 units of flower clusters per 10 cm height without reducing fruitlets could be used as a first step in the robotic management of the crop load of columnar apples.

Keywords: crop load, fruit tree, alternation, flower cluster, robotic management, *Malus* sp., return bloom, yield

INTRODUCTION

Crop load management is essential for profitable apple production. Growers aim to consistently produce high yields of fruit that are an optimal size and quality for market. A variety of practices is available. In certain conditions, techniques to promote fruit set are employed (Vercammen *et al.*, 2016), though flower and fruitlet thinning are the most commonly used crop load operations. Thinning methods include mechanical, manual, and chemical approaches, each with specific advantages and limitations. Extensive research has already been conducted (Verma *et al.*, 2023). However, most crop load studies have focused on standard commercial cultivars with conventional growth habits (Lespinasse, 1992), while columnar apple varieties have received limited attention (Iwanami *et al.*, 2019; Baba *et al.*, 2020). These cultivars exhibit genetically determined columnar growth with strong apical dominance, and dedicated breeding programs focus on them. Despite initial enthusiasm, interest in columnar types has declined due to challenges such as lower fruit quality, high establishment costs, slow canopy development, and other limitations. A significant constraint is their pronounced tendency toward biennial bearing (Blažek and Křelinová, 2011; Vávra *et al.*, 2017). Nevertheless, columnar apple cultivars remain promising, particularly as candidates for two-dimensional (2D) canopy systems. Interest in these systems has been renewed, driven by the potential for higher yields per unit area (Tustin *et al.*, 2018) and the need for simplified canopy structures that are suitable for robotic or automated orchard management (Zhang *et al*., 2019). The narrow, planar architecture of columnar trees may facilitate the development of structured wall systems, enabling more efficient automation. Additionally, ongoing breeding efforts are producing columnar cultivars with improved fruit quality, storability, and other favourable traits (Vávra *et al.*, 2021; Maryška *et al*., under review). As an initial step in implementing these varieties for automated production, we focused on thinning strategies. Our goal was to identify the appropriate crop load management strategy to ensure stable, high-quality yields and support the future automation or robotization of orchard operations.

MATERIALS AND METHODS

The trial was conducted in an apple orchard (*Malus domestica* Borkh.) containing the columnar cultivar 'Redspring' grafted onto M26 rootstock and planted in the spring 2021. Two-year-old slightly branched trees were used for planting. The orchard is located at the Research and Breeding Institute of Pomology Holovousy Ltd., Czech Republic (50.370372° N, 15.569633° E). The average annual temperature is 10.4 °C and the average annual precipitation totals 647.1 mm (averages from 2016–2024). Tree spacing is 2.5 × 0.5 m (8,000 trees/ha). The site has a neutral pH, is moderately fertile, and has a loamy soil. The orchard is drip irrigated. The trees were trained and pruned as super spindles, with side structures (branches) on the central axis that did not exceed 15 cm in length after pruning. These structures, primarily spurs and brindles, were spaced irregularly, typically 2–6 per 10 cm of the central axis. Standard integrated production practices were used for orchard maintenance. In the first year, all fruitlets were removed to promote rooting, vegetative growth, and uniform flower initiation. Starting in the second year, various crop load management treatments were applied, as detailed in Tab. I. These treatments included hand thinning of flower clusters (FC), hand thinning of fruitlets (H), and hand thinning of fruitlets on king fruit in each developing fruit cluster (HK) either alone or in combination. Target crop loads were adjusted to 2, 3, or 4 units (flower clusters or fruitlets) per 10 cm of the central axis excluding one-year-old terminal wood. An untreated control (C) was also included. Flower clusters were thinned at the beginning of bloom, and fruitlet thinning occurred by the end of the natural June drop, if applied. To support terminal growth, flower clusters from one-year-old wood of the terminal shoot were all removed in every year. The measured parameters included the length of the central axis (excluding one-year-old wood), the number of flower clusters on the central axis (excluding one year-old wood), the number of fruits in three sizes (less than 60 mm, 60–70 mm, and greater than 70 mm), and the fruit weight per tree. Crop load (number of fruits per 10 cm of central axis), yield efficiency (kg per 10 cm of central axis), and yield in tons per hectare were calculated from the gathered data. The biennial bearing index was calculated by equation adopted from Hoblyn *et al.* (1936) from the flower set of the three year period from 2022 to 2024.

Equation of biennial bearing index (BBI) where n = years of observation and Y_i = flower set in each year:

$$BBI = \frac{1}{n-1}\sum_{i=1}^{n-1}\frac{Y_{i+1} - Y_i}{Y_{i+1} + Y_i}\,.$$

Production parameters were only assessed for 2022 and 2023 because a strong late frost damaged almost all the fruit set in 2024. Only the flower set and the length of the central axis were assessed in that year. Each treatment included three replicates of three trees (9 trees per treatment). The data were analysed in RStudio (R Core Team, 2025) using the nonparametric Kruskal-Wallis test. Treatment differences were evaluated using the Wilcoxon-Mann-Whitney test.

I: *Overview of treatments*

Treatment abbreviation	Treatment applied
C	Control, no thinning.
C+HK	No thinning of the flower clusters, only hand thinning of the fruitlets on the king fruit in each developing fruit cluster.
FC2, FC3, FC4	Only reduction of the flower clusters to the load of 2, 3, or 4 flower clusters per 10 cm height of the central axis, with no additional hand thinning of fruitlets.
FC2+HK, FC3+HK, FC4+HK	Reduction in the number of flower clusters to 2, 3, or 4 flower clusters per 10 cm height of the central axis with additional thinning of the fruitlets by hand, leaving only the king fruit in each developing fruitlet cluster.
FC2+H2, FC3+H3, FC4+H4	Reduction in the flower clusters to a load of 2, 3, or 4 flower clusters per 10 cm height of the central axis, with additional hand thinning of the fruitlets to leave 2, 3, or 4 fruitlets per 10 cm of the central axis height.

RESULTS

Growth

Although there were no significant differences in the length of the central axis among the treatments in any of the three assessed years (data not shown), the trend of slightly higher growth in the strongly thinned treatments was noticeable. New terminal growth was approximately 10 and 30 cm in 2022 and 2023, respectively.

Alternation

The flower set for each year, as well as the alternation expressed by the biennial bearing index (BBI) are shown in Tab. II. Stronger alternation, with a BBI greater than 0.6, was recorded at FC4, FC3, FC3+H3, and FC4+H4. Lower alternation, with a BBI below 0.3, was recorded at FC2+H2, FC3+HK, FC2+HK, and C.

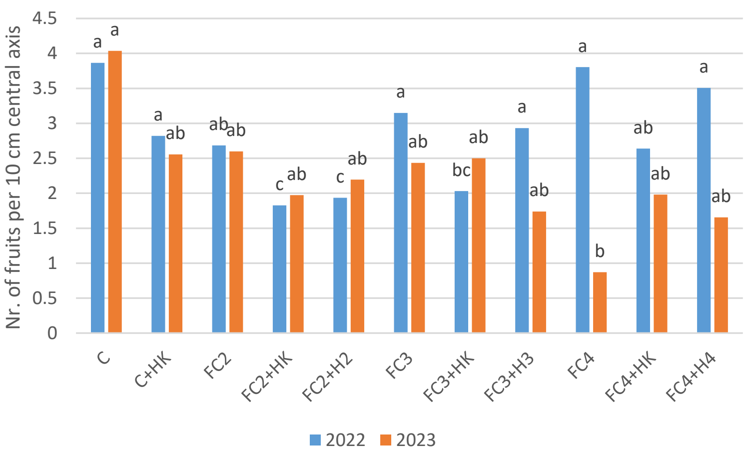
Crop Load

Crop load expressed by the number of fruits per 10 cm of the central axis is depicted in Fig. 1 for the years 2022 and 2023. In 2022, a higher crop load was recorded for treatments C, C+HK, FC3, FC3+H3, FC4, FC4+H4, while a lower crop load was recorded for treatments FC2+HK, and FC2+H2. In 2023, the highest crop load was recorded for treatment C, and the lowest was recorded for treatment FC4. A crop load difference of less than 0.3 between the first and second years was recorded for treatments C, C+HK, FC2, FC2+HK, and FC2+H2. A difference greater than 1.0 between the first and second year was recorded for the FC3+H3, FC4+H4, and FC4 treatments.

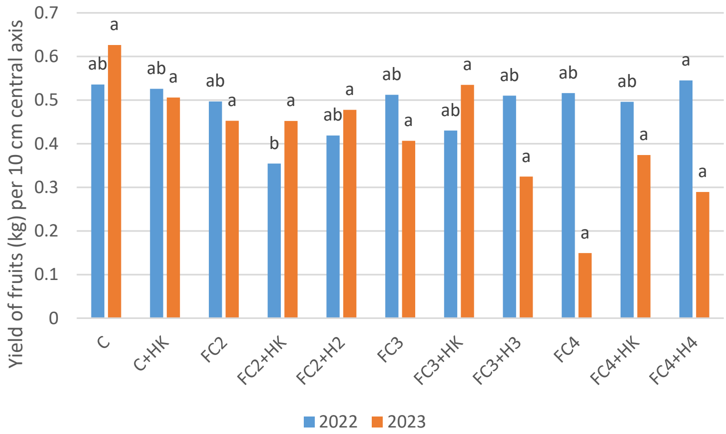
II: *Average number of flower clusters per tree before thinning and the biennial bearing index (BBI) for each treatment*

Treatment	2022	2023	2024	BBI
C	24.6 a	22.1 abc	62.7 b	**0.266**
C+HK	32.1 a	25.0 abc	82.0 ab	0.329
FC2	43.6 a	20.7 abc	79.6 ab	0.472
FC2+HK	40.1 a	34.2 ab	88.3 ab	**0.261**
FC2+H2	34.1 a	39.0 a	82.8 ab	**0.213**
FC3	43.5 a	10.0 c	77.8 ab	0.699
FC3+HK	42.1 a	35.9 a	86.7 ab	**0.247**
FC3+H3	45.0 a	11.9 bc	92.2 a	0.677
FC4	48.0 a	5.3 c	86.0 ab	0.843
FC4+HK	46.6 a	21.9 abc	79.3 ab	0.464
FC4+H4	45.5 a	12.6 bc	84.1 ab	0.653

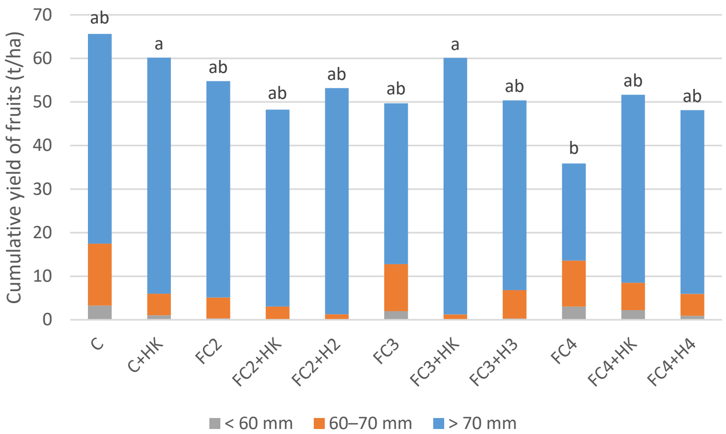
Different letters indicate significant differences for each year separately at α ≤ 0.05 according to the Wilcoxon-Mann-Whitney test.



1: *Average number of harvested fruits per 10 cm of the central axis*
Different letters indicate significant differences for each year separately at α ≤ 0.05 according to the Wilcoxon-Mann-Whitney test.



2: *Average yield in kilograms per 10 cm of the central axis in 2022 and 2023*
Different letters indicate significant differences for each year separately at α ≤ 0.05 according to the Wilcoxon-Mann-Whitney test.



3: *Average cumulative yield in each treatment from 2022 and 2023*
Different letters indicate significant differences in the cumulative yield of fruit size larger than 70 mm at α ≤ 0.05 according to the Wilcoxon-Mann-Whitney test.

Yield Efficiency

Fig. 2 shows yield efficiency expressed by the yield (weight) of fruits per 10 cm of the central axis. In 2022, the highest yield efficiency was recorded for treatment FC4+H4, and the lowest was recorded for treatment FC2+HK. In 2023, the treatments showed different values, though they were not statistically significant. The differences in yield efficiency between the first and second years were greater than 0.1 for the following treatments: FC3, FC3+HK, FC3+H3, FC4, FC4+HK, and FC4+H4.

Yield and Quality

Fig. 3 depicts the cumulative yield from 2 years 2022 and 2023. It shows the ratio of different fruit sizes to the total yield. Significant differences were observed in the main marketable size above 70 mm. A higher yield of fruits larger than 70 mm was recorded at FC3+HK and C+HK. In contrast, a lower yield was recorded at FC4. Treatments C, FC3 and FC4 had higher proportion of the fruits smaller than 70 mm.

DISCUSSION

Although we did not record a significant difference in the growth of the terminal shoot, we expect, that in following years, the difference in growth based on the crop load will become significant, and that intensely thinned trees will reach their final height and possibly their maximum yield sooner. 'Redspring' is a columnar variety with medium terminal growth (Vávra *et al.*, 2021). This means it has the disadvantage of some columnar varieties, which have relatively slow canopy development. However, there are other promising columnar varieties with faster terminal growth (Zelený, 2025), which offset this disadvantage. These varieties should be prioritized in the future when introducing them to common cultivation.

The large differences in the biennial bearing index demonstrate the strong effect of the applied treatments on the return of bloom and confirm the strong tendency of the columnar varieties to exhibit biennial bearing (Blažek and Křelinová, 2011; Vávra *et al.*, 2017). High alternation was observed in treatments with a high crop load and only flower cluster thinning FC4 and FC3, as well as in treatments with a high crop load where flower cluster thinning was followed by fruitlet thinning at high set levels FC4+H4 and FC3+H3. This indicates that a load of 3 fruits per 10 cm or higher is too high to achieve stable flower set. On the other hand, the treatments with more intense, two step thinning logically showed low alternation. Surprisingly, low alternation was also recorded for the control treatment C and C+HK. We attribute this to the low initial flower set of trees in these treatments in 2022, which impacted subsequent years. Had the initial flower set of C and C+HK been higher, we would have expected much higher alternation, similar to that of FC4. Treatment FC4 had a higher initial flower set and a high load, even after flower cluster thinning and fruitlet thinning in 2022. For this reason, we consider FC4 to be the treatment that best simulates the behaviour of the trees without any thinning. We expect the alternation to increase at C and C+HK in the coming years of continued research and for it to exhibit the natural behaviour of this columnar variety. Nevertheless, when considering these initial results, it is important to keep the above in mind and interpret the results of C and C+HK with caution.

Examining the results of crop load, expressed as the number of fruits per 10 cm of the central axis, reveals that in the first year, the results were highly and logically dependent on the applied treatment. However, in the second year, the results were influenced by both the applied treatment and flower set from the previous year. Treatments with a low biennial bearing index generally had a more stable crop load from one year to the next, and vice versa. The treatments FC3, FC3+H3, FC4, FC4+HK and FC+H4 led to a substantial decrease in crop load in the second year (more than 0.5 fruits per 10 cm). These treatments have a higher target crop load, which is too high to maintain stability, so it is expected that the fluctuation in crop load for these treatments will continue in the following years. This confirms again that a crop load higher than 3 fruits per 10 cm is too high for stable production. On the other hand, crop loads between 2 and 2.5 per 10 cm seem ideal for maintaining stable production. This is confirmed by the results of yield efficiency, where these treatments had stable numbers and sometimes even increased. This suggests that a yield efficiency of 0.4 to 0.5 kg per 10 cm may be the maximum for stable production. The yield efficiency and yield results show that treatments with more intense thinning and a lower number of fruits were able to equalise the yields to some extent by increasing fruit growth. This is a natural, expected response and one of the objectives of crop load management (Verma *et al.*, 2023). A higher ratio of fruits smaller than 70 mm was observed in the C, FC3 and FC4 treatments, which involved either no thinning or only flower cluster thinning at higher loads. However, the treatment FC2, which also involved only flower cluster thinning but on a lower load, had quite small and acceptable ratio of smaller fruits.

Based on the results, we consider the FC2, FC2+HK, FC2+H2, FC3+HK treatments promising and in line with our objective of achieving stable, high, and quality production. However, all of these treatments except the FC2 treatment require thinning of the fruitlets, which is a certain disadvantage if we consider the possibility of robotizing the thinning operation. The second step, thinning the fruitlets or flowers in clusters, has been studied and developed (Zhang *et al.,* 2019; Karkee, 2024), but it is expected to be difficult time-consuming to implement. Therefore, the treatment FC2 seems to comply with all requirements regarding productivity and the possibility of easily implementing robotic thinning based solely on reducing whole flower clusters. These results more or less confirm the findings and assumptions from the first year (Laňar *et al.*, 2024).

When considering the thinning strategies, one option is to utilize chemical thinning. However, due to the many variables that affect its efficiency and control (Robinson *et al.,* 2021; Verma *et al.*, 2023), we have chosen fully non-chemical and potentially precise thinning strategies. It allowed us exact and stable quantification of crop load. Furthermore, we expect that thinning strategies based on the number of flowers or fruitlets per 10 cm of the vertical axis, rather than the trunk or branch cross-sectional area (Iwanami *et al.*, 2019; Baba *et al.*, 2020), will be more precise and easier for implementation of robotic systems. If the flower cluster thinning method is launched (Robinson *et al.,* 2021), the FC2-based thinning strategy can potentially be used. If a method for thinning of individual flowers or fruit become commercially available (Karkee, 2024), using more precise strategies could further maximise well-marketable production. Overall, the growth of columnar trees and how they are pruned, with side structures no longer than 15 cm, should allow for the easier introduction of other robotic operations and automatic assessments. Depending on the availability and type of robotic thinning, the use of chemical thinning in combination with it can be considered potentially useful and practical. However, research on how to optimally combine them will be necessary.

The yield results of treatment FC2 indicate that, with a projected final height of 3 m and an average yield efficiency 0.45 kg per 10 cm of the central axis, a yield around 13.5 kg per tree is possible. With 8,000 trees/ha, the potentially stable yield is about 100 t/ha which is quite high for the climatic conditions in Central Europe. However, the high number of trees per hectare could be problematic due to the high establishment cost. This disadvantage could be solved by the using bi-axis or multi-axis trees (Tustin *et al.*, 2018), which is the next step toward more profitable production.

This is also the subject of our recently started parallel research. Not all columnar varieties are suitable for multi-axis trees, but our preliminary findings suggest that for varieties with stronger terminal growth are feasible and could lead to more profitable production. Furthermore, multi-axis trees allow for even more axis per hectare, which could facilitate sustainable intensification. It is necessary to mention that, formerly, these varieties were also considered suitable for low-intensity management plantations with low demands on pruning, support construction, etc. However, our research focuses on the highly precise cultivation of columnar apple trees with the goal of maximizing high-quality table fruit. Our results show the expected behaviour with lower fluctuation and higher fruit quality with intensely thinned treatments, and vice versa. Despite the three-year long study including a year with severe frost damage, it is possible to determine the optimal crop load strategies with high probability, ensuring stable and high production of quality fruit. Optimal crop loads for other columnar varieties should be determined. There will be differences in the limits, but the results will also depend on the type of training, pruning, the number of trees or axis per hectare, and climatic conditions. We consider columnar apple varieties to be a promising component of future automation-friendly, highly productive, automated orchards that are easy to manage, and we consider the obtained results to be a good foundation for further work in this area.

CONCLUSION

The main goal of the research, which was to find treatments with low alternation and high, good-quality production, was achieved through multiple treatments. However, only the FC2 treatment is promising for the easy implementation of robotic thinning. Only the columnar varieties with good quality fruit and with good architectural characteristics will be suitable for efficient, profitable cultivation with the potential for automation and robotization. It is necessary to prepare for the upcoming robotization and we hope that our research will facilitate its implementation and enhance growers' readiness.

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Contact information

Luděk Laňar: ludek.lanar@vsuo.cz, https://orcid.org/0000-0002-5401-6919 (corresponding author)
Klára Scháňková: klara.schankova@vsuo.cz, https://orcid.org/0000-0003-3398-4432
Lukáš Nývlt: lukas.nyvlt@vsuo.cz, https://orcid.org/0000-0002-4732-5844