Original article

Tree-adapted mechanical flower thinning prevents yield loss caused by over-thinning of trees with low flower set in apple

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Summary

Flower thinning compromises the continuous yield and fruit quality in the production of apple fruit. The aim of the present study was to investigate the potential of managing spatial heterogeneity in flower set by adapted tree-individual mechanical flower thinning. In the years 2011, 2014–2016, commercial orchards of 'Elstar'/M26 and 'Gala'/M9 trained as slender spindle, with an abundance of varying flower set were mechanically thinned at balloon stage (BBCH 59) with the Darwin 250 device at constant vehicle speed of 8 km h⁻¹ with varying rotational frequency ranging from 200 revolutions per minute (rpm) to 380 rpm. Rotational frequency of the thinning device was translated to average kinetic energy (E_{kin} [J]) that one string transfers into the canopy. Thinning treatments ranged between 0.15 J and 0.66 J. For low and medium flower sets, majority of trees underrun production target of 119 fruit and, therefore, no thinning was necessary. Treatments >0.23 J caused yield loss by over-thinning without any positive effect on fruit mass. At high flower set, thinning treatments of 0.23 J and 0.33 J were adequate settings to reduce crop load in 'Elstar' and 0.33 J in 'Gala' without yield loss. The concept of tree adapted flower thinning in comparison to field uniform thinning would result in the avoidance of yield loss by over-thinning of trees with low and medium flower set by 1.4–4.2 t ha⁻¹ in 'Elstar' and 2.6–7.6 t ha⁻¹ in 'Gala'. Results indicate the importance of quantifying flower set for precisely defining the intensity of thinning treatment according to the tree's yield capacity.

Keywords

crop load, 'Elstar', fruit quality, fruit tree, 'Gala', precision horticulture, yield

Significance of this study

What is already known on this subject?

- In former studies, the principle of mechanical thinning with varying parameters was intensively investigated in apple. The spatial variability of soil was shown for many orchards and heterogeneity in flower set is well known in practise.

What are the new findings?

- With the proposed method, the actual impact of mechanical thinning becomes comparable by utilizing kinetic energy as one major variable of the thinning treatment. It is shown that field uniform thinning is a cause for yield loss on trees with low flower set, while tree-adapted thinning can optimize the process considering fruit quality and yield.

What is the expected impact on horticulture?

- Cultivars showing high variability of flower set can be managed more precisely resulting in enhanced yield.

Introduction

Apple trees develop an excessive quantity of flowers exceeding the fruit bearing capacity of the tree (Lakso, 2011). This physiological characteristic is desirable regarding yield reliability even in the case of negative environmental impacts, e.g., late frost, hail and rain, which can cause unfavourable pollination conditions and reduce flower and fruit set (Heinicke, 1917; MacDaniels and Heinicke, 1929). Consequently trees frequently bear more fruit than can be supplied appropriately with carbohydrates (Lakso, 2011), leading to minor fruit size and alternate bearing (Jonkers,

1979; Looney, 1993). Endogenous regulation mechanisms of the tree initiate the reduction of crop load by means of fruit abscission. The fruit drop captures unfertilized and poorly developed fruit, which are dominated by fruit with adequate supply of exogenous and endogenous growth factors, visually measurable by common number of seeds (Luckwill, 1953; Bangerth, 2000). The endogenous regulation of fruit drop is, however, often insufficient to reduce crop load to the optimum level considering fruit quality and prevention of alternate bearing. Therefore, management of surplus fruit is required. The optimum crop load of a tree highly depends on the target of fruit size and the availability of resources, especially carbohydrates and water, per fruit. The supply of carbohydrates is limited by the leaf area to fruit ratio of the tree (Haller and Magness, 1933; Preston, 1954; Silbereisen, 1966; Hansen, 1969, 1977). Crop load management can effectively adjust the leaf area to fruit ratio and, therefore, increase fruit growth rate and advance maturity of apple (Palmer et al., 1997; Wünsche et al., 2000). Until the first half of the 20th century, hand thinning was the only production measure of crop load management (Dennis, 2000). Meanwhile, chemical thinning has been widely accepted in practice as efficient method for flower and fruit thinning. However, the efficacy depends highly on weather conditions and the thinning intensity is frequently hardly predictable (Stover and Greene, 2005). As an alternative, devices for mechanical flower thinning were developed during the last 30 years with more reliable effects (Schröder, 1996; Bertschinger et

al., 1998; Damerow et al., 2007). The principle is based on a rotating spindle with elastic strings, which remove flowers and flower clusters by the mechanical impact. The spindle is driven by a mechanical or hydraulic system, which allows the adjustment of rotational frequency in revolutions per minute (rpm). The intensity of flower thinning depends of the length of strings, the rotational frequency and the speed of the vehicle. Enhanced rotational frequencies increases flower removal (Zoth, 2011; Kon et al., 2013; Penzel et al., 2020) by the enhanced kinetic energy (E_{kin}), which is transferred by the strings into the canopy. The speed of the tractor influences the frequency of hits per tree. The approach of an integrated thinning coefficient described by Solomakhin and Blanke (2010) regards most of these factors and also includes the factor “Fruit set before June drop” in percentage of the flowers. However, the latter doesn’t allow comparing the effects of different treatments on trees with varying flower set, because the flower set dominates the resulting fruit set compared to the effect of the thinning intensity. The formula developed by Zoth (2011) totalizes the kinetic energy, which every centimeter of one string transfers into the canopy.

Apart from the intended treatment, the strings also hit branches and spur leaves emerging earlier than flowers (Kon et al., 2013). Therefore, it is assumed that mechanical thinning has an effect on ethylene production and export from the tissue (Kong et al., 2009), which might trigger fruit abscission (Bangerth, 2000). In general, flower thinning using a mechanical thinning device potentially improves fruit quality and supports return bloom the same way as chemical or mechanical hand thinning (Weibel et al., 2008; Hehnen, 2012). Moreover the profitability can be enhanced due to reduction of labor input (Schupp et al., 2008). Consequently, machine flower thinning is an effective and environmental friendly way of crop load management (Solomakhin and Blanke, 2010), which can also be applied in organic fruit production (Weibel et al., 2008; Sinatsch, 2014) and at any weather condition. In practice, mechanical thinning is performed with field-uniform rotational frequency in the entire orchard, not considering the tree’s individual flower set. This can potentially lead to yield losses by over-thinning of trees with low flower set or minor fruit quality, considering size and taste, as result of under-thinning trees with heavy flower set. Measures of precision horticulture as mentioned by Zude-Sasse et al. (2016) would analyse the spatial heterogeneity in flower set within orchards, and optimize the thinning intensity according to these information. However, there is still a lack of data on machine thinning and quantified gain in yield when optimizing the thinning measure based on the flower set.

The aim of this study was to analyze the effect of field-uniform thinning intensity on (i) the yield considering trees with low, medium, and high flower set, and (ii) the fruit quality and percentage of marketable yield obtained from trees with low, medium, and high flower set.

Materials and methods

Experimental sites

The study was carried out in two commercial orchards of *Malus × domestica* Borkh. in the fruit production region of Werder, Brandenburg, Germany. In 2002, trees of the cultivars ‘Elstar’ and ‘Gala’, trained as slender spindle, were planted with a spacing of 3.2 m × 1.2 m, which accounts for 2,604 trees ha⁻¹. The rootstock was M26 for ‘Elstar’ and M9 for ‘Gala’. The soil type was a sandy loam. Trees were irri-

gated by drip irrigation. Management of the trees was performed according to the national regulations of integrated production.

For ‘Elstar’, 200 trees were selected for the years 2011, 2014, 2015, while in ‘Gala’ 100 trees were selected in 2014 and 200 trees in 2015 and 2016. The position of every tree was recorded, using a real time kinematic global positioning systems (RTK-GPS) (HiPer Pro, Topcon Corporation, Japan) to investigate the spatial effect on yield parameters.

Trees were thinned mechanically when 50–80% of the flowers reached balloon stage (2011: 27.04; 2014: 22.04; 2015: 30.04; 2016: 06.05.), BBCH 59 (Meier, 1997). Mechanical thinning was carried out using a rotating string thinner (Darwin 250, FruitTec, Germany) equipped with 270 plastic strings each with a length of 60 cm. Diameter of the internal tube of the spindle was 50 mm. The tractor speed was constant at 8 km h⁻¹ during the treatment, while varying rotational frequency ranging between 200 rpm and 380 rpm was applied. Thinning at 210 + 10 rpm served as basic rotational frequency (brf) and was considered as control, since no or minimum thinning effect was found. No additional hand thinning was conducted.

Assessment of flower set, thinning efficacy, yield and average fruit mass

The number of flowers was counted from 12 whole trees of ‘Elstar’ in 2011 and 110 branches per cultivar in 2014 to obtain the conversion factor from flowers to clusters, calculated as arithmetic mean of counts. The factors found in 2014 were applied in 2015 and 2016. Prior to each thinning treatment the number of clusters was counted manually for each tree. All fruits were harvested during commercial harvest of this orchard (2011: 17.08; 2014: 05. and 16.09; 2015: 10.-11.09; 2016: 07.-09.09). Crop load, yield, fruit mass, and percentage of marketable yield considering fruit size >65 mm was measured tree-individual with a commercial sorting line (TrueSort, Ellips B.V., The Netherlands). Total thinning efficacy was determined by the percentage of final fruit set (FFS [%]) as number of fruit at harvest per 100 flowers.

Fruit quality

In every year, at harvest fruit samples from each treatment (2011: 787; 2014: 63; 2015: 2118; 2016: 165 fruits) were analyzed regarding fruit quality. Soluble solids content (SSC [%Brix]) of squeezed juice was measured using a digital refractometer (DR-301-95, Krüss, Germany). Starch breakdown was analyzed by staining the fruit halves with Lugol’s iodine solution and interpreting the starch hydrolysis on a scale between 1 and 10. Fruit flesh firmness (N cm⁻²) was measured with motor-driven, digital penetrometer (Texture-Analyser, TA.XT, Stable Micro Systems Ltd., UK). A handheld spectrophotometer (Pigment Analyzer PA1101, CP, Germany) was used for non-destructive measurement of chlorophyll-related normalized difference vegetation index (NDVI [-1; 1]; Zude, 2003).

Thinning coefficient

The thinning coefficient was calculated by the average kinetic energy (E_{kin} [J]) that one string transfers into the canopy. The E_{kin} calculated for the middle of the string is affected by the mass, m [kg], and the speed, w [m s⁻¹] of the string (Eq. 1).

$$E_{kin} = \frac{1}{2} \cdot m \cdot w^2 \quad (\text{Eq. 1})$$

FIGURE 1. Scheme of the operating mode of the mechanical thinning device and velocity vectors (d = diameter of the inner tube of the rotating spindle, where the string is attached; l = length of the string; α = the angle between w_x and w_y).

The magnitude of the velocity vector w of the string consists from the translational movement, w_x , from the tractor in direction x and the rotary movement, w_y , in direction y , from the spindle (Eq. 2; Figure 1). It is assumed that the rotation is conducted in parallel to the ground and no movement in direction z occurs.

$$w^2 = w_x^2 + w_y^2 \quad (\text{Eq. 2})$$

The speed w_x results from the addition of the vector components v_x and u_x in the driving direction of the tractor x (Eq. 3). The vector v_x equates the speed, v [m s^{-1}], of the tractor because the motion is rectilinear in one direction.

$$w_x = v_x + u_x \quad (\text{Eq. 3})$$

The speed w_y results from the addition of the vector components v_y in direction y , which equates 0 because the movement of the tractor occurs only in direction x , and u_y in direction y upright to the direction x (Eq. 4).

$$w_y = v_y + u_y \quad (\text{Eq. 4})$$

The vector components u_x and u_y follow from multiplying the circumferential speed u [m s^{-1}] of the string and the cosine, or sinus respectively of the angle, α [rad], which is formed by w_x and w_y . Because the string hits the tree vertically to the position of the string, 90° are added to α . (Eq. 5 and 6).

$$u_x = u \cdot \cos(\alpha + 90) \quad (\text{Eq. 5})$$

$$u_y = u \cdot \sin(\alpha + 90) \quad (\text{Eq. 6})$$

The circumferential speed u [m s^{-1}] results from multiplying the radius, r [m], at the middle of the string with the rotational frequency n [rad s^{-1}] of the rotating spindle

(Eq. 7). The radius at the middle of the string, r [m], captures the half diameter, d [m], of the inner tube of the rotating spindle, where the string is attached and the half-length, l [m], of the string (Eq. 8). The rotational frequency n [rad s^{-1}] results from converting the revolutions per minute (rpm) into the unit rad s^{-1} by using Eq. 9.

$$u = r \cdot n \quad (\text{Eq. 7})$$

$$r = \frac{d}{2} + \frac{l}{2} \quad (\text{Eq. 8})$$

$$n = \frac{s}{60} \cdot 2 \cdot \pi \quad (\text{Eq. 9})$$

Eq. 10 displays the resulting overall formula for E_{kin} illustrated in Figure 1.

$$E_{\text{kin}} = \frac{1}{2} m \cdot \left(\left(v + \left(\frac{d}{2} + \frac{l}{2} \right) \cdot \frac{s}{60} \cdot 2 \cdot \pi \cdot \cos(\alpha + 90) \right)^2 + \left(\left(\frac{d}{2} + \frac{l}{2} \right) \cdot \frac{s}{60} \cdot 2 \cdot \pi \cdot \sin(\alpha + 90) \right)^2 \right) \quad (\text{Eq. 10})$$

Statistical analysis

Statistical analyses were carried out in software R v. 3.4.1 (R Core Team, 2018) using the packages 'nlme' (Pinheiro et al., 2018), 'gstat' (Pebesma, 2004), 'sp' (Pebesma and Bivand, 2005), and 'multcomp' (Hothorn et al., 2008). The spatial covariance of latitude and longitude was included in the analysis of variance (ANOVA) when analyzing the effect of thinning treatment on the yield parameters (crop load, final fruit set, average fruit mass, yield and percentage of marketable yield) as described by Crawley (2013). ANOVA results are expressed as p values in the text. In the case that no significant effect of latitude and longitude on individual traits was found, Dunn's Test (Dinno, 2017) was used for pairwise comparisons of treatments at 5% confidence level.

Results

Number of flowers

The average number of flowers per cluster was 4.3 ± 0.6 for 'Elstar' in 2011 and 4.7 ± 0.3 for 'Elstar' and 5.2 ± 0.3 for 'Gala' in 2014. The absolute number and the distribution of the estimated flower set, based on counting clusters of the investigated trees, varied considerably between cultivars and years (Figure 2). 'Elstar' showed a low flower set with arithmetic mean of 249, 246, 646 in 2011, 2014, 2015, respectively, in comparison to 'Gala' with a flower set of 541, 532, 1,434 in 2014, 2015, 2016, respectively. In 'Elstar', trees with no flowers appeared, which were excluded from further analysis (Table 1). The highest flower set of 'Elstar' was 2,162 observed on one single tree in 2015, however the 95th quantile of the flower set was 1,206, demonstrating that 'Elstar' possesses a huge variability in flower set. For 'Gala',

the maximum flower set was 3,245 in 2016, representing an extreme value regarding 95th quantile of 2,149 in the same year. Trees showing extreme high flower set were excluded as residues to avoid overestimation of the effect of thinning intensity. Trees were grouped in 3 classes according to low, medium, and high flower set per year (Tables 1 and 2).

Thinning coefficient

The angle of the string to the driving direction has an impact on E_{kin} (Figure 3). Considering the settings of the Darwin device used in the present trials, the angle of the string generated a difference in E_{kin} of 0.29 J at 380 rpm, 8 km h⁻¹ due to the possible angles between 0 and 180 degrees, with 0 degree and 180 degrees resulting in maximum and 90° in minimum E_{kin} for each rotation.

The speed of the tractor resulted in a reduced effect on E_{kin} considering the operation speeds described earlier and,

FIGURE 2. Distribution of number of flowers per tree estimated by counting the ratio flowers to clusters in one year and clusters in all years in 'Elstar'/M26 and 'Gala'/M9 providing a class width of 150. Dashed line marks the mean value.

TABLE 1. Class ranges of flower set defined as low, medium, and high used for further analyses in three years of 'Elstar'/M26.

Flower set	Class	2011		2014		Flower set	Class	2015	
		n	$\bar{x}$	n	$\bar{x}$			n	$\bar{x}$
0	–	–	–	18	0	0	–	2	0
1–200	Low	99	84.5	89	57.5	1–350	Low	57	195.9
201–400	Medium	64	292.8	52	296.5	351–700	Medium	67	519.4
401–800	High	44	529.3	46	556.6	701–1,400	High	82	962.5
Residue	–	2	–	8	–	Residue	–	9	–

TABLE 2. Class ranges of flower set defined as low, medium, and high used for further analyses in three years of 'Gala'/M9.

Flower set	Class	2014		2015		Flower set	Class	2016	
		n	$\bar{x}$	n	$\bar{x}$			n	$\bar{x}$
50–350	Low	22	242.5	30	269.2	650–1,150	Low	45	989.6
350–600	Medium	45	510.5	105	479.6	1,151–1,650	Medium	75	1,412.7
600–1,000	High	29	740.9	58	742.7	1,651–2,150	High	56	1,849.5
Residue	–	4	–	7	–	Residue	–	24	–

to our knowledge, applied in practice ranging from 2.5 km h⁻¹ to 12.0 km h⁻¹ (Kon et al., 2013). At rotational frequency of 380 rpm, this difference in tractor speed caused a maximum spread of 0.19 J, regarding the angle of the string at 135° to the driving direction. However, the effects of rotational frequency and length of the string represent the major factors with quadratic effect on E_{kin} per hit calculated for the middle of the rotating string (Eq. 10). For the 60-cm strings and 8 km h⁻¹ used in the present study, the average E_{kin} per hit calculated at the middle of the string at an angle of 135 degree, ranged from 0.15 J at 200 rpm to 0.66 J at 380 rpm.

Thinning efficacy, yield, fruit mass

1. Spatial autocorrelation. Variograms (21 figures per trial, not shown) were used for selecting post hoc or adapted post hoc test. For the final fruit set (FFS) and percentage of marketable yield no spatial effect was found in any trial. In 'Elstar', an adapted post hoc test was applied for yield, crop load, and average fruit mass where a spatial effect was found until a distance of 30 m between the trees. For 'Gala' spatial effects were found until a distance of 15 m in 2014 and until 20 m in 2015 and 2016, considering the variables yield, crop load, and average fruit mass.

2. Influence of thinning treatment on final fruit set. The FFS, representing the percentage of fruit developed from 100 flowers, differed between cultivars, years and particularly within the same year between the three classes of flower set (Tables 1 and 2). Furthermore, FFS was influenced by thinning treatment in both cultivars in every year. FFS ranged from 2.7% considering trees with high flower set in 2016 to 48.4% considering trees with low flower set in 2015.

For low flower set, in 'Elstar' 2011 (Figure 4) and 2014, thinning treatment of 0.33 J and higher reduced FFS (2011: $p < 0.01$; 2014: $p = 0.03$) in comparison to the basic rotational frequency (brf) of 0.15 J. In 2015, treatment above or equal to 0.28 J had an effect (2015: $p < 0.001$) on FFS in comparison to brf of 0.19 J (Table 3). In 'Gala' 2014, no effect of thinning treatment on FFS was observed for trees with low flower set (Figure 5). In 2015, no statistical evaluation was possible since significant differences in flower set occurred within this class. In 'Gala' 2016, treatments of 0.39 J and higher reduced FFS ($p < 0.01$) considering trees with low flower set from 8.2% to 3.8% and lower.

At medium flower set, in 'Elstar' 2011 treatments of 0.33 J and 0.45 J reduced FFS ($p < 0.01$) in comparison to brf (Figure 4), while in 2014 only 0.45 J caused a significant re-

FIGURE 3. Calculated E_{kin} occurring during mechanical thinning, considering one hit of in the middle of the 60 cm string at varying tractor speed (2.5 km h⁻¹ = square, 8.0 km h⁻¹ = circle, and 12.0 km h⁻¹ = triangle) at 90° (open symbol) and 180° (closed symbol) angle of the string to the driving direction.

FIGURE 4. Effect of mechanical thinning treatment (solid lines = 0.15 J, dashed lines = 0.23 J, dotted lines = 0.33 J, dash-dotted lines = 0.45 J) on crop load (CL as number of fruit per tree), fresh mass (FM in g), absolute yield (Y in kg), and percentage of marketable yield (MY, %) considering classes of flower set: (A) low: 1–200, (B) medium: 201–400, and (C) high: 401–800 flowers (F) of ‘Elstar’/ M26 in 2011.

TABLE 3. Effect ($\alpha=5\%$) of mechanical thinning treatment (first letter) and flower set (second letter) on yield parameters of ‘Elstar’ in two years.

Flower set	Thinning treatment E_{kin} (J)	Crop load (fruit/tree)	Final fruit set (fruit 10^{-2} flowers)	Yield (kg)	Fruit mass (g)	Marketable yield (%)
2014						
Low	0.15	21.8 ^{BC, a}	38.9 ^{B, b}	4.0 ^{BC, a}	196.9 ^{A, b}	97.7 ^{A, b}
	0.23	33.3 ^{C, a}	39.6 ^{B, b}	5.3 ^{C, a}	182.8 ^{A, b}	95.5 ^{A, b}
	0.33	14.6 ^{AB, a}	26.4 ^{A, a}	2.7 ^{AB, a}	182.1 ^{A, b}	96.5 ^{A, b}
	0.45	16.2 ^{A, a}	27.8 ^{A, a}	2.7 ^{A, a}	171.1 ^{A, b}	93.8 ^{A, b}
Medium	0.15	100.5 ^{A, b}	35.4 ^{B, b}	13.1 ^{A, b}	130.8 ^{A, a}	77.7 ^{A, a}
	0.23	110.3 ^{A, b}	39.4 ^{B, ab}	16.0 ^{A, b}	145.8 ^{A, a}	86.2 ^{A, a}
	0.33	101.4 ^{A, b}	35.7 ^{B, b}	15.5 ^{A, b}	153.4 ^{A, b}	90.3 ^{A, b}
	0.45	87.4 ^{A, b}	26.8 ^{A, a}	12.4 ^{A, b}	136.0 ^{A, a}	84.6 ^{A, ab}
High	0.15	131.9 ^{A, c}	25.3 ^{B, a}	16.0 ^{A, b}	119.9 ^{A, a}	67.9 ^{A, a}
	0.23	126.5 ^{A, b}	24.5 ^{AB, a}	14.7 ^{A, b}	116.6 ^{A, a}	63.3 ^{A, a}
	0.33	125.2 ^{A, b}	22.8 ^{AB, a}	14.7 ^{A, b}	117.1 ^{A, a}	69.7 ^{A, a}
	0.45	107.3 ^{A, b}	19.0 ^{A, a}	12.9 ^{A, b}	118.6 ^{A, a}	72.5 ^{A, a}
2015						
Low	0.19	85.5 ^{C, a}	48.4 ^{C, b}	13.4 ^{C, a}	168.4 ^{A, b}	91.2 ^{A, b}
	0.23	58.1 ^{BC, a}	36.1 ^{BC, a}	10.0 ^{BC, a}	176.1 ^{A, c}	95.7 ^{A, b}
	0.28	40.3 ^{AB, a}	21.7 ^{AB, a}	6.9 ^{AB, a}	159.0 ^{A, b}	87.4 ^{A, b}
	0.45	26.7 ^{A, a}	11.8 ^{A, a}	4.3 ^{A, a}	146.8 ^{A, a}	89.4 ^{A, a}
Medium	0.19	123.4 ^{B, ab}	23.2 ^{B, a}	17.8 ^{B, a}	144.9 ^{A, b}	85.4 ^{A, b}
	0.23	113.2 ^{B, b}	22.5 ^{B, a}	16.4 ^{B, ab}	141.6 ^{A, b}	80.8 ^{A, ab}
	0.28	110.8 ^{B, b}	21.5 ^{B, a}	13.6 ^{AB, b}	131.7 ^{A, ab}	76.0 ^{A, ab}
	0.45	73.5 ^{A, b}	14.3 ^{A, a}	10.7 ^{A, b}	149.7 ^{A, a}	87.8 ^{A, a}
High	0.19	162.8 ^{B, b}	17.1 ^{B, a}	16.1 ^{A, a}	100.7 ^{A, a}	55.3 ^{A, a}
	0.23	172.9 ^{B, c}	19.1 ^{B, a}	18.4 ^{A, b}	106.0 ^{A, a}	60.7 ^{A, a}
	0.28	142.3 ^{AB, c}	15.9 ^{AB, a}	16.0 ^{A, b}	113.3 ^{A, ab}	65.9 ^{A, a}
	0.45	108.5 ^{A, b}	10.8 ^{A, a}	15.3 ^{A, b}	146.9 ^{B, b}	87.1 ^{B, b}

FIGURE 5. Effect of thinning intensity (solid lines = 0.15 J, dashed lines = 0.23 J, dotted lines = 0.33 J, dash-dotted lines = 0.45 J) on absolute crop load (CL in number of fruit per tree), fresh mass (FM in g), total yield (Y in kg), and percentage of marketable yield (MY, %) considering classes of flower set: (A) low: 50–350, (B) medium: 351–600, and (C) high: 601–1,000 flowers (F) of ‘Gala’/M9 in 2014.

duction in ‘Elstar’ ($p=0.05$) and in ‘Gala’ ($p<0.01$) (Figure 5). In 2015, treatments of 0.45 J and higher reduced FFS (2015: $p=0.02$) in ‘Elstar’, while 0.28 J and higher resulted in a reduction of FFS in ‘Gala’ 2015 ($p=0.01$) and 0.39 J and higher in 2016 ($p<0.001$).

At high flower set, ‘Elstar’ in 2011 (Figure 4), treatment of 0.33 J and 0.45 J caused again reduction of FFS ($p=0.04$; $p<0.01$), while in 2014 and 2015 (Table 3) only 0.45 J resulted in the same effect (2014: $p=0.04$; 2015: $p=0.02$). In ‘Gala’ 2014 (Figure 5), at high flower set only treatment of 0.45 J had a reducing effect on FFS in comparison to brf ($p=0.05$). In 2015, treatments of 0.28 J and higher E_{kin} reduced flower set at $p=0.01$ and $p<0.01$, respectively.

3. Influence of thinning treatment on yield. The sampling date for laboratory analyses of fruit quality was set at the

commercial harvest date for direct marketing from the same orchards. No correlation was found between crop load and quality parameters except for fruit mass (Figures 4 and 5). In ‘Elstar’, trees with low flower set and thinning treatment equal or higher than 0.33 J in 2011, 2014 and 0.28 J in 2015 had a reduced crop load compared to brf, resulting in yield losses (Figure 4; Table 3). In none of the trials thinning showed a positive effect on fruit mass or percentage of marketable yield (Table 4). In ‘Gala’, trees with low flower set showed no reduction in yield in 2014, however, at 0.45 J average fruit mass was enhanced by 35.8 g ($p=0.01$) to 166.4 g with an effect on percentage of marketable yield ($p=0.01$) which reached 99.0%. In 2016, treatment with 0.39 J caused reduction ($p=0.02$) of marketable yield by 5.4 kg per tree in comparison to brf.

TABLE 4. Change of marketable yield (fruit size >65 mm) caused by mechanical thinning treatment in comparison to basic rotational frequency (brf) in ‘Elstar’/M26 considering three classes of flower set.

Year	Marketable yield at brf (kg)	Lowest treatment causing yield reduction* (J)	Reduction* of marketable yield per tree (kg)	Reduction of marketable yield per ha (t)
Low flower set				
2011	4.2	0.33	0.9	1.1
2014	3.9	0.33	1.3	1.4
2015	12.2	0.33	6.2	4.2
Medium flower set				
2011	7.4	No reduction	0	0
2014	10.2	No reduction	0	0
2015	14.5	0.45	5.1	5
High flower set				
2011	12.3	0.33	4	2.2
2014	10.9	0.45	1.5	1.5
2015	8.9	No reduction	0	0

*: Reduction of marketable yield in comparison to brf calculated as mean value from the total yield and percentage of marketable yield >65 mm per tree.

In 'Elstar' trees with medium flower set, thinning treatment with 0.33 J reduced crop load in 2011 and 0.45 J in 2015, hence yield was reduced. In 2011, thinning at 0.33 increased fruit mass ($p=0.03$) by 14.6 g in comparison to brf, however without effect on percentage of marketable yield (Figure 4). In 2014, 'Gala' showing medium flower set responded to the treatment with 0.45 J ($p<0.001$) (Figure 5). Already at 0.33 J, fruit mass ($p=0.04$) was enhanced. At 0.45 J, average yield per tree was reduced with positive effect on percentage of marketable yield ($p<0.001$), which was enhanced by 20.7% to 97.5% (Figure 5). No effect was found in 2015 and 2016.

At high flower set, in 2011 crop load was reduced in 'Elstar' at 0.33 J ($p<0.01$) and 0.45 J ($p=0.02$) reducing yield per tree with no effect on average fruit mass (Figure 4; Table 4). At high flower set in 'Elstar' 2015 treatment with 0.45 J reduced crop load ($p=0.02$), while gaining fruit mass ($p=0.02$) and increasing the marketable yield ($p=0.004$) (Table 3). In 'Gala' 2014, only treatment with 0.45 J reduced crop load ($p=0.03$) and percentage of marketable yield was enhanced ($p=0.001$) to 99.3% (Figure 5). In 2015 and 2016, at high flower set, 0.28 J reduced crop load and yield per tree in comparison to brf. Average fruit mass was not affected by thinning treatment, as well as percentage of marketable yield, which was already close to 100% at brf. Due to lack of changes in the marketable yield, which was already high in years 2015 and 2016, Tables 3 and 4 weren't reproduced for 'Gala'.

Discussion

Flower set

Variability in flower set occurs naturally within orchards and was described earlier (Bukovac et al., 2010; Stopar, 2010; Hočevár et al., 2014; Sinatsch et al., 2014; Beber et al., 2016). In the present study, the variability among flower set was used to classify trees according to the apparent flower set in order to investigate the effect of thinning intensity for each class separately. The size of the classes resulted from the pragmatic approach to meet the requirements for statistical analysis (Table 1). Analysis of variance showed no significant differences in flower set within the classes (Stopar, 2010).

Variability in flower set in the present trials can be explained with the light terrain gradient within the orchard causing spatial distribution of water availability (Moore et al., 1993), nutrients supply (Aandahl, 1948), and occurrence of frost (Weise, 1978). Since these factors have a known effect on crop load (Powell, 1974; Hansen, 1980; Heinicke, 1917), they influence flower bud initiation, leading to spatial variability of flower set. On the hillside, trees showed a tendency of enhanced flower set compared to trees located in region of slightly lower elevation showing stronger vegetative growth assumingly due to late frost events. In cultivar 'Elstar', a higher percentage of trees with low flower set was found compared to 'Gala', which was expected because 'Elstar' is known in practice as biannual bearing cultivar. In order to achieve the growth capacity, trees should bear approximately one apple per 14–42 leaves (Haller and Magness, 1933; Preston, 1954; Silbereisen, 1966; Hansen, 1969) depending on cultivar and growth factors. Unpublished data of 2008 from the same 'Elstar' orchard showed that the leaf number per trees ranged between 2,600 and 4,540. Under the assumption that the necessary leaf number per fruit to produce a marketable size is 30, the trees can hypothetically support 87–151 fruit. This huge variation points to spatial variation

in growth production target (PT) which was in average 117 fruit per tree. The number of flowers to reach the optimum crop load per tree should be slightly enhanced to the PT due to natural fruit drop taking place after flower thinning. In 'Elstar', the fruit drop resulted in crop loads slightly below the PT. In 'Gala', on the other hand, a high percentage of the trees reached PT. The counting of flowers or clusters in practice is time consuming, but necessary to conclude on the target thinning intensity. Automated counting of flowers is required and can be performed with optical sensors and corresponding algorithms (Hočevár et al., 2014; Krikeb et al., 2017). Integrated systems for flower counting and actuator for adaptive mechanical flower thinning are under development (Pflanz et al., 2016), while quantitative data on the thinning requests of individual trees are still rare.

Thinning coefficient

For comparing the effect of thinning treatments of different experiments, a thinning coefficient is proposed regarding the variables of the devices and treatments. Most important, the coefficient includes the number, length, and mass of the strings, the tractor speed, and the rotational frequency. The formula developed by Zoth (2011) was modified in the present work by adding the angle of the string to the driving direction as a separate factor, which also has an effect on the kinetic energy, E_{kin} (Figure 3). As simplification, the average E_{kin} is emphasized, which is achieved in the middle of the string. E_{kin} at different points of the string varies, consistently according to the distance to the rotating spindle (Figure 3). The E_{kin} is limited because it ignores the frequency of hits per string in the turbulent application, which is affected by the distance between the device and the tree and the amount of strings of the device. Particularly, the number of stings has a significant effect on thinning efficacy (Kon et al., 2013), but more experiments are needed to test linearity of various numbers of strings and resulting E_{kin} . For this purpose the distance of the tractor to the tree row needs to be included to calculate the size of the section of tree row which one string possibly hits at one rotation and the depth one string penetrates the canopy. This could be a helpful tool for further optimization of the settings of the device and additionally the shape of the canopy. Clearly visible already with the present simple approach is the effect of the length of one string, which explains the frequently observed phenomenon in practice that used, worn-out strings demand a higher rotational frequency to achieve the same efficacy as new strings.

Thinning efficacy, yield, fruit mass

Mechanical thinning is an effective measure for crop load management in practice (Schröder, 1996; Bertschinger et al., 1998; Damerow et al., 2007; Weibel et al., 2008; Schupp et al., 2008; Kong et al., 2009; Solomakhin and Blanke, 2010; Hehnen et al., 2012; Kon et al., 2013; Sinatsch et al., 2014; McClure and Cline, 2015; Beber, 2016; Lordan et al., 2018). An overview about the settings of the devices and the thinning efficacy from the literature is given by Kon et al. (2013). A model was developed by Lordan et al. (2018) to predict the final fruit number per tree from the number of flower clusters at different settings of the Darwin thinner considering vehicle speed and rotational frequency. All previous studies report a reduction of fruit set by means of mechanical field-uniform thinning in comparison to the control. Few work was published on thinning intensity adapted to the actual flower intensity (Stopar, 2010; Beber

et al., 2016) although spatial variation within orchards was proved earlier (Manfrini et al., 2009; Aggelopoulou et al., 2010, 2011; Bukovac et al., 2010). Stopar (2010) classified trees according to the number of flower clusters to precisely assess the effect of varying thinning treatments. In the present study, the spatial correlation was recognized by means of semi-variograms (Crawley, 2013).

Results indicate an expected close relationship between flower set and final fruit set. In trees with low flower set, fruit drop was apparently reduced as pointed out earlier (Penzel et al., 2020). Consequently, the comparison of final fruit set (FFS) after varying thinning treatment should be carried out considering trees with similar abundance of flower set, which is a factor with a strong effect on FFS. Furthermore, a positive correlation exists between mechanical thinning and reduction of fruit set regardless of flower set as confirmed in the present study. At low flower set, thinning was not necessary, because in none of the trials the production target of 119 was realized. The 0.23 J treatment showed no effect on FFS in comparison to brf. Consistently, the fruit mass and percentage of marketable yield was hardly affected by thinning treatment, similar to the findings in the literature on mechanical thinning (Beber et al., 2016) and chemical thinning (Greene, 1989; Stophar, 2010). Beber et al. (2016) pointed out that thinning is not necessary to achieve good fruit quality when trees had <80 flower clusters, which equals <400 flowers assuming that one cluster consists of an average of five flowers in the cultivar 'Jonagold'. Mechanical thinning treatment further reduced FFS leading to absolute yield losses. The cortex cell number is positively correlated with fruit mass and thinning at full bloom is the optimum timing for stimulating cell division (Goffinet et al., 1995). However, in the present trials effect on fruit mass was limited, since it can be assumed that the remaining fruit had a sufficient supply of carbohydrates, nutrients and water. Also, no effect of thinning treatments on fruit maturity was found for trees with low crop load as previous studies suggested (Volz et al., 1993; Wünsche and Ferguson, 2005) considering maturity parameters as background color, firmness, and starch index.

At medium flower set, thinning was still hardly necessary as PT of 119 in 'Elstar' was obtained in 2015 and 'Gala' in 2014 at brf. In the other trials, final fruit number at low thinning treatment was below the optimum and further reduced by thinning treatment ≥ 0.33 J for 'Gala' and ≥ 0.33 J or ≥ 0.45 J, depending on the year, in 'Elstar'. However, the percentage of marketable yield showed no increase in 'Elstar' considering any year, pointing out that obviously a crop load equal or lower than the PT will have no effect on percentage of marketable yield. Though, average fruit mass of 'Elstar' 2011 was further enhanced by thinning treatments, which may indeed have a positive effect on market value. In 'Gala', fruit mass was significantly enhanced in two years, whereas the percentage of marketable yield was enhanced only in 2014. In the subsequent years the low fruit set resulted in high percentage of marketable yield of >90% in all treatments. Consequently, thinning at medium flower set results in yield losses as the effect on quality was marginal. Maximum thinning treatment in medium classes of flower set therefore should be 0.23 J for the two cultivars.

At high flower set PT was not exceeded when thinned at brf (Sinatsch et al., 2014; McClure and Cline, 2015). For 'Gala' in 2014 treatment of 0.33 J was appropriate to reach PT. Enhanced thinning treatment reduced fruit set heavily, and fruit mass was increased with every fruit having a

marketable size. Lower thinning treatments resulted in crop load exceeding PT with negative effect on fruit mass. Kon (2013) reported for similar $E_{kin} \geq 0.27$ J, calculated with prior described thinning coefficient, that leaf injury is high. Such finding may be explained by higher frequency of hits per leaf than in the present study because of the lower vehicle speed. Also, McClure and Cline (2015) noticed leaf injuries when vehicle speed was low. As compromise of thinning response and tree damage, Kon (2013) suggested thinning at lower rotational frequencies equaling 0.14 J or 0.20 J for 'Gala'. However, it was emphasized that these intensities may not thin sufficiently in heavy cropping years and recommended the combination with other thinning methods. McClure and Cline (2015) also reported no effect on fruit mass when thinned up to 0.29 J at low vehicle speed, though marketable yield was adequate already in the control.

In 'Elstar' 2011, treatment of 0.23 J reduced crop load close to PT, though no effect on fruit mass was achieved. This may have resulted from damage on spur leaves, which was not further evaluated. In 2014, treatments of 0.23 J and 0.33 J provided the optimum thinning treatment in terms of crop load, while in 2015 treatments >0.28 J and <0.45 J have caused best results regarding crop load level and fruit mass as crop load at applied treatments exceeded or underrun PT. For practical use, considering high levels of flower set on 'Elstar', 0.23 J and 0.33 J are adequate treatments to reduce crop load. Sinatsch et al. (2014) suggested treatments of 0.19 J or 0.23 J for 'Elstar' trees with high flower set positively affecting fruit size and reducing biannual bearing.

In summary all treatments indicate that different levels of flower set require different settings of the thinning device for best thinning results. A model for thinning response depending on flower set and settings for the Darwin with high R^2 as Lordan and co-workers (Lordan et al., 2018) developed for two cultivars was not possible from the present data. However, data indicate that tree adapted mechanical thinning can decrease possible yield losses by over-thinning at low and medium flower set. High flower set in contrast requires enhanced thinning intensity as crop loads possibly exceed PT. Reduced percentage of marketable yield by field-uniform mechanical thinning ranged from 1.4 t ha^{-1} – 4.2 t ha^{-1} in 'Elstar' in years 2011, 2014, 2015, and 2.6 t ha^{-1} – 7.6 t ha^{-1} in 'Gala' in 2014. Consequently, tree-adapted thinning is a promising method to increase production volume without increasing land consumption. When commercial systems for tree-adapted thinning become available, the economic aspect is crucial for the farmer.

Conclusion

The present study showed that heterogeneity in flower set is existing and trees with different abundance of flowers demand adapted treatment in terms of flower thinning intensity. The concept of mechanical thinning considering the flower set was further evaluated and showed the capability to reduce yield losses by over-thinning of trees with low flower set, while increasing yield per hectare by 1.4 – 4.2 t ha^{-1} in 'Elstar' and 2.6 – 7.6 t ha^{-1} in 'Gala'. When commercially available, this approach of precise management can potentially balance spatial heterogeneity within orchards.

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