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Effects of Runner Removal and Partial Defoliation on the Growth and Yield Performance of 'Favori' Everbearing Strawberry Plants

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Abstract: It is not known to what degree growth and fruit yield are source-limited in everbearing strawberry plants. The growth and yield performance effect of bi-weekly removal of all runners and/or one or two leaves during the cropping season of tunnel-grown 'Favori' everbearing strawberry plants was determined. Plants were grown on a table-top system in an open plastic tunnel under natural light conditions in Norway from May to October. Removal of runners and leaves was bi-weekly from 5 June until 25 September. Fruits were harvested from 5 July to 7 October. Bi-weekly runner removal increased total and marketable yield and number and size of fruits, while increasing leaf thinning had the opposite effects. However, none of the treatments affected the fruit number and yield of the first fruiting flush. The treatments did not affect realization of the yield potential of the plants at planting, whereas the continued floral initiation and fruit growth were enhanced by runner removal. Increasing leaf thinning had the opposite effects. Both floral initiation and fruit growth in heavily flowering and fruiting everbearing strawberry are source-limited owing to the high fruit/leaf ratio of such plants.

Keywords: fruit yield; leaf thinning; plant growth; runner removal; source limitation

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1. Introduction

Source–sink relations play a fundamental role in the regulation of vegetative growth and flower and fruit development in berry crops [1,2]. In the plant, a "source" can be defined as a photosynthesizing tissue or organ with net export of carbon skeletons, typically comprising all kinds of green leaves, while a "sink" can be defined as a heterotrophic tissue or organ, which is dependent on net import of photosynthetic compounds for its development. Typical examples of sinks are fruits > flowers > roots > shoots > leaves, in that order of strength hierarchy. During ontogeny, some of these organs may change from sinks to sources over time [2]. This means that, in berry crops in general, the fruit growth regulatory source–sink relationship is mainly determined by the fruit/leaf ratio of the plant. Accordingly, plant manipulations to alter this ratio have the potential to be used as a means to modify plant and crop yield.

In strawberry, the relationship is complicated by the presence of runners, which are known as strong sinks for leaf assimilates, water, and nutrients in competition with developing flowers and fruits [3,4]. However, the yield effect of de-runnering and other leaf canopy manipulations have varied considerably between cultivars, production systems, and with varying time and duration of application, for example, [5–7].

In an experiment with the short day (SD) cultivar 'Toyonoka' grown in an annual subtropical winter production system in Taiwan, runner removal increased the fruit number and yield, whereas crown and aboveground plant weight, and in particular growth and dry weight of roots decreased [7]. Canopy reduction by leaf thinning had the opposite yield effect [7]. In a similar production system in Colombia with the everbearing (EB) cv. 'Chandler', the removal of one or two leaflets on all leaves as they emerged was used to attain 38 and 67% reduction in leaf area, respectively, compared with control plants [8]. Such leaf area reductions dramatically reduced the fruit size, yield, and quality (soluble solids, pH, and so on). Leaf area reduction beyond 38% produced fruits that did not even meet marketing criteria.

Similar results were obtained with varying severity of runner removal in the EB cultivars 'Albion' and 'Seascape'. Spring planted plants of both of these cultivars were grown in a modified hill system at two growing sites in Ontario, Canada [9]. Runner removal (once, three times, and weekly for two months) increased total and marketable yields in the 'Albion' cultivar at both sites in the planting year, while few effects were observed in the second year. At the cooler climate site, both 'Albion' and 'Seascape' produced larger yields in the planting year with weekly runner removal, but not with less frequent removal. At the warmer site, total yield of 'Albion', but not 'Seascape', was reduced by 30% when runners were not removed. Plant dry weight and number of crowns increased with increasing frequency of runner removal [9]. Plant spraying with prohexadione-calcium, a chemical that blocks the biosynthesis of active gibberellins in plants, also strongly suppressed runner development and increased fruit yield in summer-planted 'Honeoye' SD strawberry grown in a plasticulture system in Maine, USA [4]. Both runner suppression in the planting year and yield increase in the following season were strongly enhanced with increasing rates and application numbers and were in most cases more effective than removal of runners by hand. However, the plant dry weights were also reduced by prohexadione-calcium, but only at the two highest rates and frequencies of application.

In Europe, the use of everbearing strawberry cultivars has greatly increased in importance and popularity since cultivars with adequate fruit taste and quality have been introduced on the market. They have been particularly popular for spring planting and annual cropping of ready-to-flower so-called Tray and Mini Tray plants under field conditions and on table-top production systems in high tunnels [10,11]. This is an intensive and high-cost production system that requires high yields of quality fruits to be profitable. An undesirable characteristic of the production system is, however, that it does not give continuous fruit production during the cropping season, but typically has a skip in fruit production after the first fruit flush. This characteristic may be explained by an increased competition of resources from leaves/runners. To achieve a more continuous fruit production, various measures have been tried, e.g., [11]. Here, we report the results of an experiment conducted in a tunnel/table-top system in South-East Norway. The main objective was to study the physiological sink–source effects of leaf canopy manipulation by removal of runners and/or leaves, and in particular, to explore the possibility of continuous and increased fruit yield by removal of runners in such a high-cost production system.

2. Materials and Methods

2.1. Plant Material and Cultivation

'Favori' plants of 'Mini Tray' standard were purchased from Flevoplant B.V. (Ens, The Netherlands) in early May 2019 and transplanted into 50 cm long table-top containers with 8 L capacity (three plants in each) in a mixture of 80% limed and fertilized sphagnum peat and 20% granulated perlite (*v*/*v*) on 7 May. For a 9-day establishment period, the plants were placed in an unheated plastic greenhouse, watered with tap water, and covered with a double layer of fiber cloth before they were transferred on 16 May to an open Haygrove plastic tunnel, where they remained for the entire cropping season. From then onwards, all plants were drip irrigated with nutrient solution [electric conductivity of 1.6 mS cm^{-1}, 1:1 Calcinit/Kristalon Scarlet (Yara, Norway)]. Based on inspection of the growing medium moisture, the dripping rate was reduced from 3 to 2 drips (1.2 L h^{-1}) from 30 July in containers in which runners were removed. As a protection against mildew, all plants were sprayed with an elemental sulphur suspension (Thiovit Jet®, Syngenta, Basel, Switzerland) at planting and weekly after planting until the end of May, and with chemical fungicides until mid-June. A recommended program for the use of beneficials against pests was followed, and *Amblyseius cucumeris* and *Amblyseius swirskii* were applied against thrips, spider mite, and whitefly regularly throughout the growing season. The daily mean temperature in the tunnel during the experiment is shown in Figure 1.

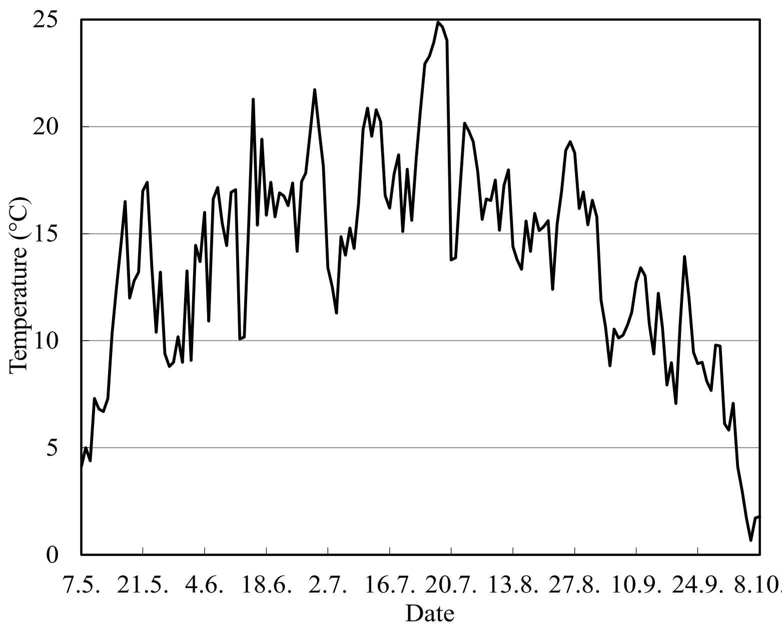

Figure 1. Daily mean temperatures at the experimental site at NIBIO Apelsvoll during the summer months of 2019.

2.2. Experimental Design and Data Collection and Analysis

The experiment had a randomized block design with three replicates, each with six plants kept in two adjacent containers and representing a 1 m running row. Bi-weekly removal of runners and leaves on each plant started on 5 June and continued until 25 September (nine removal dates in total). On each removal date, one or two of the oldest fully developed, and healthy leaves were removed on each plant per treatment. The total number of runners produced per plant, as well as daughter plants per runner, were recorded throughout the season. Ripe berries were harvested 2–3 times per week from 5 July to 7 October. The number and weight of all berries including rotten berries were recorded as well as the proportion of healthy berries with diameter > 25 mm. At termination of the experiment on 7 October, plant height (measured from base to top of the leaf canopy), number of crowns, and leaves per plant and plant fresh weight (plant weight excluding runners and roots) were recorded on all plants, as well as the number of flowers and berries not reaching maturity.

Experimental data were subjected to analysis of variance (ANOVA) using the GLM procedure of the MiniTab® Statistical Software program package (Release 15, Minitab Inc., State College, PA, USA). Percentage values were always subjected to an arc sin transformation before analysis of variance (ANOVA). Separation of significant treatment means was performed by Fisher's least significant difference (LSD) method.

3. Results

Removal of runners and leaves did not affect the date of first berry harvest, nor did it significantly affect berry yield during the first 11 harvests constituting the first fruit flush (Figures 2 and 3).

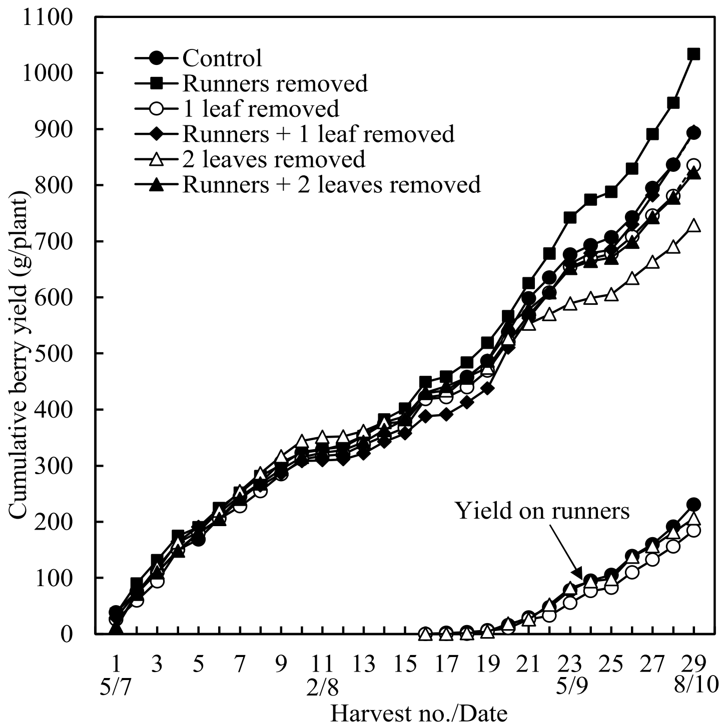

Figure 2. Time course of cumulative berry yield (g per plant, as average of three replicates with six plants each) in the everbearing strawberry cv. 'Favori' depending on bi-weekly removal of runners and leaves during the season.

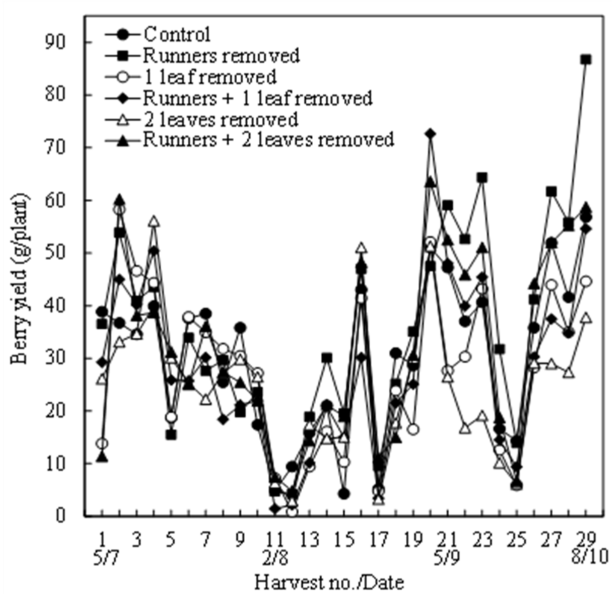

Figure 3. Time course of berry yield per harvest (g per plant, average of three replicates with six plants each) in the everbearing strawberry cv. 'Favori' depending on bi-weekly removal of runners and leaves during the season.

However, after a lag period of 2–3 weeks, the cropping continued, triplicating the total berry yield. During this period, the accumulated yield was less in plants with leaf removal, with the gap between control plants and plants with reduced leaf canopy increasing progressively over time with increasing leaf removal, while runner removal had the opposite effect and produced a parallel and progressive yield increase over the control. As a result, the total yield by termination of the harvest on 7 October was significantly higher in the de-runnered plants than in the control, while it was significantly and progressively lower in plants subjected to increasing leaf removal (Table 1).

Table 1. Effects of bi-weekly runner removal and leaf thinning in the period 5 June to 25 September on yield performance (berries harvested from 5 July to 7 October) of the everbearing strawberry cv. 'Favori'. The data are means (±SD) of three replicates with six plants each.

Bi-weekly Treatments	Yield per Plant (g)	Yield Incl. Runners [1] (g)	Berries per Plant	Berries >25 mm (%)	Berry Size (g per Berry)	Non-Marketable Berries (%)	Flowers and Fruits not Harvested per Plant
Control (no removals)	893 ± 57 b	911 ± 62 b	50 ± 6 a (+14)	99 ± 1.0 a	18.0 ± 1.1 ab	1.4 ± 0.6	46 ± 9
Runners removed	1033 ± 48 a	1033 ± 9 a	54 ± 3 a	99 ± 0.4 a	18.7 ± 0.5 a	1.7 ± 0.7	62 ± 9
1 leaf removed	835 ± 58 b	848 ± 57 bc	44 ± 4 b (+11)	98 ± 0.3 ab	18.8 ± 1.0 a	1.4 ± 0.7	47 ± 12
Runners + 1 leaf removed	895± 68 b	895 ± 68 b	49 ± 6 a	98 ± 0.6 a	18.4 ± 1.1 a	1.0 ± 0.2	64 ± 6
2 leaves removed	728 ± 57 c	749 ± 64 c	43 ± 2 b (+13)	97 ± 0.5 b	16.9 ± 0.7 b	1.7 ± 0.9	37 ± 9
Runners + 2 leaves removed	822 ± 65 bc	822 ± 11 bc	49 ± 6 a	99 ± 0.3 a	18.4 ± 0.6 a	1.5 ± 0.9	51 ± 2
Mean	*868*	*876*	*48*	*98*	*18.2*	*1.4*	*51*
p-value	0.001	0.002	0.03	0.03	0.04	ns	ns

[1] Includes yield harvested and recorded on treatments where runners where kept. Values within the same columns followed by different lower-case letters are significantly different at $p \leq 0.05$ by least significant difference (LSD) test for the different treatments. ns, not significant.

However, the combination of both runner and leaf removal had intermediate effects, with yields not significantly different from the control. The number of berries per plant varied in parallel with the yields, as did the berry size and the proportion of berries with diameter >25 mm, although the effects were smaller than those on fruit yields. The proportion of non-marketable berries was not significantly affected by runner and leaf removal, nor was the number of flowers and fruits that did not reach maturity significantly affected.

In plants where no runners were removed, the runner plants immediately started to flower as they developed, and from harvest no. 16 onwards, these runners contributed to the total yield of the plants (Figure 2). Inclusion of these runner berries in the total yield did not change the significance of the yield levels of the various treatments, with the total yield still being significantly higher in the de-runnered plants than in the control. Leaf removal had no significant effect on fruit yield of the runner plants, nor did it significantly affect the number and size of the runner berries (Table 2).

Table 2. Effects of bi-weekly runner removal and leaf thinning in the period 5 June to 25 September on runner yield performance (berries harvested from 5 July to 7 October) of the everbearing strawberry cv. 'Favori'. The data are means (±SD) of three replicates with six plants each.

Bi-weekly Treatments	Yield per Plant (g)	Berries per Plant	Berries >25 mm (%)	Berry Size (g per Berry)	Non-Marketable Berries (%)	Flowers and Fruits not Harvested per Plant
Control (no removals)	231 ± 5	14 ± 0.1	97 ± 1.8	16.5 ± 0.3	4.2 ± 2.3	17 ± 6
1 leaf removed	185 ± 22	11 ± 2.1	98 ± 0.4	17.1 ± 1.4	6.5 ± 3.9	25 ± 9
2 leaves removed	206 ± 34	13 ± 1.3	95 ± 0.3	15.5 ± 1.1	6.9 ± 4.1	21 ± 14
Mean	*207*	*13*	*97*	*16.4*	*5.9*	*21*
p-value	ns	ns	ns	ns	ns	ns

ns, not significant.

Crop height and number of crowns were not significantly affected by runner and leaf removal, while, as expected, the final number of leaves declined markedly with increasing leaf removal (Table 3).

Table 3. Effects of bi-weekly runner removal and leaf thinning in the period 5 June to 25 September on growth performance recorded on 7 October of the everbearing strawberry cv. 'Favori'. The data are means (±SD) of three replicates with six plants each.

Bi-weekly Treatments	Plant Height (cm)	Crowns per Plant	Leaves per Plant	Runners Produced per Plant	Daughter Plants per Runner	Plant Fresh Weight (g) [1]	Flowers and Fruits not Harvested per Plant
Control (no removals)	30 ± 4	4.4 ± 1.9	33 ± 8 a	3.3 ± 1.2	3.7 ± 1.2	201 ± 44 ab	46 ± 10
Runners removed	30 ± 4	4.1 ± 1.5	35 ± 9 a	3.6 ± 0.4	-	238 ± 64 a	62 ± 10
1 leaf removed	27 ± 3	3.4 ± 1.3	20 ± 7 ab	2.7 ± 1.5	4.2 ± 0.9	131 ± 56 bc	47 ± 18
Runners + 1 leaf removed	30 ± 3	4.9 ± 1.0	26 ± 5 ab	3.2 ± 0.2	-	178 ± 23 ab	64 ± 13
2 leaves removed	25 ± 3	3.2 ± 1.3	15 ± 5 b	2.8 ± 0.8	3.8 ± 1.0	86 ± 37 c	37 ± 9
Runners + 2 leaves removed	27 ± 4	4.7 ± 2.0	17 ± 4 b	3.8 ± 1.0	-	129 ± 66 bc	51 ± 5
Mean	*28*	*4.1*	*24*	*3.2*	*3.9*	*160*	*51*
p-value	ns	ns	0.004	ns	ns	0.001	ns

Values within the same columns followed by different lower-case letters are significantly different at $p \leq 0.05$ by LSD test for the different treatments. ns, not significant. [1] Weight excluding runners and roots.

Runner removal, on the one hand, did not significantly increase leaf numbers compared with the control, and while runner removal slightly counteracted the negative effect of leaf removal on final leaf numbers, the effect was barely significant. Nor was the total number of runners produced during the experiment significantly affected by any of the treatments, while plant fresh weight (excluding roots and runners) decreased markedly with increasing leaf removal. Runner removal, on the other hand, tended to increase plant weight and, when runners were removed in combination with leaf removal, it counteracted the negative effect of leaf removal on plant fresh weight (Table 3).

4. Discussion

The results show that for the everbearing strawberry cultivar 'Favori', total and marketable yields as well as number and size of berries increased significantly in plants subjected to bi-weekly runner removal, while bi-weekly removal of two leaves reduced the yields and berry number and size compared to the control (Table 1, Figure 2). However, none of the treatments affected the fruit yield of the first fruit flush, which originated from inflorescences initiated in the nursery during the previous autumn [12]. In other words, the leaf canopy manipulations did not affect the realization of the yield potential of the plants at planting. On the other hand, the continued fruit production, which originated from flower primordia initiated in the current season [12], increased significantly in derunnered plants, while reduced leaf canopy reduced the fruit yield. It is interesting to note that the appearance of flowers and fruits on runner plants coincided closely in time with the appearance of second flush flowers and fruits on the main plants, thus confirming the concurrent origin of the flower primordia, giving rise to the continuing fruit flushes. Because leaf canopy manipulations affected both the fruit number and size (Table 1), it is evident that both the initiation of flowers and their development to mature fruits were affected by the treatments. This concurs with the results with the SD cv. Honeoye in which chemical or manual reduction of runners during floral initiation in late summer and autumn strongly increased berry yield in the subsequent season, mainly through increasing the number of berries [4].

Because of the continuous initiation of new inflorescences and flowers concurrent with plant growth and initiation of new leaves in EB cultivars, they establish a much higher fruit/leaf ratio than do SD cultivars as they grow. This is especially the case under LD and high temperature conditions, which favor flowering in EB. The low proportion of leaves in EB cultivars makes them particularly vulnerable to leaf thinning.

In the present experiment with the EB cv. 'Favori', fruit yield and plant weight were affected by the leaf canopy and runner manipulations (Tables 1 and 3); both being increased when runners were removed and decreased when leaves were removed. Reduction of the leaf canopy reduced the yield. The fact that both fruit numbers and fruit size were involved as yield components (Table 1) indicates that not only fruit growth, but also floral initiation was negatively influenced by the reduced plant canopy. This is not surprising as it is generally found that an adequate photosynthetic and energy status of the plant is required for normal flowering response [13]. The results in Table 3 demonstrate that bi-weekly removal of two leaves reduced the leaf canopy to the extent that it severely constrained both plant weight accumulation and initiation of flowers (Tables 1 and 3), whereas bi-weekly de-runnering had the opposite effect. Other studies [7] demonstrated that root growth in strawberry is also severely reduced by partial defoliation, an effect that we also noticed in 'Favori'. An interesting response noticed in this cultivar was that, while leaf removal severely reduced plant fresh weight, the response was reduced when leaf thinning was combined with runner removal (Table 3), apparently through the growth-promoting effect of runner removal.

5. Conclusions

In conclusion, our study demonstrates that, in the permanently flowering and fruiting EB strawberry cv. 'Favori', both continued floral initiation and fruit growth are source-limited and are dependent on a good leaf canopy. Furthermore, the results of the experiment show that runner removal of such plants can be an efficient cultivation measure for counteracting these limitations for fruit yield in EB strawberries. On the other hand, none of the leaf canopy regulation treatments prevented the problem of discontinuous flowering and fruiting following completion of the first fruiting flush.

Author Contributions: Conceptualization, methodology, formal analysis, resources, validation, review and editing, A.S., T.L.W., and O.M.H.; data curation, software, investigation, A.S. and T.L.W.; original draft preparation, O.M.H.; resources, funding acquisition, project management, project administration, A.S.; writing—review and editing, A.S., T.L.W., and O.M.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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