Screening of eco-friendly thinning agents and adjusting mechanical thinning on ‘Gala’, ‘Golden Delicious’ and ‘Fuji’ apple trees

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Abstract

Fruit thinning is the most important yet difficult practice that drives orchard profitability. High labor costs and difficulty to improve return bloom by hand thinning have left chemical thinning as the main method used by growers. However, unpredictability and safety/environment concerns regarding chemical thinning have set mechanical thinning as a sound alternative. Thirteen field experiments were performed during 2004-2016 in order to evaluate several agents for their use as new thinners, and adjust mechanical thinning on ‘Gala’, ‘Golden Delicious’ and ‘Fuji’. Olive oil applied at bloom reduced crop load, but russetting was also increased. Therefore, while their use is not advisable for russetting prone cultivars such as ‘Golden Delicious’, it could be a good thinner for cultivars like ‘Red Delicious’. Lime sulfur did not have a consistent thinning effect in our study when applied at bloom. Overall, no differences regarding economic value between hand, chemical, and mechanical blossom thinning were observed, suggesting mechanical thinning as a valid alternative approach. For ‘Gala’ strains, 6 km·h^{-1} and 250 rpm with 270 strings was the best configuration to provide an ideal crop load of ~6 fruit/cm^{2} of TCSA and an average fruit size of 170 g. For ‘Fuji’, 5 km·h^{-1} and 320 rpm with 270 strings provided a crop load in accordance to the optimum range for this cultivar in our conditions. However, combination of mechanical thinning plus chemical treatments might be the ideal strategy for ‘Fuji’ strains when the initial number of flower clusters per tree is above 500. For ‘Golden Delicious’ strains, 6 km·h^{-1} and 230 rpm with 270 strings was the best configuration to provide an ideal crop load within the optimum range. Mechanical thinning timing was also examined at different phenological stages (E_2, F_1, F_2, and G), with no significant differences regarding yield, fruit size or crop load between them. Two prediction models (‘Gala’ & ‘Golden Delicious’) were developed to adjust the right tractor and rotational speeds depending on the initial number of flower clusters. The method begins with first calculating the final fruit number needed per tree (crop load for each particular cultivar) in order to achieve the desired yield. Then, tractor and rotational speeds can be determined by the model once knowing the initial number of flower clusters per tree.

Keywords: *Malus x domestica*, Darwin, rotating string machine, organic, crop load

Introduction

Through management of fruit number, size, and quality, thinning is the most important yet difficult practice that drives orchard profitability (Costa et al., 2012; Dennis, 2000;

Greene and Costa, 2012; Robinson et al., 2013). Chemical and hand thinning have been the main methods used by growers during the last decades to achieve a regular and consistent crop load over the seasons (Costa, 2016; Dennis, 2000).

Hand thinning is generally too expensive, and the need to wait after the period of natural drop may compromise fruit size and return bloom (Dennis, 2000; Fallahi and Greene, 2010; Mcartney et al., 1996). On the other hand, chemical thinning is highly dependent on weather conditions and cultivar, which can create inconsistent results (Greene and Costa, 2012; Robinson and Lakso, 2004). For this reason, many studies have been carried out in order to address the lack of predictability of thinner response (Greene and Lakso, 2013; Lakso and Robinson, 2015; Lakso et al., 2001).

Food safety concern and awareness of environment protection have limited the available chemical thinning agents, thus, more environmentally-friendly thinning agents and mechanical thinning implementation could become the alternatives (Bertschinger et al., 1998; Blanke and Damerow, 2008; Greene and Costa, 2012; Kon et al., 2013). Some authors reported a thinning effect of products such as vegetable oils, potassium bicarbonate or molasses, sprayed at bloom (Ju et al., 2001; Pfeiffer and Rueß, 2002b; Stopar, 2004; Warlop, 2002b; Weibel et al., 2012). However, these results are not always conclusive.

Several mechanical thinning trials have been reported abroad (Asteggiano et al., 2015; Damerow et al., 2007; Dorigoni et al., 2010; Mcclure and Cline, 2015; Mika et al., 2016; Miranda Sazo et al., 2016; Reighard and Henderson, 2012; Schupp and Kon, 2014; Seehuber et al., 2014b; Theron and De Villiers, 2014; Theron et al., 2016). However, great disparity exists regarding the machine configuration in order to get a good thinning result, and in some cases additional chemical or hand thinning treatments need to be combined to achieve satisfactory results (Basak et al., 2016; Beber et al., 2016; Hampson and Bedford, 2011; Kirstein, 2015; Kon et al., 2013).

Unlike chemical thinning agents, mechanical thinning results are not subject to cultivar, year, or weather conditions (Dorigoni et al., 2010). However, it can damage spur leaves of the flower cluster and therefore it can reduce photosynthesis, and in some cases increase fire blight (*Erwinia amylovora* Burill) (Greene and Costa, 2012; Ngugi and Schupp, 2009).

In any case, both chemical and mechanical thinning strategies save labor (Blanke and Damerow, 2008) (Seehuber et al., 2014b) and must be adjusted for each cultivar (Steyn et al., 2014). The aim of this study was to evaluate several new thinning agents, and evaluate various configurations for mechanical thinning on ‘Gala’, ‘Golden Delicious’ and ‘Fuji’.

Materials and Methods

Experiment 1: Kaolin, soap, vinegar, oils, and lime sulfur on ‘Red Chief® Camspur^{cov}’

A field experiment was conducted in 2004-2006 in Gimenells, Lleida, Spain (lat. 41.656203°, long. 0.389703°). We compared hand thinning with applications of kaolin (Kaolin type A, Guadasequies, Valencia, Spain) at 5 kg·hL^{-1} in 2004, and two consecutive sprays: 1st one at 5 kg·hL^{-1} and 2nd one at 3 kg·hL^{-1} in 2005-2006, potassium soap (E-Coda Oleo K, Coda, Almacelles, Lleida, Spain) at 4 L·hL^{-1}, pure vinegar (Pla d’Urgell Sat. Coop. C. Ltda., Mollerussa, Lleida, Spain) at 30 L·hL^{-1}, surfactant (nonylphenol polietilenglicol ether, Mojante no iónico, Químicas Oro, San Antonio de Benagéber, Valencia, Spain) at 1 $L \cdot hL^{-1}$, paraffin oil (Oil Oro, Químicas Oro, San Antonio de Benagéber, Valencia, Spain) at 2.5 $L \cdot hL^{-1}$, extra virgin olive oil (Pla d'Urgell Sat. Coop. C. Ltda., Mollerussa, Lleida, Spain) at 5 $L \cdot hL^{-1}$ emulsified with the above mentioned surfactant at 1 $L \cdot hL^{-1}$, corn oil (Borgesol, Borges, Tàrrega, Lleida, Spain) at 5 $L \cdot hL^{-1}$ emulsified with the surfactant above mentioned at 1 $L \cdot hL^{-1}$, and lime sulfur (LS) (Sulfocálcico Concentrado Key, Industrial Química Key, Tàrrega, Lleida, Spain) at 2, 4, and 6 $L \cdot hL^{-1}$ on 'Red Chief®' (Table 1). Applications were done between 50 and 80% F_2 (Fleckinger, 1964) to trees of 'Red Chief® Camspur^{cov}' on 'Merton MI-793', planted in 1995 with a tree spacing of 4 m x 1.5 m. Control trees were not sprayed and not mechanically or hand thinned either. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 2: Kaolin, soap, oils, lime sulfur, potassium permanganate, calcium chloride, and ammonium thiosulfate on 'Golden Smoothee® CG 10 Yellow Delicious'

A field experiment was conducted in 2005-2008 in Gimenells, Lleida, Spain where we compared hand thinning with two consecutive applications of kaolin (Surround® WG Crop protectant, BASF, Barcelona, Spain) at 5 $kg \cdot hL^{-1}$ (1st spray) and at 3 $kg \cdot hL^{-1}$ (2nd spray) (2005), potassium soap (E-Coda Oleo K, Coda, Almacelles, Lleida, Spain) at 4 $L \cdot hL^{-1}$ (2005-2007), extra virgin olive oil (Pla d'Urgell Sat. Coop. C. Ltda., Mollerussa, Lleida, Spain) emulsified with potassium soap (E-Coda Oleo K, Coda, Almacelles, Lleida, Spain) at 5:4 $L \cdot hL^{-1}$ (2005-2007), paraffin oil (Oil Oro, Químicas Oro, San

Antonio de Benagéber, Valencia, Spain) at 2.5 $L\cdot hL^{-1}$ (2005), LS at 4 $L\cdot hL^{-1}$ (2005-2008), salt (sodium chloride, Clásica, Sal Costa, Barcelona, Spain) at 2 $kg\cdot hL^{-1}$ (2005-2006), potassium permanganate (Permanganato Potasico Pure Grade, Barcelonesa, Cornellà de Llobregat, Barcelona, Spain) at 1 (2006) or 2 (2007-2008) $kg\cdot hL^{-1}$, calcium chloride (Cloruro Cálcico 77% Aliment. E-509, Drogueria-Pinturas El Barco, Xativa, Valencia, Spain) at 2 $kg\cdot hL^{-1}$ (2006-2007), ammonium thiosulfate (ATS) (Ger-ATS LG, L. Gobbi, Campo Ligure, Genova, Italy) at 1 $L\cdot hL^{-1}$ (2008), and lime sulfur (Sulfocálcico Concentrado Key, Industrial Química Key, Tàrrega, Lleida, Spain) plus paraffin oil at 4:1 $L\cdot hL^{-1}$ (2008) on 'Golden Smoothee®' (Table 1). Applications were done at 80% F_2 to trees of 'Golden Smoothee® CG 10 Yellow Delicious' on 'Malling M.9 Pajam® 2', planted in 1994 with a tree spacing of 4 m x 1.4 m. Control trees were not sprayed and not mechanically or hand thinned either. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 3: Chemical *vs* mechanical thinning on 'Fuji Kiku® 8 Brak' and 'Brookfield Gala® Baigent^{cov}'

A field experiment was conducted in 2010-2011 in Mollerussa, Lleida, Spain (lat. 41.618682°, long. 0.870560°) where we compared chemical and mechanical thinning, on 'Fuji Kiku® 8' and 'Brookfield Gala®', both planted in 2004 on 'Malling M.9' with a tree spacing of 3.5 m x 1.4 m. (Table 1). Chemical thinning treatments included benzyladenine (BA) (MaxCel®, Valent BioSciences Corp., Libertyville, IL) at 150 $mg\cdot L^{-1}$, and naphthalene acetic acid (NAA) (Etifix®, Nufarm España, S.A., Barcelona, Spain) at 10 $mg\cdot L^{-1}$. Thinning sprays were applied when fruit size was 10 mm. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string machine (Fuet; Fruttur®, Lleida, Spain) at 5 km·h^{-1} of tractor speed and 320 rpm of rotational speed with 210 strings. Control trees were not sprayed and not mechanically or hand thinned either. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 4: Mechanical *vs* chemical thinning on 'Golden Reinders®'

A field experiment was conducted in 2010 in La Tallada d'Empordà, Girona, Spain (lat. 42.054349°, long. 3.061983°) where we compared chemical *vs* mechanical thinning using a Darwin® 250 machine (Darwin®; Fruit-TeL Deggenhausertal, Germany) on 'Golden Reinders®' planted in 2003 on 'M.9 NAKB 337' with a tree spacing of 3.8 m x 1.1 m. Mechanical thinning was done at 80% F_1, at 7 or 8 km·h^{-1} and 270, 290, or 310 rpm with 270 strings (Table 1). Chemical thinning included BA (MaxCel®) at 100 mg·L^{-1}. Thinning sprays were applied when fruit size was 10 mm. Control trees were not sprayed and not mechanically or hand thinned either. The experiment was organized in a randomized complete block design with three replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 5: Mechanical *vs* chemical *vs* hand thinning on 'Gala Galaxy'

A field experiment was conducted in 2010 in La Tallada d'Empordà, Girona, Spain where we compared hand *vs* chemical *vs* mechanical thinning using a Darwin® 250 machine on 'Gala Galaxy' planted in 2000 on 'M.9 NAKB 337' with a tree spacing of

3.7 m x 1 m. Mechanical thinning was done at 80% F_1, at 5, 6, or 7 $km \cdot h^{-1}$ and 230, 270, or 310 rpm with 270 strings (Table 1). Chemical thinning included one application of naphthalene acetamide (NAD) (Amid-Thin®, Nufarm España, S.A., Barcelona, Spain) at 50 $mg \cdot L^{-1}$ 5 days after full bloom (DAFB), and another spray with MaxCel® at 150 $mg \cdot L^{-1}$ plus NAA at 12 $mg \cdot L^{-1}$ at 10 mm. The experiment was organized in a randomized complete block design with five replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 6: Mechanical *vs* chemical *vs* mechanical+chemical *vs* hand thinning on 'Brookfield Gala® Baigent^{cov}'

A field experiment was conducted in 2011 in La Tallada d'Empordà, Girona, Spain where we compared hand *vs* chemical *vs* mechanical *vs* mechanical+chemical thinning using a Darwin® 250 machine on 'Brookfield Gala® Baigent^{cov}' planted in 1999 on 'M.9 NAKB 337' with a tree spacing of 3.8 m x 1 m. Mechanical thinning was done at 80% F_1, 6 $km \cdot h^{-1}$ and 230 or 270 rpm with 270 strings (Table 1). Chemical thinning was the standard procedure used by the growers, and included two applications. The first application was done 5 DAFB with NAD (Amid-Thin®) at 50 $mg \cdot L^{-1}$, and the second one at 10 mm stage with BA (MaxCel®) at 150 $mg \cdot L^{-1}$ plus NAA at 12 $mg \cdot L^{-1}$. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of five trees. Data was taken on the three central trees of each experimental unit.

Experiment 7: Mechanical *vs* hand thinning on 'Golden Reinders®'

A field experiment was conducted in 2011 in La Tallada d'Empordà, Girona, Spain where we compared hand *vs* mechanical thinning using a Darwin® 250 machine on 'Golden Reinders®' planted in 2003 on 'M.9 NAKB 337' with a tree spacing of 3.8 m x 1.1 m. Three treatments of mechanical thinning (6 $km \cdot h^{-1}$ and 270 rpm with 270 strings) were done at E_2, F_1, and F_2 (Fleckinger, 1964) to evaluate the effect of phenological stage on the efficacy of the Darwin® device (Table 1). The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 8: Mechanical *vs* chemical *vs* mechanical+chemical *vs* hand thinning on 'Fuji Zhen® Aztec^{cov}'

A field experiment was conducted in 2011 in La Tallada d'Empordà, Girona, Spain where we compared hand *vs* chemical *vs* mechanical *vs* mechanical+chemical thinning using a Darwin® machine on 'Fuji Zhen® Aztec^{cov}' (Table 1) planted in 2006 on 'M.9 NAKB 337' with a tree spacing of 3.8 m x 1.1 m. Mechanical thinning was done at 80% F_1, 6 $km \cdot h^{-1}$ and 210 or 250 rpm with 270 strings. There were three chemical treatments: 1) ATS (AZOS™ 300, Yara Iberian, Madrid, Spain) at 3 $L \cdot hL^{-1}$, 2) ATS at 3 $L \cdot hL^{-1}$ + BA (MaxCel®) at 150 $mg \cdot L^{-1}$, and 3) mechanical + BA at 150 $mg \cdot L^{-1}$. All the chemical treatments were applied at 10 mm stage. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of five trees. Data was taken on the three central trees of each experimental unit.

Experiment 9: Mechanical *vs* chemical *vs* mechanical+chemical thinning on 'Gala Galaxy'

A field experiment was conducted in 2012 in La Tallada d'Empordà, Girona, Spain where we compared chemical *vs* mechanical *vs* mechanical plus chemical thinning using a Darwin® 250 machine on 'Gala Galaxy' planted in 2000 on 'M.9 NAKB 337' with a tree spacing of 3.7 m x 1 m. Mechanical thinning was done at 80% F_1, 6 km·h^{-1} and 250 rpm with 270 strings on the whole tree or just at the top of the tree (Table 1). There were two chemical treatments: 1) chemical standard, and 2) ATS. Chemical standard was the common thinning protocol used by the growers, and included two applications. The first application was done 5 DAFB with NAD (Amid-Thin®) at 50 mg·L^{-1}, and the second application was done at 10 mm stage with BA (MaxCel®) at 150 mg·L^{-1} plus NAA (Etifix®, Nufarm España, S.A., Barcelona, Spain) at 12 mg·L^{-1}. The second treatment included 3 sprays of ATS (AZOS™ 300, Yara Iberian, Madrid, Spain) at 2.5 L·hL^{-1} each at F_2, F_2 plus 4 days, and G (Fleckinger, 1964) plus the chemical standard treatment. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 10: Mechanical thinning at different phenological stages on 'Golden Reinders®'

A field experiment was conducted in 2012 in La Tallada d'Empordà, Girona, Spain where we compared the effect of mechanical thinning at different phenological stages using a Darwin® 250 machine on 'Golden Reinders®' planted in 2003 on 'M.9 NAKB

337’ with a tree spacing of 3.8 m x 1.1 m. Mechanical thinning was done at E_2, F_1, and F_2 at 6 km·h^{-1} and 270 rpm with 270 strings (Table 1). Mechanical thinning treatments were compared to control trees. Control trees were not sprayed and not mechanically or hand thinned either. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 11: Mechanical *vs* chemical *vs* hand thinning on ‘Golden Crielaard®’

A field experiment was conducted in 2013 in La Tallada d’Empordà, Girona, Spain where we compared hand *vs* chemical *vs* mechanical thinning using a Darwin® 250 machine on ‘Golden Crielaard®’ planted in 2006 on ‘M.9 NAKB 337’ with a tree spacing of 3.8 m x 1 m. Mechanical thinning was done at three different phenological stages (E_2, F_1, and G) at 6 km·h^{-1} and 230 rpm with 270 strings (Table 1). Chemical thinning consisted of two lime sulfur sprays (Sulfocálcico Concentrado Key, Industrial Química Key, Tàrrega, Lleida, Spain) at 4 L·hL^{-1}, at F_1, and 2 days after F_1. Control trees were not sprayed and not mechanically or hand thinned either. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 12: Mechanical *vs* hand thinning on ‘Gala Annaglo^{cov}’

A field experiment was conducted in 2014 in La Tallada d’Empordà, Girona, Spain where we compared hand *vs* mechanical thinning using a Darwin® 250 machine on ‘Gala

Annaglo^{cov}' planted in 2010 on 'M.9 NAKB 337' with a tree spacing of 3.8 m x 1.2 m. Mechanical thinning was done at 6 or 8 km·h^{-1}, and 250 or 290 rpm with 270 strings at 80% F_1 (Table 1). The experiment was organized in a randomized complete block design with three replications, with each experimental unit being a section of four trees. Data was taken on the two central trees of each experimental unit.

Experiment 13: Mechanical *vs* chemical thinning on 'Gala Schniga® Schnitzer'

A field experiment was conducted in 2016 in La Tallada d'Empordà, Girona, Spain where we compared the effect of mechanical *vs* chemical thinning using a Darwin® 250 machine on 'Gala Schniga®' (Table 1) planted in 2004 on 'M.9 NAKB 337' with a tree spacing of 3.8 m x 1 m. Mechanical thinning was done at 80% F_1, at 6 km·h^{-1} and 270 rpm with 270 strings. Chemical thinning consisted of one spray of BA (MaxCel®) at 150 mg·L^{-1} at 12 mm stage. The experiment was organized in a randomized complete block design with four replications, with each experimental unit being a section of five trees. Data was taken on the three central trees of each experimental unit.

Chemical application, hand thinning, and data collection

All chemical treatments were applied with a handgun sprayer until run-off. The spray volumes were 1000 L·ha^{-1} except in La Tallada d'Empordà for ATS applications that were performed at 500 L·ha^{-1} (Table 1). For all the experiments, trees were trained to a fruiting wall system with an average tree height of 4 m and canopy width of 1.5 m in Gimenells and Mollerussa, and 2.8 m height and 1.2 m width in La Tallada d'Empordà. Hand thinning was adjusted to 0.5-1 fruit per cluster and/or setting fruits apart within >15 cm to each other. Control trees were not sprayed and not mechanically or hand thinned either. Trials were managed within IPM management according to industry standards.

For each experiment, the following data was recorded for each single tree: (1) Trunk circumference (20 cm above the graft union) (cm), (2) total number of flower clusters, (3) total number of fruits and (4) yield (kg). Trunk cross-sectional area (TCSA), crop load (fruit # cm^2 of TCSA), fruit set, and fruit size were then calculated. Return bloom was measured the following spring, by counting the total number of flower clusters per tree (experiments 1-5, & 8).

All harvested fruit from each elemental plot were graded into classes according to size and color through a commercial sorting machine (trials of Lleida: MAF RODA Iberica, Alzira, Spain; trials of La Tallada d'Empordà: CALINDA, Caustier Ibérica, S.A. apple sorting and packing line by Aweta Technology). Fruit color was only assessed on 'Gala' and 'Fuji' (experiments 3, 5-6, 8-9, 12-13). From this data we calculated a simulated packout (economic value). Packout returns were taken from statewide averages of typical apple industry.

Data analysis

Each experiment was analyzed individually. Response variables for each experiment, year, and cultivar were modeled using linear mixed effect models. Mixed models including treatment as fixed factor and block as a random factor were built to separate treatment effects for the number of flower clusters per tree, fruit number, fruit number per 100 clusters, yield, TCSA, return bloom, economic value, crop load, and fruit size. Initial number of flower clusters per tree and tractor/rotational speed ratios from experiments 3-7 & 9-12 ('Gala' & 'Golden Delicious') were used to build a mixed model to predict the final fruit number output for each cultivar. For all the models, when the main effect (treatment) was significant, comparisons among treatments were made by Tukey's HSD test at *P* values ≤ 0.05. Residual analysis was performed to ensure that model assumptions were met. Data were analyzed using the JMP statistical software package (Version 12; SAS Institute Inc., Cary, NC).

Results

Experiment 1: Kaolin, soap, vinegar, oils, and lime sulfur on 'Red Chief®'

Overall in 2004, yield, fruit number per tree, and fruit number per 100 clusters were higher on control and hand thinned trees, as well as kaolin, surfactant, and vinegar sprayed-trees (Table 2). Kaolin sprayed-trees had the smallest fruits (191 g), and LS at 6% the largest (268 g). Significant differences for crop load were observed in 2004: Kaolin had the highest value (2.7 fruit/cm^2 of TCSA), whereas olive oil had the lowest (0.9 fruit/cm^2 of TCSA). However, significant differences within treatments were observed in 2004 regarding the initial number of flower clusters per tree, being control and hand thinned trees, and corn oil, LS 4-6%, olive oil and paraffin oil sprayed-trees the ones with the lowest number. No significant differences within treatments were observed in 2005 and 2006, when the initial number of flower clusters per tree was the same in all treatments.

Experiment 2: Kaolin, soap, oils, lime sulfur, potassium permanganate, calcium chloride, and ammonium thiosulfate on ‘Golden Smoothee®’

No significant differences regarding the initial number of flower clusters per tree and TCSA were observed (Table 3). In 2005, number of fruits per 100 clusters and yield were higher on control, LS, paraffin oil, and sodium chloride treatments. Fruit size was smaller for control, paraffin oil, and sodium chloride sprayed trees. Olive oil had the highest return bloom, whereas control trees, kaolin, paraffin oil, potassium soap, and sodium chloride had the lowest. Other than olive oil treatment, which had the lowest value, no significant differences were observed regarding economic value for the rest of the treatments. There were no significant differences regarding crop load between treatments, with the exception of olive oil (2.7 fruit/cm^2 of TCSA), which was significantly lower than control trees, paraffin oil, and sodium chloride treatments (~ 6.3 fruit/cm^2 of TCSA). In 2006, no significant differences among treatments were observed (Table 3).

In 2007, calcium chloride and control trees had the highest yields, fruit number per tree, and economic values, whereas olive oil sprayed-trees had the lowest (Table 3). No significant differences among treatments were observed in 2008.

Experiment 3: Chemical *vs* mechanical thinning on ‘Fuji Kiku® 8’ and ‘Brookfield Gala®’

No significant differences were observed in flower clusters per tree, TCSA, return bloom, and economic value for either ‘Gala’ or ‘Fuji’ trees among different treatments in 2010 and 2011 (Table 4). For ‘Gala’, fruit number and fruit number per 100 clusters were significantly lower for mechanical thinning compared to control trees. On the other hand, differences in yield were only observed in 2011, where mechanical thinning had lower yield than control or chemical treatments, but without significantly affecting the economic value. Fruit size was significantly larger for mechanical thinning than for control trees. Fruit number per tree in 2010 was higher than the ideal (155-185 fruit/tree for mature 'Gala' orchards in our conditions) for all the treatments, which considerably compromised fruit size (averaged for all treatments: 130 g in 2010 *vs* 183 g in 2011). In 2011, fruit number per tree was higher than the ideal range for control trees, whereas mechanical thinning gave values lower than the optimum range for our conditions (~125 fruit/tree *vs* 155-185 fruit/tree).

For 'Fuji', larger fruits were observed in 2010 when mechanical at 5 $km \cdot h^{-1}$ and 320 rpm plus chemical thinning was applied in comparison to control trees (Table 4). In 2010, fruit number per tree was considerably higher than the ideal range for mature 'Fuji' orchards in our conditions (150-170 fruit/tree, lower than 'Gala' to reduce biennial bearing). In 2011, fruit number per tree for mechanical thinning (without chemical follow up) was within the optimum range (156 fruit/tree); however, no significant differences between treatments were observed for both 2010 and 2011. No significant differences were observed in the rest of the variables either.

Experiment 4: Mechanical *vs* chemical thinning on 'Golden Reinders®'

Lower number of fruits per tree were observed on mechanical thinning treatments compared to control trees, whereas there were no significant differences between mechanical and chemical thinning treatments (Table 5). Similar yields were observed for control trees, chemical thinning, and Darwin® at 7 $km \cdot h^{-1}$ and 310 rpm, and 8 $km \cdot h^{-1}$ and 290 rpm. The lowest tractor (7 $km \cdot h^{-1}$) and rotation (270-290 rpm) speeds had lower yields than control trees. No significant differences among treatments were observed for fruit size, TCSA, return bloom, and economic value. Control trees had a crop load of 5.4 fruit/cm^2 of TCSA, whereas it was lower for chemical (4.7 fruit/cm^2 of TCSA) and mechanical thinning (2.2-3.3 fruit/cm^2 of TCSA), especially when tractor speed was at 7 $km\cdot h^{-1}$ and 270-290 rpm. Since this was a mature orchard (8th leaf), fruit number per tree should be used rather than crop load. In order to achieve good yields and fruit size, the optimum range for 'Golden Delicious' in our conditions is 80-110 fruit/tree. Control trees were already within the optimum range (99 fruit/tree). The chemical treatment reduced the crop slightly below the optimum range (78 fruit/tree), whereas mechanical treatments provided too much thinning (38-52 fruit/tree).

Experiment 5: Mechanical *vs* chemical *vs* hand thinning on 'Gala Galaxy'

No significant differences regarding TCSA, return bloom, and economic value were observed among chemical, hand, and mechanical thinning for 'Gala Galaxy' (Table 6). Fruit number and yield were higher for chemical thinning and mechanical at 6 $km\cdot h^{-1}$ and 230 rpm, whereas the lowest values were observed when tractor speed was 6 $km\cdot h^{-1}$ and 310 rpm. Chemical thinning had the smallest fruits (141 g), whereas mechanical thinning at 6 $km\cdot h^{-1}$ and 310 rpm had the largest fruits (180 g). Higher crop load values were observed for chemical thinning, hand thinning, and Darwin® at 6 $km\cdot h^{-1}$ and 230 rpm and at 7 $km\cdot h^{-1}$ and 270 rpm, the lowest value (3.6 fruit/cm^2 of TCSA) was observed when mechanical thinning was performed at 6 $km\cdot h^{-1}$ and 310 rpm. Since this was a mature orchard (11th leaf), fruit number per tree should be used rather than crop load. In order to achieve good yields, fruit size, and color, the optimum range for 'Gala' strains in our conditions is 155-185 fruit/tree. Chemical thinning was a little bit higher than the optimum range (192 fruit/tree), which compromised fruit size. On the other hand, mechanical at 6 km·h^{-1} and 230 rpm provided an optimum value (156 fruit/tree). The rest of the mechanical treatments, and even hand thinning provided values lower than the optimum.

Experiment 6: Mechanical *vs* chemical *vs* mechanical+chemical *vs* hand thinning on 'Brookfield Gala®'

No significant differences among yield, TCSA, and economic value were observed among chemical, mechanical, and hand thinning for 'Brookfield Gala®' (Table 7). On the other hand, higher number of fruits was observed for chemical thinning, followed by mechanical at 6 km·h^{-1}a and 230 rpm plus chemical, mechanical at 6 km·h^{-1} and 270 rpm, mechanical at 6 km·h^{-1} at 270 rpm plus chemical, and then hand thinning with the lowest values. Fruit size was largest for hand thinning (166 g), and smallest for chemical and mechanical at 6 km·h^{-1} and 230 rpm plus chemical (137 g and 142 g, respectively). Significant differences for crop load values were only observed between hand thinning and Darwin® at 6 km·h^{-1} and 270 rpm. However, both chemical and mechanical thinning at 6 km·h^{-1} and 230-270 rpm tended to have higher crop load values (~9 fruit/cm^2 of TCSA), which also compromised fruit size 137 g *vs* 166 g. In terms of thinning effect, hand thinning (176 fruit/tree) was the only treatment that provided a fruit number per tree within the ideal range (155-185 fruit/tree), the rest of the treatments had much higher number of fruits per tree, and mechanical plus chemical treatments were not even enough to reach that optimum range.

Experiment 7: Mechanical *vs* hand thinning on 'Golden Reinders®'

No significant differences regarding fruit number, yield, TCSA, crop load, and economic value were observed between mechanical and hand thinning for 'Golden Reinders®' (Table 8). Since this was a mature orchard (9^{th} leaf), fruit number per tree should be used rather than crop load. The initial number of flower clusters per tree was very high (>450), and trees were not thinned enough for any of the treatments (196-299 fruit/tree *vs* the optimum range of 80-110 fruit/tree), which compromised fruit size, resulting in only 123 g on average among all treatments.

Experiment 8: Mechanical *vs* chemical *vs* mechanical+chemical *vs* hand thinning on 'Fuji Zhen® Aztec^{cov}'

No significant differences were observed among chemical, mechanical, and hand thinning in any of the variables such as fruit number, yield, fruit size, TCSA, return bloom, crop load, and economic value for 'Fuji Zhen® Aztec^{cov}' (Table 9). Since this was a young orchard (6^{th} leaf) where trees did not fill their allotted space, crop load is a better indicator than fruit number in this case. Crop load values were significantly higher (~9 fruit/cm^2 of TCSA) than the ideal range for our conditions (3-4 fruit/cm^2 of TCSA).

Experiment 9: Mechanical *vs* chemical *vs* mechanical+chemical thinning on 'Gala Galaxy'

No differences in yield, fruit number, and TCSA were observed for 'Gala Galaxy' between chemical and mechanical thinning (Table 10). Significantly more fruits per 100 clusters were observed for chemical thinning treatments compared to mechanical thinning at the top of the trees plus chemical thinning sprays. Fruit size was larger when chemical thinning was applied in combination with mechanical thinning at the top of the trees. Higher economic value was observed for the standard chemical thinning, whereas the lowest was when mechanical thinning was done only at the top of the trees. Darwin® at 6 $km\cdot h^{-1}$ and 250 rpm at the top of the trees, plus a chemical spray had the lowest crop load value (4.7 fruit/cm^2 of TCSA), whereas the chemical treatment had the highest (8.5 fruit/cm^2 of TCSA). In terms of thinning effect, fruit number per tree should be used since this was a mature orchard (13^{th} leaf). Darwin® at 6 $km\cdot h^{-1}$ and 250 rpm provided numbers of fruit per tree within the ideal range of 155-185 fruit/tree, with better fruit sizes than when it was performed only at the top of the trees. Lower values than the ideal range were obtained when chemical thinning followed up mechanical, or when ATS plus the chemical standard were applied.

Experiment 10: Mechanical thinning at different phenological stages on 'Golden Reinders®'

Significantly higher number of fruits was observed on control trees than on mechanically thinned (Table 11). The lowest yield and fruit number per 100 clusters were observed when mechanically thinning at stage F_1, followed by stage E_2, stage F_2, and then control trees. Fruit size was larger when mechanical thinning was done at E_2 and F_2 stages compared to control. No significant differences regarding TCSA and economic value were observed. Significant differences were observed regarding crop load, having the mechanical thinning lower values (~3 fruit/cm^2 of TCSA) than control trees (6.1 fruit/cm^2 of TCSA). Since this was a mature orchard (10^{th} leaf), fruit number per tree should be used rather than crop load. For this experiment, the initial number of flower clusters per tree was significantly lower (~100), and the final fruit/tree for control trees was close to the ideal range, but with slightly higher number of fruit (119 fruit/tree *vs* 80-110 fruit/tree), which compromised fruit size. Mechanical treatments provided too much thinning, lower than the ideal range (50-67 fruit/tree *vs* 80-110 fruit/tree).

Experiment 11: Mechanical *vs* chemical *vs* hand thinning on 'Golden Crielaard®'

Similar results regarding yield and fruit number were observed for control trees, mechanical thinning at 6 $km \cdot h^{-1}$ and 230 rpm at stage G, and chemical thinning with LS (Table 12). Largest fruits were observed for hand thinning treatments (184 g), whereas the smallest ones were for chemical and control (150 g), and mechanical thinning at 6 $km \cdot h^{-1}$ and 230 rpm at E_2 (154 g). No significant differences regarding TCSA and economic value were observed. Control and LS treatments had the highest crop load values (10.6 and 8.8 fruit/cm^2 of TCSA), notably higher than hand thinning (5.4 fruit/cm^2 of TCSA). Hand thinning (5.4 fruit/cm^2 of TCSA) and mechanical at stages F_1 and G (6.8 fruit/cm^2 of TCSA) had crop values with no significant differences among them. Since this was a mature orchard (8th leaf), fruit number per tree should be used rather than crop load. With the exception of Darwin® performed at petal fall (G phenological stage), mechanical and hand thinning provided a final fruit number per tree within the optimum range (80-110 fruit/tree), whereas chemical and control trees had too many fruit, which compromised fruit size.

Experiment 12: Mechanical *vs* hand thinning on 'Gala Annaglo^{cov}'

No significant differences for fruit number, yield, fruit size, TCSA, and economic value were observed between mechanical and hand thinning for 'Gala Annaglo^{cov}' (Table 13).

No significant differences within treatments were observed regarding crop load. Since this was a young orchard (5th leaf) where trees did not fill their allotted space, crop load is a better indicator than fruit number in this case. While all the mechanical treatments had crop load values within the optimum range for our conditions (5-6 fruit/cm^2 of TCSA), Darwin® at 8 $km \cdot h^{-1}$ tended to have lower values (~5 fruit/cm^2 of TCSA) than at 6 $km \cdot h^{-1}$ (6 fruit/cm^2 of TCSA).

Experiment 13: Mechanical *vs* chemical thinning on 'Gala Schniga® Schnitzer'

No significant differences for yield, fruit size, TCSA, and economic value were observed among treatments for 'Gala Schniga®' (Table 14). Fruit number was similar when comparing chemical *vs* mechanical thinning, and significantly lower when mechanical and thinning treatments were combined. While no significant differences within treatments were observed regarding crop load, values were halved when mechanical and chemical thinning were combined. For all the three different treatments, fruit number per tree was far from the optimum range of 155-185 fruit/tree, which also compromised fruit size.

Mechanical thinning output model

With low root mean square error values for both models (24-28), tractor/rotational speed ratio and initial number of flower clusters per tree were highly significant in predicting the final fruit number per tree once mechanical thinning was performed (Table 15). The tractor/rotational speed ratio (speed/rpm) had a positive slope for 'Gala', and negative for 'Golden Delicious', suggesting different behavior for each cultivar. For 'Gala', the model was: Fruit# = – 172.32 + 6925.75(speed/rpm) + 0.64(flower cluster #/tree) + (speed/rpm – 0.02242)*[(flower clusters/tree – 252.235)*36.14]. For 'Golden Delicious', the model was: Fruit# = 291.63 – 12818.91(speed/rpm) + 0.55(flower cluster #/tree) + (speed/rpm – 0.0239)*[(flower clusters/tree – 243.21)*64.99]. For both models, high R^2 were obtained, 0.9 for 'Gala', and 0.92 for 'Golden Delicious'.

Discussion

Fruit thinning is one of the most important yet difficult practices that drives orchard profitability. In addition, the effect of the thinners changes among years and cultivars and therefore, mid to long term trials must be carried out to get reliable results. The first set of trials that we performed consisted on the application of several products at bloom to cause a thinning effect by hindering flower pollination or fecundation (Experiments 1 and 2). No significant differences for fruit number per tree and fruit size between thinning treatments and control trees of Experiment 1 (2004-2006) & Experiment 2 (2006-2007) suggested that no thinning was needed for those years. Therefore, conclusions from these trials could be only extracted from year 2005 of Experiment 2. In that case, olive oil had a considerable thinning effect since the fruit set was lower than the control, and even the increase in fruit size (180 g *vs* 159 g), was not enough to prevent a significant reduction in economic value. The rest of the treatments were not able to thin enough flowers to affect fruit weight. Experiments with different vegetable oils (corn, rape, and olive) have reported a fruit set reduction but an increase of fruit size (Ju et al., 2001; Pfeiffer and Rueß, 2002a; Warlop, 2002a). In addition, higher russetting was observed when olive oil or potassium soap were applied (data not shown). Therefore, their use is not advisable for russetting prone cultivars such as 'Golden Delicious'. On the other hand, they could be alternative thinner agents for cultivars such as ‘Red Delicious’; however, further tests should be addressed to confirm rates.

Regarding other treatments, LS did not have a consistent thinning effect in our study. Similarly, Hampson and Bedford (2011) and Weibel et al. (2004) reported certain thinning effect, but was not enough since hand thinning was still required to achieve the desired thinning. On the other hand, Warlop (2002a) did achieve a good thinning effect. Combinations of LS plus olive oil were used by Alrashedi and Singh (2014), however, leaf burning was observed. Mcartney et al. (2006) suggested that the thinning effect of LS may be caused by the reduction in carbohydrate supply to fertilized flowers; hence, repeat applications of LS may be needed.

In the second set of trials (Experiments 3-13), we assessed different tractor and rotational speeds to adjust on three cultivars and, we tested if mechanical thinning reached similar efficacy as chemical or manual thinning. Overall, no differences regarding economic value between hand, chemical, and mechanical thinning were observed. This indicates mechanical thinning as an alternative approach to chemical and hand thinning, since all three methods were equally valid regarding the desired level of thinning effect. Some studies have even reported mechanical thinning to improve fruit quality (Asteggiano et al., 2015; Hehnen et al., 2012; Seehuber et al., 2010; Solomakhin and Blanke, 2010; Veal et al., 2011). In our study, there were some experiments where the economic value for control tress was no different than thinning treatments (Experiments 3-4 & 10-11). However, in those cases no differences regarding fruit number were neither observed for control *vs* chemically thinned trees (Experiments 3-4), or fruit number per tree for control trees was already too low (Experiment 10), suggesting that no thinning was needed in these cases. No differences regarding economic value between chemical, hand, and mechanical thinning *vs* control trees were neither observed in Experiment 11; nevertheless, the fact that control trees had significantly higher number of fruit per tree, might affect economic value the following year due to poor return bloom.

Similar fruit size and yield were observed for chemical and mechanical thinning at 5 $km \cdot h^{-1}$ and 320 rpm of rotational speed when performed on 'Fuji' (Experiment 3). On the other hand, while no significant differences were observed for 'Brookfield Gala®' in 2010, lower yield on mechanical thinning treatments was observed in 2011 (Experiment 3). Similar effects on yield were also reported by Solomakhin and Blanke (2010) when using 300 rpm and 5 $km \cdot h^{-1}$ with a Baum® machine on 'Mondial Gala®', or by Hehnen et al. (2012) on 'Buckeye Gala®', when increasing rotational speed to 360 rpm and reducing tractor speed to 2.5 $km \cdot h^{-1}$. Solomakhin et al. (2012) reported a 45% of yield decrease on 'Mondial Gala®' when rotational speed was increased up to 420 rpm. Mcclure and Cline (2015) with a Darwin® machine at 3.2 $km \cdot h^{-1}$ and 180-240 rpm did not observe a significant yield reduction on 'Royal Gala®'. Both Kon et al. (2013) with a Darwin®, and Damerow et al. (2007) with a Baum® machine, reported higher blossom removal as rotational speed increased. On the other hand, a study conducted by Sinatsch et al. (2010) on 'Pinova^{cov}', did not reveal significant differences when maintaining a tractor speed at 3.2 $km \cdot h^{-1}$, and rotational speeds from 200 to 220 rpm. In our successive experiments, further configurations of rotational and tractor speeds were tested. Keeping the same tractor speed at 5 $km \cdot h^{-1}$ and reducing the rotational speed from 300 to 270 rpm provided the same yield as hand thinning, but lower than chemical thinning on 'Gala Galaxy' (Experiment 5). On the other hand, 6 $km \cdot h^{-1}$ and 230 rpm had similar yields as chemical and hand thinning treatments, and provided 156 fruit/tree, which is within the ideal range of a commercial mature crop for 'Gala' in our conditions (155-185 fruit/tree). In contrast, 270 rpm at 5, 6, or 7 km·h^{-1} gave lower values (111-135 fruit/tree), which are significantly lower than the ideal values for our conditions. In another of our experiments with 'Gala Brookfield®' (Experiment 6), no differences regarding fruit size were observed, whereas higher number of fruit per tree (257 *vs* 176 fruit/tree) when using Darwin® at 6 km·h^{-1} and 270 rpm *vs* hand thinning was attained. Further experiments that we performed with 'Gala' strains (Experiments 9 & 12) confirmed 6 km·h^{-1} and 250 rpm as the best set parameters to provide an ideal fruit number per tree for mature orchards (155-185 fruit/tree) or an ideal crop load of ~6 fruit/cm^2 of TCSA for non mature orchards, and an average fruit size of 170 g, with no significant differences to the standard chemical and hand thinning practices. Increasing tractor speed to 8 km·h^{-1} seemed to reduce fruit number per tree, however, no significant differences were observed. Conversely, Dorigoni et al. (2010) reported that increasing tractor speed will decrease the thinning effect, whereas increasing rotational speed will increase it. A study made by Solomakhin et al. (2012) reported higher yields with 'Mondial Gala®' when tractor speed was set at 7.5 km·h^{-1} and rotation speed at 360 rpm.

For 'Fuji', 6 km·h^{-1} and 250 rpm provided a crop load of 9 fruit/cm^2 of TCSA, and 236 g of average fruit size (Experiment 8), values that are not in accordance to the optimum range for young orchards for this cultivar in our conditions (3-4 fruit/cm^2 of TCSA). On the other hand, 5 km·h^{-1} and 320 rpm provided 156 fruit/tree (Experiment 3), within our optimum goal (150-170 fruit/tree). However, that range was only achieved when the initial number of flower clusters per tree was 200 or below. With about 500 flower clusters per tree, mechanical at 5 $km \cdot h^{-1}$ and 320 rpm plus chemical thinning were not enough to achieve the desired thinning. Even though no significant differences with the hand thinning treatment were observed regarding yield, return bloom, and economic value, ‘Fuji’ has a marked biennial bearing habit. Therefore, combination of mechanical thinning plus chemical treatments might be the ideal strategy when the initial number of flower clusters per tree is above 500. In addition, reducing the rotational speed from 250 to 210 rpm plus a chemical spray of BA gave a similar crop load and fruit size values, suggesting as an alternative for those areas where spring frost might be a problem. A study made by Dorigoni et al. (2010) in Italy, reported 6 $km \cdot h^{-1}$ and 230 rpm to provide a slightly higher yield than the optimum for ‘Fuji’, which reduced return bloom the following year. In that study, a combination of mechanical thinning (with the aforementioned parameters) plus chemical sprays (either BA or NAA) gave the best results. In our study, return bloom was not reduced when using either 210 or 250 rpm compared to hand thinning. Thus, the higher rotational speed that we used (250 rpm *vs* 210 rpm) can save fruitlet a chemical thinning treatment thereafter.

With ‘Golden Delicious’, we started our tests with 7-8 $km \cdot h^{-1}$ and 270-310 rpm (Experiment 4), which provided too much thinning; however, control trees in that year were already within the optimum range. On the following test with ‘Golden Delicious’ (Experiment 7), we reduced the tractor speed to 6 $km \cdot h^{-1}$ and kept the rotational speed to 270 rpm, but the thinning was not enough, even for the hand thinned treatments (no significant differences with the mechanical), which also compromised fruit size. In that experiment the initial number of flower clusters per tree was very high (>450), which may explain why not any mechanical treatment and even the hand thinning were enough to achieve the desired optimum range. The same tractor and rotational speeds were used in Experiment 10, but in that case the final fruit number per tree that was achieved for mechanical thinning treatments was lower than the optimum range. Since control trees were already close to that optimum, just a slight thinning to improve fruit size should have been performed that year. Yet, that same tractor and rotational speeds (6 km·h^{-1} and 270 rpm) significantly reduced the crop compared to control. Rotational speed was reduced from 270 to 230 rpm in a successive experiment (#11), which provided the final fruit number per tree within the optimum range, with no significant differences this time regarding yield and fruit size compared to hand or chemical thinning. These results are consistent with Dorigoni et al. (2010) and Seehuber et al. (2014a), who found that reducing rotational speed decreased the thinning effect. A study made by Solomakhin et al. (2012) on 'Golden Reinders®' did not see significant differences in yield when comparing hand to mechanical thinning at 5-7.5 km·h^{-1} and 300-480 rpm. On the other hand, another study by Veal et al. (2011) suggested 5-7.5 km·h^{-1} and 300-420 rpm to get the best thinning efficacy on 'Golden Delicious', 'Gala', 'Elstar', and 'Braeburn'.

Mechanical thinning timing was also examined at different phenological stages (E_2, F_1, F_2, and G (Fleckinger, 1964)) in our study (Experiments 7, 10, & 11). However, no significant differences regarding yield, fruit size, fruit set (fruit number/100 clusters), or crop load were observed among them. Seehuber et al. (2014b) suggested E_2 to F_2 as the ideal timing window for mechanical thinning, whereas a wider window was suggested by Veal et al. (2011) (E_2 to G). Hence, reference studies have been performed at different stages like F_1 (Basak et al., 2016; Mcclure and Cline, 2015), pink bud (E_2) to full bloom (F_2) (Miranda Sazo et al., 2016; Solomakhin et al., 2012; Veal et al., 2011), at full bloom

(F_2) (Hehnen et al., 2012; Kirstein, 2015; Kon et al., 2013; Solomakhin and Blanke, 2010), or even at 30% of petal fall (Kirstein, 2015). The fact that mechanical thinning is less dependent on phenological stage than timing of chemical thinners will allow more time to manage different spring situations, like spring frost forecasts, in order to delay the treatment for safety reasons.

Performing such a large number of experiments was key to indicate the best parameter configuration to mechanically thin 'Fuji', 'Gala', and 'Golden Delicious' in order to achieve optimum fruit number per tree ranges. However, these parameters might vary, or not be that accurate in other conditions or where the initial number or flower clusters per tree is quite different.

In spite of both 'Gala' and 'Golden Delicious' having a type III growth habit (Lespinasse, 1977), 'Gala' has narrower branch angles (Ferree and Warrington, 2003), which may affect its response to mechanical thinning. Furthermore, cultivar-specific return bloom associated with different optimum fruit/tree values for each cultivar (80-110 fruit/tree 'Golden Delicious', 155-185 fruit/tree 'Gala') may also require different approaches. In order to address that, two prediction models were developed in our study to adjust the right tractor and rotational speeds depending on the initial number of flower clusters. Therefore, following a similar protocol that is often used for precision chemical thinning (Robinson et al., 2014; Robinson and Lakso, 2011a; Robinson and Lakso, 2011b; Robinson et al., 2013) these models will help to set more accurate parameters (tractor and rotational speeds) once the desired number of fruits per tree is decided. Conversely to what happens with chemical thinning, obtaining good results from mechanical thinning will be much easier, since it is not so reliable to year or environmental/weather conditions

(Dorigoni et al., 2010). Furthermore, thinning strategies used for chemical and mechanical thinning may need to be combined in scenarios of high return bloom, when the initial number of flower clusters is high (>400 flower cluster per tree). New research is focusing in the development of a mechanical thinner prototype that include cameras to adjust thinning intensity based on the actual flower density (Pflanz et al., 2016). However, feasibility of this approach is still being studied (Pflanz et al., 2016). Based in our study, 6 $km \cdot h^{-1}$ and 250 rpm would be an initial starting point to adjust mechanical thinning. Furthermore, these parameters (tractor and rotational speeds) can be set more accurately if we know the initial number of flower clusters per tree. To our knowledge, these are the first models that help to adjust mechanical thinning to a desired final fruit number per tree. The method begins with first calculating the final fruit number needed per tree in order to achieve the desired yield (crop load for each particular cultivar, depending on local conditions/historic experience and market price according to fruit size). Then, once knowing the initial number of flower clusters per tree, tractor and rotational speeds can be adjusted.

In this study, we evaluated several agents and mechanical thinning to offer an alternative to conventional thinners. The overall analysis of the results showed that olive oil can cause thinning but its rate must be adjusted to avoid fruit russetting. On the other hand, mechanical thinning offers more consistent results than chemical thinning, and comparable to the desired levels achieved by hand thinning.

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Tables

Table 1. List of experiment number, year, location, cultivar, treatments and timing performed for the different thinning trials.

Experiment #	Year	Location	Cultivar	Treatments	Timing
1	2004	Gimenells, Lleida,	Red Chief®	Kaolin 5 kg·hL^{-1} (2004)	80% F2
	2005	Spain		Kaolin 5+3 kg·hL^{-1} (2005 & 2006)	
	2006			Potassium soap 4 L·hL^{-1} (2004-2006)	
				Vinegar 30 L·hL^{-1} (2004-2006)	
				Surfactant 1 L·hL^{-1} (2004-2006)	
				Paraffin oil 2.5 L·hL^{-1} (2004-2006)	
				Olive oil 5 L·hL^{-1} (2004-2006)	
				Corn oil 5 L·hL^{-1} (2004-2005)	
				Lime sulfur 2 L·hL^{-1} (2004-2006)	
				Lime sulfur 4 L·hL^{-1} (2004-2006)	
				Lime sulfur 6 L·hL^{-1} (2004-2006)	
				Untreated control (2004-2006)	
				Hand thinning (2004-2006)	
2	2005	Gimenells, Lleida,	Golden Smoothee®	Kaolin 5+3 kg·hL^{-1} (2005)	80% F2
	2006	Spain		Potassium soap 4 L·hL^{-1} (2005-2007)	
	2007			Olive oil 5 L·hL^{-1} + potassium soap 4 L·hL^{-1} (2005-2007)	
	2008			Paraffin oil 2.5 L·hL^{-1} (2005)	
				Lime sulfur 4 L·hL^{-1} (2005-2008)	
				Sodium chloride 2 kg·hL^{-1} (2005-2006)	
				Potassium permanganate 1 kg·hL^{-1} (2006)	
				Potassium permanganate 2 kg·hL^{-1} (2007-2008)	
				Calcium chloride 2 kg·hL^{-1} (2006-2007)	
				Ammonium thiosulfate (ATS) 1 L·hL^{-1} (2008)	
				Lime sulfur 4 L·hL^{-1} + paraffin oil 1 L·hL^{-1} (2008)	
				Untreated control (2005-2008)	
				Hand thinning (2005-2007)	
3	2010	Mollerussa, Lleida,	Fuji Kiku® 8	Chemical: BA 150 mg·L^{-1} + NAA 10 mg·L^{-1}	10 mm

Experiment #	Year	Location	Cultivar	Treatments	Timing
	2011	Spain	Gala Brookfield®	Fuet Fruttur® 5 km·h^{-1} & 320 rpm	80% F1
				Fuet Fruttur® 5 km·h^{-1} & 320 rpm → chemical	
				Untreated control	
4	2010	La Tallada d'Empordà, Girona, Spain	Golden Reinders®	Darwin® 7 km·h^{-1} & 270 rpm	80% F1
				Darwin® 7 km·h^{-1} & 290 rpm	
				Darwin® 7 km·h^{-1} & 310 rpm	
				Darwin® 8 km·h^{-1} & 290 rpm	
				BA 100 mg·L^{-1}	10 mm
				Untreated control	
5	2010	La Tallada d'Empordà, Girona, Spain	Gala Galaxy	NAD 50 mg·L^{-1} (5DAFB) & BA 150 mg·L^{-1} + NAA 12 mg·L^{-1} (10 mm)	
				Darwin® 5 km·h^{-1} & 270 rpm	80% F1
				Darwin® 6 km·h^{-1} & 230 rpm	
				Darwin® 6 km·h^{-1} & 270 rpm	
				Darwin® 6 km·h^{-1} & 310 rpm	
				Darwin® 7 km·h^{-1} & 270 rpm	
				Hand thinning	
6	2011	La Tallada d'Empordà, Girona, Spain	Gala Brookfield®	Chemical: NAD 50 mg·L^{-1} (5DAFB) & BA 150 mg·L^{-1} + NAA 12 mg·L^{-1} (10 mm)	
				Darwin® 6 km·h^{-1} & 270 rpm	80% F1
				Darwin® 6 km·h^{-1} & 230 rpm → chemical	
				Darwin® 6 km·h^{-1} & 270 rpm → chemical	
				Hand thinning	
7	2011	La Tallada d'Empordà, Girona, Spain	Golden Reinders®	Darwin® 6 km·h^{-1} & 270 rpm	E2
				Darwin® 6 km·h^{-1} & 270 rpm	F1
				Darwin® 6 km·h^{-1} & 270 rpm	F2
				Hand thinning	
8	2011	La Tallada d'Empordà, Girona, Spain	Fuji Zhen® Aztec^{cov}	ATS 3 L·hL^{-1}	10 mm
				ATS 3 L·hL^{-1} → BA 150 mg·L^{-1}	
				Darwin® 6 km·h^{-1} & 210 rpm	80% F1
				Darwin® 6 km·h^{-1} & 250 rpm	
				Darwin® 6 km·h^{-1} & 210 rpm → BA 150 mg·L^{-1}	80% F1 + 10 mm
				Hand thinning	

Experiment #	Year	Location	Cultivar	Treatments	Timing
9	2012	La Tallada d'Empordà, Girona, Spain	Gala Galaxy	Chemical: NAD 50 $mg\cdot L^{-1}$ (5DAFB) & BA 150 $mg\cdot L^{-1}$ + NAA 12 $mg\cdot L^{-1}$	(10 mm)
				Darwin® 6 $km\cdot h^{-1}$ & 250 rpm on the whole tree	80% F1
				Darwin® 6 $km\cdot h^{-1}$ & 250 rpm at the top of the tree	
				Darwin® 6 $km\cdot h^{-1}$ & 250 rpm at the top → chemical	
				ATS $mg\cdot L^{-1}$ 3x (F2, F2+4 & G) → chemical	
10	2012	La Tallada d'Empordà, Girona, Spain	Golden Reinders®	Darwin® 6 $km\cdot h^{-1}$ & 270 rpm at E2	E2
				Darwin® 6 $km\cdot h^{-1}$ & 270 rpm at F1	F1
				Darwin® 6 $km\cdot h^{-1}$ & 270 rpm at F2	F2
				Untreated control	
11	2013	La Tallada d'Empordà, Girona, Spain	Golden Crielaard®	Lime sulfur $mg\cdot L^{-1}$ 2x (F1 & F1+2D)	
				Darwin® 6 $km\cdot h^{-1}$ & 230 rpm at E2	E2
				Darwin® 6 $km\cdot h^{-1}$ & 230 rpm at F1	F1
				Darwin® 6 $km\cdot h^{-1}$ & 230 rpm at G	G
				Untreated control	
				Hand thinning	
12	2014	La Tallada d'Empordà, Girona, Spain	Gala Annaglo[cov]	Darwin® 6 $km\cdot h^{-1}$ & 250 rpm	80% F1
				Darwin® 8 $km\cdot h^{-1}$ & 250 rpm	
				Darwin® 8 $km\cdot h^{-1}$ & 290 rpm	
				Hand thinning	
13	2016	La Tallada d'Empordà, Girona, Spain	Gala Schniga®	BA 150 $mg\cdot L^{-1}$	10 mm
				Darwin® 6 $km\cdot h^{-1}$ & 270 rpm	80% F1
				Darwin® 6 $km\cdot h^{-1}$ & 270 rpm →BA150	

Table 2. Effects of corn oil, kaolin, lime sulfur (LS), olive oil, paraffin oil, potassium soap, surfactant, vinegar, and hand thinning on 'Red Chief®' in Gimenells 2004-2006 (Experiment 1). Applications were done at 80% F_2 (Fleckinger, 1964). Control trees were unsprayed. Return bloom was measured the following spring, by counting the total number of flower clusters per tree. Economic value was calculated using the simulated packout and the industry price standards.

Year	Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA[z] (cm^2)	Return bloom(flower clusters #/tree)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
2004	Control	154 B	185 AB	119 A	38 AB	219 AB	94	495	11 ABCD	1.9 ABC
	Corn oil	197 B	118 B	61 BC	28 BC	251 AB	95	542	9 BCD	1.3 BC
	Hand	164 B	150 B	95 ABC	36 ABC	250 AB	92	533	12 ABC	1.6 ABC
	Kaolin	248 AB	277 A	116 AB	51 A	191 B	104	523	13 AB	2.7 A
	LS 2%	213 AB	138 B	71 ABC	32 BC	236 AB	91	577	10 ABCD	1.5 ABC
	LS 4%	181 B	120 B	75 ABC	28 BC	238 AB	100	560	9 CD	1.3 BC
	LS 6%	198 B	114 B	59 C	28 BC	268 A	109	540	9 ABCD	1.0 BC
	Olive oil	171 B	88 B	54 C	22 C	255 AB	99	489	7 D	0.9 C
	Paraffin oil	185 B	146 B	86 ABC	34 BC	240 AB	104	479	11 ABCD	1.4 BC
	Potassium soap	311 A	182 AB	60 C	37 ABC	212 AB	103	479	11 ABCD	1.9 ABC
	Surfactant	212 AB	178 AB	98 ABC	39 AB	225 AB	103	532	12 ABC	1.7 ABC
	Vinegar	205 AB	195 AB	96 ABC	43 AB	228 AB	91	520	13 A	2.1 AB
	P	0.0014	0.0002	0.0011	<0.0001	NS	NS	NS	0.0004	0.0003
2005	Control	495	356	74	65	186	106	293	17	3.4
	Corn oil	542	372	69	64	177	101	197	16	3.7
	Hand	533	293	55	60	205	97	363	17	3.1
	Kaolin	523	416	81	72	176	106	269	17	3.9
	LS 2%	577	366	63	64	179	96	279	15	3.8
	LS 4%	560	392	70	69	179	107	317	17	3.7
	LS 6%	540	336	62	62	189	116	297	16	2.9
	Olive oil	489	277	55	52	190	104	284	14	2.8
	Paraffin oil	479	363	77	66	186	111	248	17	3.3
	Potassium soap	479	320	66	62	195	107	312	17	3.0
	Surfactant	532	332	62	61	186	108	328	16	3.1

	Vinegar	520	380	73	64	173	97	269	15	3.9
	P	NS	NS	NS	NS	NS	NS	NS	NS	NS
2006	Control	293	94	33	26	276	112		9	0.8
	Hand	363	102	29	28	277	108		9	0.9
	Kaolin	269	82	30	23	280	123		8	0.7
	LS 2%	279	71	24	19	279	104		6	0.7
	LS 4%	317	70	21	19	282	119		6	0.6
	LS 6%	297	61	21	18	299	127		6	0.5
	Olive oil	284	61	22	17	277	115		6	0.5
	Paraffin oil	248	64	32	18	289	128		6	0.5
	Potassium soap	312	89	29	23	259	115		7	0.8
	Surfactant	328	74	23	20	282	117		7	0.6
	Vinegar	269	68	28	20	287	106		6	0.6
	P	NS	NS	NS	NS	NS	NS		NS	NS

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 3. Effects of kaolin, lime sulfur (LS), olive oil, paraffin oil, potassium soap, sodium chloride, ammonium thiosulfate (ATS), potassium permanganate, and hand thinning on 'Golden Smoothee®' in Gimenells 2005-2008 (Experiment 2). Applications were done at 80% F_2 (Fleckinger, 1964). Control trees were unsprayed. Return bloom was measured the following spring, by counting the total number of flower clusters per tree. Economic value was calculated using the simulated packout and the industry price standards.

Year	Treatment	Flower clusters/tree	Fruit #/tree		Fruit #/ 100 clusters		Yield/tree (kg)		Fruit size (g)		TCSA[z] (cm^2)	Return bloom (flower clusters#/tree)		Economic value (€/tree)		Crop load (fruit #/TCSA cm^2)	
2005	Control	360	493	A	137	A	78	A	159	C	79	63	B	14	A	6.3	A
	Hand	359	305	CD	87	BC	59	C	194	A	79	86	AB	14	A	3.9	AB
	Kaolin	285	390	ABC	139	A	64	BC	165	BC	77	70	B	12	AB	5.2	AB
	LS	339	386	ABC	114	AB	65	ABC	170	BC	78	86	AB	13	A	5.1	AB
	Olive oil	325	230	D	71	C	41	D	180	AB	86	127	A	9	B	2.7	B
	Paraffin oil	341	474	AB	140	A	73	AB	155	C	75	58	B	13	A	6.4	A
	Potassium soap	321	371	BC	118	AB	63	BC	170	BC	76	80	B	13	A	5.0	AB
	Sodium chloride	338	462	AB	137	A	72	ABC	156	C	81	65	B	12	A	6.3	A
	P	NS	<0.0001		<0.0001		<0.0001		<0.0001		NS	0.0010		0.0007		0.0135	
2006	Calcium chloride	121	146		166		24		165		92	394		4		1.6	
	Control	176	315		242		48		156		79	438		7		4.1	
	Hand	225	195		125		33		187		81	392		6		2.4	
	LS	223	287		162		41		157		90	367		6		3.0	
	Olive oil	179	242		185		36		152		87	448		6		2.8	
	Potassium permanganate	252	307		179		45		164		93	303		7		3.4	
	Potassium soap	261	334		201		49		152		73	346		7		4.5	
	Sodium chloride	165	256		243		38		158		85	356		6		3.0	
	P	NS	NS		NS		NS		NS		NS	NS		NS		NS	
2007	Calcium chloride	425	197	A	46	A	32	A	162		86	247		6	A	2.3	AB
	Control	392	175	AB	44	AB	29	AB	166		69	330		5	A	2.6	A
	Hand	398	112	AB	28	C	21	AB	189		92	309		5	AB	1.3	AB

	LS	403	128	AB	31	ABC	21	AB	161	81	363	4	AB	1.7	AB
	Olive oil	421	91	B	20	C	15	B	175	91	457	3	B	1.0	B
	Potassium permanganate	402	135	AB	34	ABC	22	AB	164	87	322	4	AB	1.6	AB
	Potassium soap	403	114	AB	29	BC	19	AB	163	92	363	3	AB	1.3	AB
	P	NS	0.0195		0.0006		0.0139		NS	NS	NS	0.0075		0.0128	
2008	ATS	123	101		82										
	Control	128	123		97										
	LS	127	75		60										
	LS+paraffin oil	129	75		59										
	Potassium permanganate	130	71		54										
	P	NS	NS		NS										

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 4. Effects of chemical *vs* mechanical (Fuet Fruttur®) thinning on 'Brookfield Gala®' and 'Fuji Kiku® 8' in Mollerussa 2010-2011 (Experiment 3). Chemical thinning included benzyladenine (BA) at 150 mg·L^{-1}, and naphthalene acetic acid (NAA) at 10 mg·L^{-1} when fruit size was 10 mm. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string machine at 5 km·h^{-1} of tractor speed and 320 rpm of rotational speed. Control trees were unsprayed. Return bloom was measured the following spring, by counting the total number of flower clusters per tree. Economic value was calculated using the simulated packout and the industry price standards.

Cultivar	Year	Treatment	Flower clusters/tree	Fruit #/tree		Fruit #/ 100 clusters		Yield /tree (kg)		Fruit size (g)		TCSA[z] (cm^2)	Return bloom (flower clusters#/tree)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)	
Gala Brookfield®	2010	BA150+NAA10	643	252	AB	39	B	32		127	AB	23	428	5	11.2	AB
		Control	600	299	A	50	A	36		120	B	22	427	6	13.5	A
		Fuet5/320	553	229	B	41	B	31		136	A	22	363	7	10.5	B
		Fuet5/320→BA150+NAA10	601	220	B	37	B	30		135	A	20	427	6	10.9	AB
		P	NS	0.0264		0.0040		NS		0.0021		NS	NS	NS	0.0375	
	2011	BA150+NAA10	428	175	A	41	AB	31	A	177	AB	25	654	11	7.4	AB
		Control	427	195	A	46	A	32	A	167	B	23	664	10	8.4	A
		Fuet5/320	363	125	B	34	BC	24	B	193	A	24	631	9	5.2	B
		Fuet5/320→BA150+NAA10	427	127	B	30	C	24	B	193	A	24	614	9	5.3	B
		P	NS	0.0007		0.0006		0.0017		0.0039		NS	NS	NS	0.0062	
Fuji Kiku® 8	2010	BA150+NAA10	493	230		46		48		209	AB	36	210	7	6.5	
		Control	427	234		55		43		184	B	26	165	6	9.1	
		Fuet5/320	446	223		52		44		202	AB	32	201	6	7.2	
		Fuet5/320→BA150+NAA10	495	188		37		42		223	A	32	158	7	5.9	
		P	NS	NS		NS		NS		0.0405		NS	NS	NS	NS	
	2011	BA150+NAA10	210	173		80		37		219		38	355	7	5.3	

Control	165	186	107	35	202	30	315	5	7.2
Fuet5/320	201	156	95	34	230	36	370	6	4.4
Fuet5/320→BA1 50+NAA10	158	124	101	31	254	36	374	6	4.1
P	NS	NS	NS	NS	NS	NS	NS	NS	NS

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 5. Effects of chemical *vs* mechanical (Darwin®) thinning on 'Golden Reinders®' in La Tallada d'Empordà in 2010 (Experiment 4). Chemical thinning included benzyladenine (BA) at 100 mg·L^{-1} when fruit size was 10 mm. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 7 or 8 km·h^{-1} and 270, 290, or 310 rpm of rotational speed. Control trees were unsprayed. Return bloom was measured the following spring, by counting the total number of flower clusters per tree. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA[z] (cm^2)	Return bloom (flower clusters#/tree)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
BA100	155	78 AB	50 AB	15 AB	188	17	450	3	4.7 AB
Control	154	99 A	64 A	18 A	185	18	460	4	5.4 A
Darwin7/270	157	38 B	24 C	8 B	201	15	431	2	2.4 C
Darwin7/290	158	39 B	25 C	8 B	206	19	565	2	2.2 C
Darwin7/310	153	48 B	33 BC	10 AB	206	16	469	2	3.0 BC
Darwin8/290	157	52 B	34 BC	10 AB	198	16	500	2	3.3 ABC
P	NS	0.0035	0.0009	0.0112	NS	NS	NS	NS	0.0022

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 6. Effects of chemical *vs* hand *vs* mechanical (Darwin®) thinning on 'Gala Galaxy' in La Tallada d'Empordà in 2010 (Experiment 5). Chemical thinning included one application of naphthalene acetamide (NAD) at 50 $mg \cdot L^{-1}$ 5 days after full bloom, and another spray with benzyladenine (BA) at 150 $mg \cdot L^{-1}$ plus naphthalene acetic acid (NAA) at 12 $mg \cdot L^{-1}$ at 10 mm. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 5, 6, or 7 $km \cdot h^{-1}$ and 230, 270, or 310 rpm of rotational speed. Return bloom was measured the following spring, by counting the total number of flower clusters per tree. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree		Fruit #/ 100 clusters		Yield/tree (kg)		Fruit size (g)		TCSA[z] (cm^2)	Return bloom (flower clusters #/tree)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)	
NAD50→BA150 +NAA12	211	192	A	92	A	27	A	141	C	26	308	4	7.7	A
Darwin5/270	211	115	BC	56	CD	18	BC	164	AB	21	306	4	5.3	ABC
Darwin6/230	207	156	AB	76	AB	24	AB	152	BC	24	293	4	6.6	AB
Darwin6/270	213	111	BC	53	CD	19	BC	169	AB	22	348	4	5.0	BC
Darwin6/310	208	81	C	40	D	15	C	180	A	22	343	4	3.6	C
Darwin7/270	208	135	B	65	BC	21	AB	158	BC	24	315	4	5.7	ABC
Hand	207	124	BC	62	BC	20	BC	159	BC	22	342	4	6.0	ABC
P	NS	<0.0001		<0.0001		<0.0001		<0.0001		NS	NS	NS	0.0015	

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 7. Effects of chemical *vs* hand *vs* mechanical (Darwin®) thinning on 'Gala Brookfield®' in La Tallada d'Empordà in 2011 (Experiment 6). Chemical thinning was the standard procedure used by the growers, and included two applications. First application was done 5 days after full bloom with naphthalene acetamide (NAD) at 50 mg·L^{-1}, and the second one at 10 mm stage with benzyladenine (BA) at 150 mg·L^{-1} plus naphthalene acetic acid (NAA) at 12 mg·L^{-1}. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 6 km·h^{-1} and 230 or 270 rpm of rotational speed. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA^{Z} (cm^2)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
NAD50→BA150+NAA12	469	292 A	62 A	40	137 B	33	7	9.0 AB
Darwin6/230→CHM	472	282 A	60 A	40	142 B	32	7	9.1 AB
Darwin6/270	467	257 AB	55 AB	37	143 AB	27	7	9.5 A
Darwin6/270→ NAD50→BA150+NAA12	470	220 AB	47 BC	34	155 AB	28	7	8.1 AB
Hand	469	176 B	37 C	29	166 A	28	8	6.3 B
P	NS	0.0083	0.0002	NS	0.0131	NS	NS	0.0461

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). ^{Z}Trunk cross sectional area (TCSA). ^{NS}Nonsignificant at $P \leq 0.05$.

Table 8. Effects of hand *vs* mechanical (Darwin®) thinning on 'Golden Reinders®' in La Tallada d'Empordà in 2011 (Experiment 7). Mechanical thinning was done at E_2, F_1, and F_2 (Fleckinger, 1964) using a rotating string at 6 km·h^{-1} and 270 rpm of rotational speed. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA^Z (cm^2)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
Darwin6/270E2	462	282	61	34	120 B	18	4	15.4
Darwin6/270F1	455	272	57	32	113 B	18	4	14.7
Darwin6/270F2	456	299	66	37	120 AB	21	5	14.4
Hand	451	196	44	27	139 A	20	4	9.8
P	NS	NS	NS	NS	0.0115	NS	NS	NS

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). ^{Z}Trunk cross sectional area (TCSA). ^{NS}Nonsignificant at $P \leq 0.05$.

Table 9. Effects of chemical *vs* mechanical (Darwin®) thinning on 'Fuji Zhen® Aztec^{cov}' in La Tallada d'Empordà in 2011 (Experiment 8). There were three chemical treatments: 1) Ammonium thiosulfate (ATS) AZOS™ 300 at 3 L·hL^{-1}, 2) ATS AZOS™ 300 at 3 L·hL^{-1} + benzyladenine (BA) at 150 mg·L^{-1}, and 3) mechanical + BA at 150 mg·L^{-1}. All the chemical treatments were applied at 10 mm stage. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 6 km·h^{-1} and 210 or 250 rpm of rotational speed. Return bloom was measured the following spring, by counting the total number of flower clusters per tree. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA^z (cm^2)	Return bloom (flower clusters #/tree)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
ATS	201	122	61	28	226	12	13	7	9.8
ATS→BA	203	121	60	29	243	14	37	7	8.9
Darwin6/210	202	130	64	30	230	15	28	8	8.9
Darwin6/210→BA	202	110	55	26	236	13	42	6	8.5
Darwin6/250	204	120	59	28	236	13	23	8	8.9
Hand	203	115	57	23	195	12	11	5	9.3
P	NS	NS	NS	NS	NS	NS	NS	NS	NS

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). ^{Z}Trunk cross sectional area (TCSA). ^{NS}Nonsignificant at $P \leq 0.05$.

Table 10. Effects of chemical *vs* mechanical (Darwin®) thinning on 'Gala Galaxy' in La Tallada d'Empordà in 2012 (Experiment 9). There were two chemical treatments: 1) chemical standard, and 2) ATS. Chemical standard was the common thinning protocol used by the growers, and included two applications. First application was done 5 days after full bloom with naphthalene acetamide (NAD) at 50 $mg \cdot L^{-1}$, and the second application was done at 10 mm stage with benzyladenine (BA) at 150 $mg \cdot L^{-1}$ plus naphthalene acetic acid (NAA) at 12 $mg \cdot L^{-1}$. Second treatment included 3 sprays of ammonium thiosulfate (ATS) at AZOS™ 300 2.5 $L \cdot hL^{-1}$each at F_2, F_2 plus 4 days, and G plus the chemical standard treatment. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 6 $km \cdot h^{-1}$ and 250 rpm of rotational speed on the whole tree or just at the top. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA[z] (cm^2)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
ATS3x→NAD50+BA150 +NAA12	258	146 A	57 A	24	167 AB	26	4 AB	5.8 AB
NAD50→BA150+NAA12	260	199 A	78 A	32	161 ABC	24	5 A	8.5 A
Darwin6/250	262	185 A	71 AB	29	160 BC	28	4 AB	6.6 AB
Darwin6/250 TOP	258	184 A	74 AB	27	146 C	24	3 B	7.8 AB
Darwin6/250 TOP→ NAD50→BA150+NAA12	257	131 A	51 B	23	179 A	29	4 AB	4.7 B
P	NS	0.0404	0.0135	NS	0.0020	NS	0.0174	0.0150

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 11. Effects of mechanical (Darwin®) thinning on 'Golden Reinders®' in La Tallada d'Empordà in 2012 (Experiment 10). Mechanical thinning was done at at E_2, F_1, and F_2 (Fleckinger, 1964) using a rotating string at 6 km·h^{-1} and 270 rpm of rotational speed. Control trees were unsprayed. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA^z (cm^2)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
Control	140	119 A	85 A	20 A	169 B	20	4	6.1 A
Darwin6/270E2	91	57 B	63 AB	11 B	205 A	18	3	3.2 B
Darwin6/270F1	104	50 B	49 B	10 B	194 AB	18	2	3.1 B
Darwin6/270F2	107	67 B	63 AB	14 AB	207 A	22	3	3.3 B
P	NS	0.0070	0.0195	0.0189	0.0163	NS	NS	0.0162

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). ^{Z}Trunk cross sectional area (TCSA). ^{NS}Nonsignificant at $P \leq 0.05$.

Table 12. Effects of chemical *vs* mechanical (Darwin®) thinning on 'Golden Crielaard®' in La Tallada d'Empordà in 2013 (Experiment 11). Chemical thinning consisted of two lime sulfur (LS) sprays Sulfocálcico Concentrado Key at 4 $L \cdot hL^{-1}$, at F_1, and 2 days after F_1 (Fleckinger, 1964). Mechanical thinning was done at three different phenological stages (E_2, F_1, and G) (Fleckinger, 1964) using a rotating string at 6 $km \cdot h^{-1}$ and 230 rpm of rotational speed. Control trees were unsprayed. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA^z (cm^2)	Econom ic value (€/tree)	Crop load (fruit #/TCSA cm^2)
Control	257	168 A	74 A	25 A	150 B	16	4	10.6 A
Darwin6/230E2	258	99 B	38 B	15 B	154 B	14	3	7.3 ABC
Darwin6/230F1	259	97 B	38 B	17 B	170 AB	14	3	6.8 BC
Darwin6/230G	258	121 AB	47 AB	20 AB	163 AB	20	4	6.8 BC
Hand	259	83 B	33 B	15 B	184 A	16	3	5.4 C
LS	259	119 AB	46 B	18 AB	150 B	14	3	8.8 AB
P	NS	0.0013	0.0036	0.0115	0.0007	NS	NS	0.0027

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). ^{z}Trunk cross sectional area (TCSA). ^{NS}Nonsignificant at $P \leq 0.05$.

Table 13. Effects of mechanical (Darwin®) thinning on 'Gala Annaglo[cov]' in La Tallada d'Empordà in 2014 (Experiment 12). Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 6 or 8 km·h^{-1} and 250 or 290 rpm of rotational speed. Economic value was calculated using the simulated packout and the industry price standards

Treatment	Flower clusters/tree	Fruit #/tree	Fruit #/ 100 clusters	Yield/tree (kg)	Fruit size (g)	TCSA^z (cm^2)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
Darwin6/250	101	35	37	7	187	6	3	6.0
Darwin8/250	78	30	38	5	173	6	2	4.9
Darwin8/290	88	28	32	5	177	6	2	5.2
Hand	90	36	42	6	168	5	2	6.7
P	NS	NS	NS	NS	NS	NS	NS	NS

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). ^{Z}Trunk cross sectional area (TCSA). ^{NS}Nonsignificant at $P \leq 0.05$.

Table 14. Effects of chemical *vs* mechanical (Darwin®) thinning on 'Gala Schniga®' in La Tallada d'Empordà in 2016 (Experiment 13). Chemical thinning consisted of one spray of benzyladenine at 150 $mg \cdot L^{-1}$ at 10 mm stage. Mechanical thinning was done at 80% F_1 (Fleckinger, 1964) using a rotating string at 6 $km \cdot h^{-1}$ and 270 rpm of rotational speed. Economic value was calculated using the simulated packout and the industry price standards.

Treatment	Flower clusters/tree	Fruit #/tree		Fruit #/ 100 clusters		Yield/tree (kg)	Fruit size (g)	TCSA[z] (cm^2)	Economic value (€/tree)	Crop load (fruit #/TCSA cm^2)
BA150	150	420	A	282	A	54	130	18	10	23.6
Darwin6/270	147	404	A	278	A	53	131	17	10	24.8
Darwin6/270→BA150	149	226	B	151	B	35	166	22	9	12.7
P	NS	0.0073		0.0046		NS	NS	NS	NS	NS

Means within a column followed by different letters denotes significant differences among treatments (Tukey's honestly significant difference, $P \leq 0.05$). [Z]Trunk cross sectional area (TCSA). [NS]Nonsignificant at $P \leq 0.05$.

Table 15. Summary of fit and parameter estimates of ‘Gala’ and ‘Golden Delicious’ models built to predict the final number of fruits per tree after performing mechanical thinning with Darwin®. Model coefficients are tractor ($km \cdot h^{-1}$) and rotational (rpm) speed ratio, and initial number of flower clusters per tree. Data from experiments 3, 5, 6, 9, and 12 were used for ‘Gala’; whereas experiments 4, 7, 10, and 11 were used for ‘Golden Delicious’.

Gala RSquare	0.90				
RSquare Adj	0.89				
Root Mean Square Error	24.48				
Mean of Response	129.03				
Observations (or Sum Wgts)	50.00				
Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	-172.32	30.00	44.63	-5.74	<.0001
Speed/rpm	6925.75	1046.56	43.04	6.62	<.0001
Flower clusters/tree	0.64	0.04	44.39	17.59	<.0001
(Speed/rpm-0.02242)*(Flower clusters/tree-252.235)	36.14	5.61	44.14	6.45	<.0001
Golden Delicious RSquare	0.92				
RSquare Adj	0.91				
Root Mean Square Error	28.11				
Mean of Response	123.03				
Observations (or Sum Wgts)	48.00				
Term	Estimate	Std Error	DFDen	t Ratio	Prob>|t|
Intercept	291.63	56.49	43.31	5.16	<.0001
Speed/rpm	-12818.91	2215.73	43.94	-5.79	<.0001
Flower clusters/tree	0.55	0.04	8.65	14.13	<.0001
(Speed/rpm-0.0239)*(Flower clusters/tree-243.208)	-64.99	24.12	24.58	-2.69	0.0125