Institut für Landtechnik

# Effect of blossom thinning on apple quality with conventional methods and study on laser application for selective thinning

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**Prud Netsawang**

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Referent**:** Prof. Dr.-Ing. Peter Schulze Lammers
Korreferent**:** Prof. Dr. Wolfgang Büscher
Fachnahes Mitglied: Prof. Dr. Georg Noga
Prüfungsvorsitz: Prof. Dr. Karl-Heinz Südekum
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Angefertigt mit Genehmigung der Landwirtschaftlichen Fakultät der Universität Bonn

*My family*

*&*

*Lutz Damerow*

**Abstract**

**Effect of blossom thinning on apple quality with conventional methods and study on laser application for selective thinning**

Crop-load regulation by blossom thinning has an important role to improve the fruit quality and mitigate an alternate bearing on apple fruit production. This method aims to reduce excessive flowers to regulate the final fruit yield with marketable fruit quality. Although several techniques of blossom thinning already provide efficient thinning, the development of more effective thinning techniques is still essential to achieve selective thinning and to prevent a negative effect on trees and the environment.

In **study 1**, the efficacy of three different thinning methods on the regulation of fruit set, June drop, return bloom, fruit quality, fruit yield and the source–sink relationship were investigated. Mechanical, chemical and manual thinning were applied on apple trees cv. 'Roter Boskoop' at the Klein-Altendorf field laboratory of the University of Bonn. The results clearly showed that fruit production benefits from crop load management by blossom thinning. All thinning methods in this experiment gave evidence of improvement in fruit quality in terms of fruit size and weight. The fruit yield reduction by manual removal of ≥50% of flower clusters improved the return bloom as did the mechanical thinning with a rotor speed of 320 rpm. These three methods of thinning provided the optimal fruit yield of 14–18 kg per tree with acceptable fruit size and weight.

**Study 2** was undertaken to explore an alternative approach for selective flower removal by applying laser radiation. This study was performed under laboratory conditions at the Institute of Agricultural Engineering, University of Bonn to investigate the efficacy of flower removal by applying laser radiation based on three different factors: the phenological growth stage of the apple flower, laser spot position and laser energy density. The results demonstrate that applying laser radiation can be used as an alternative technique to increase the thinning selectivity. An application of laser radiation with a low energy density of 1.02 J $mm^{-2}$ to remove flowers was successful during balloon and full bloom stages when the laser spot was in the three positions, a) from the front of a flower cluster (FFC), b) from the side of a flower (FSF) and c) from the front of a flower (FFF). Applying laser radiation on the front of the flower cluster (FFC) during balloon and full bloom stages provided the most suitable condition for selective flower removal. The lowest applicable laser energy density of 1.02 J $mm^{-2}$ reduced

2–3 flowers in a cluster on average, while the highest applicable laser energy density of 3.06 J $mm^{-2}$ removed 3–4 flowers on average, i.e. 50% of the flowers on the cluster.

**Kurzfassung**

**Auswirkung der Blütenausdünnung auf die Apfelqualität mit konventionellen Methoden und Untersuchung der Anwendung von Laserstrahlung zur selektiven Ausdünnung**

Die Regulierung der Fruchtbehangs durch Ausdünnen der Blüten spielt eine wichtige Rolle bei der Verbesserung der Fruchtqualität und bei der Abschwächung der Alternanz. Der Eingriff in die Obstbaumblüte zielt darauf ab, überschüssige Blüten zu reduzieren, um den Apfelertrag auf eine hohe marktfähige Fruchtqualität einzustellen. Obwohl verschiedene Techniken der Blütenausdünnung bereits eine effiziente Ausdünnung ermöglichen, ist die Entwicklung präziserer Ausdünnungsverfahren ein Forschungsziel, um eine selektive Ausdünnung zu erreichen und negative Auswirkungen auf die Bäume und die Umwelt zu vermeiden.

In Studie 1 wurde die Wirksamkeit von drei verschiedenen Ausdünnungsverfahren auf die Regulierung des Fruchtansatzes, des Junifalls, der Blühstärke im Folgejahr, der Fruchtqualität, des Fruchtertrags und der Quelle-Senke-Beziehung untersucht. Es wurden Versuche zur mechanischen, chemischen und manuellen Ausdünnung an Apfelbäumen der Sorte 'Roter Boskoop' auf dem Feldlabor Klein-Altendorf der Universität Bonn durchgeführt. Die Ergebnisse zeigen, dass die Fruchtqualität von der Ausdünnung der Blüten profitiert. Alle Ausdünnungsmethoden in diesem Versuch zeigten eine Verbesserung der Fruchtqualität in Bezug auf Fruchtgröße und -gewicht. Die Reduzierung des Fruchtertrags durch die manuelle Ausdünnung von 50 % oder mehr Blütenbüscheln verbesserte die Blühstärke im Folgejahr ebenso wie die mechanische Ausdünnung mit einer Rotordrehzahl von 320 U/min. Diese Ausdünnungsmethoden lieferten einen Fruchtertrag von 14–18 kg pro Baum bei akzeptabler Fruchtgröße und -gewicht.

Studie 2 wurde durchgeführt, um einen alternativen Ansatz zur selektiven Blütenentfernung durch Anwendung von Laserstrahlung zu erforschen. Diese Studie wurde unter Laborbedingungen am Institut für Agrartechnik der Universität Bonn durchgeführt, um die Wirksamkeit der Blütenentfernung durch Laserstrahlung in Abhängigkeit von drei verschiedenen Faktoren zu untersuchen: dem phänologischen Wachstumsstadium der Apfelblüte, der Position des Laserpunktes auf der Blüte bzw. der Knospe und der Dichte der Laserenergie. Die Ergebnisse zeigen, dass Laserstrahlung als alternative Technik zur selektiven Entfernung von Blüten eingesetzt werden kann. Die Emittierung von Laserstrahlung auf die Vorderseite einer Blütentraube (FFC) im Ballon- und Vollblütestadium war die geeignetste Position für die Blütenreduzierung. Die Laserdiode mit einer niedrigen Leistung von 4 W und

einer Laserenergiedichte von mindestens 1,02 J $mm^{-2}$ erzeugte letale Schäden an den Blüten im Ballon- und Vollblütestadium in drei Positionen des Laserspots: a) von der Vorderseite eines Blumenbüschels (FFC), b) von der Seite einer Blüte (FSF) und c) von der Vorderseite einer Blüte (FFF). Die niedrigste anwendbare Laserenergiedichte von 1,02 J $mm^{-2}$ reduzierte im Durchschnitt 2 Blüten in einem Büschel. Mit der in diesem Versuch höchsten Laserenergiedichte von 3,06 J $mm^{-2}$ konnten bis zu 50 % der Blüten in einem Blütenbüschel entfernt werden.

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**Abbreviations**

| | |
|---|---|
| ° E | East of the Greenwich meridian |
| ° N | Northern hemisphere |
| °C | Degree Celsius |
| 6-BA | 6-Benzyladenine |
| *A* | Laser spot area |
| ABA | Abscisic acid |
| ART | Apfel-Reife-Test |
| ASE | Artificial spur extinction |
| ATS | Ammoniumthiosulfate |
| BA | Benzyladenine |
| BBCH | Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie |
| C | Chemical thinning |
| CH | Carbohydrates |
| CLM | Crop load management |
| cm | centimetre |
| cv. | cultivar |
| DAA | Days after application |
| DC | Direct current |
| *E* | Laser energy |
| EU | European Union |
| Eurostat | The statistical office of the European Union |
| Faostat | The Food and Agriculture Organization Corporate Statistical Database |
| FFB | From the front of the flower bud |
| FFC | From the front of the flower cluster |
| FFF | From the front of the flower |
| Fig. | Figure |
| *FS* | Fruit set |
| FSC | From the side of the flower cluster |
| FSF | From the side of the flower |
| g | gram |
| g $L^{-1}$ | gram per litre |

| | |
|---|---|
| g per fruit | gram per fruit |
| GA3 | Gibberellic acid |
| H | Hand thinning or hand removal of flower cluster |
| h | hour |
| ha | hectare |
| Hz | Hertz |
| *I* | Laser energy density |
| ICT | Integrated coefficient of thinning |
| J | Joule |
| J $mm^{-2}$ | Joule per square millimeter |
| kg | kilogram |
| kg $cm^{-2}$ | kilogram per square centimeter |
| kg per tree | kilogram per tree |
| km $h^{-1}$ | kilometre per hour |
| kPa | kilopascal |
| kW | kilowatt |
| L | Litre |
| L $ha^{-1}$ | Litre per hectare |
| LIDAR | Light detection and ranging or laser imaging, detection, and ranging |
| LLS | Liquid lime sulfur |
| LSD | Least significant difference |
| m | metre |
| *M* | Mass of the rope in the brush |
| M | Mechanical thinning |
| m $s^{-1}$ | metre per second |
| mm | millimetre |
| $mm^2$ | square millimetre |
| MPa | megapascal |
| ms | millisecond |
| *N* | Number of damaged flowers |
| n.a. | Not applicable |
| NAA | Naphthaleneacetic acid |
| NAD | Naphthaleneacetamide |

| | |
|---|---|
| nm | nanometre |
| *P* | Laser power |
| *R* | Length of the rope in the brush |
| $R^2$ | Coefficient of determination |
| rpm | Revolutions per minute |
| s | second |
| *S* | Rotor speed |
| *T* | Exposure time |
| U | Unthinned control |
| USA | United States of America |
| USDA | United States Department of Agriculture |
| V | Volt |
| *V* | Vehicle speed or velocity |
| W | Watt |

# 1. Introduction

## 1.1 Problem

In 2019, about 65 million hectares of land was used for global fruit production (Faostat, 2019). Based on the quantities of fruit globally produced in 2019, the most popular fresh fruits worldwide were bananas (116 million tons), watermelon (100 million tons) and apples (87 million tons). The bulk of apple are mainly produced in Asia, followed by Europe and America. Eurostat (2020) reported that in 2019, the EU produced 13.7 million tons of pome fruit (apples, pears and quinces) and 7.3 million tons of stone fruit (peaches, nectarines, apricots, cherries, plums, sloes and medlar). Spain and Italy are the main producers of fruit in the EU, but one quarter of apples produced in the EU come from Poland. Indeed, ~27% of the apples harvested in the EU come from Poland, whereas 19.9% come from Italy and 15.1% from France. According to USDA (2021) forecast, apple production in the EU is expected to increase by over 500,000 tons to 12.2 million tons in 2021.

In Germany, apples are a major element of all the fruits produced for the market. According to a statistical report from Statistisches Bundesamt (2021), approximately 48,776 ha of land area was used for fruit production in Germany in 2020 and 70% (33,905 ha) of this area was used to produce apples with a yield of 1.02 million tons (Fig. 1.1 and Fig. 1.2). The apple yield in 2021 is expected to be ~937,000 tons.

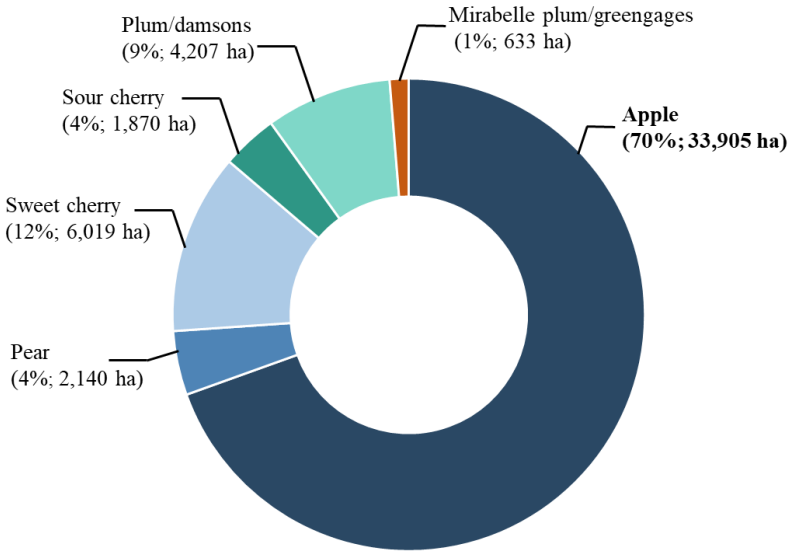



Fig. 1.1: Relative area of land used to produce fruit for the market in Germany in 2020 (Statistisches Bundesamt, 2021).

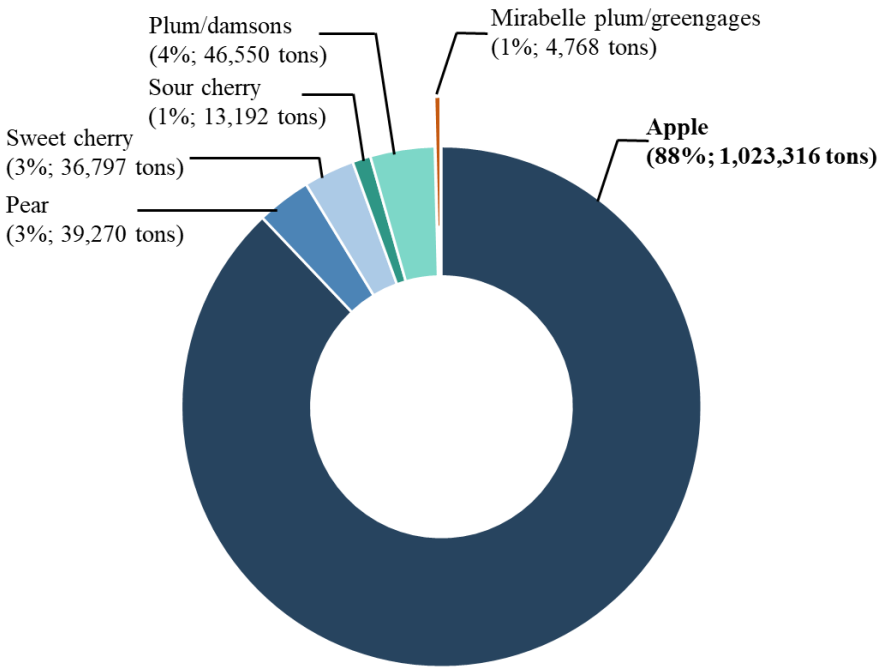



Fig. 1.2: Relative quantities of fruit harvested for the market in Germany in 2020 (Statistisches Bundesamt, 2021).

In fruit trees, a large number of fruits can result in slow fruit growth and small fruit size, and therefore a reduction of fruit load at flowering or during fruit development can be beneficial to achieve an optimum of fruit quality. Crop load management (CLM) is an elegant strategy used for improving fruit quality (Seehuber et al., 2011). The two CLM methods regularly used in fruit cultivation are pruning and thinning. All CLM methods also aim to overcome alternate bearing (Hehnen et al., 2012), a major problem in pome, stone and citrus fruit cultivation worldwide, which causes severe fluctuations in yield from year to year (Martínez-Fuentes et al., 2013). Alternate bearing may be cultivar dependent (Krasniqi et al., 2013) and is influenced by a) biotic factors, such as fruit load, carbohydrates and hormones associated with flowering, seed development, basipetal gibberellic acid (GA3) transport and b) abiotic environmental factors, such as drought and spring frost (Pellerin et al., 2011).

Blossom thinning, a common CLM method used for controlling the number of fruit produced, has a positive effect on fruit size, colour, sugar content, firmness and storability (Meland, 2009; Solomakhin & Blanke, 2010). An early reduction in the number of flowers by thinning can overcome alternate bearing in pome fruit (Meland & Gjerde, 1993). In some years, apple trees can produce an abundance of flowers, not all of which are required for a sufficient harvest of

high quality fruit (Costa et al., 2013). Indeed, Untiedt and Blanke (2001) reported that only 7% of flowers are necessary in apple trees to achieve a sufficient yield with high fruit quality.

The number of unwanted flowers is generally reduced using three main thinning techniques. First, flower buds can be removed by hand at the inflorescence emergence stage (Breen et al., 2015; Tustin et al., 2012); however, this technique has extensive labour requirements. Second, chemical agents, such as ammoniumthiosulfate (ATS) and ethephon, can be applied to remove excess flowers (Maas, 2016; Wertheim, 2000). It has been found that chemical blossom thinning improves fruit quality, but its efficiency is unpredictable and dependent on weather conditions and cultivars (Wertheim, 2000; Williams, 1979). Third, the flowers can be physically removed, e.g. with string thinners, which is as an environmentally friendly method (Seehuber et al., 2011). Several machines have been designed for blossom thinning and are used in bio-orchards, particularly as labour-saving devices (Damerow et al., 2007; Kon et al., 2013; Lopes et al., 2019; McClure & Cline, 2015; Wouters, 2014).

Physical thinning has some disadvantages, which have been reported in several studies. As part of CLM, mechanical blossom thinning allows subsequent chemical and/or hand thinning to be conducted at a later stage to fine-tune the fruit set (Basak et al., 2016; Seehuber et al., 2014). Thinning by shading can lead to over-thinning as it is difficult to determine the optimal shading duration (Zibordi et al., 2009). Peifer et al. (2018) found that only five fruitlets remained on a shaded tree after the June drop when a shade net (94%) was applied for 8 days in a shading experiment. Recently, selective thinning has been studied as a means to enhance thinning efficacy. Several flower removal techniques can be employed to locate the target positions of single flowers and precisely remove these flowers or fruits at the correct position. However, such flower removal techniques require further development. This study aimed to explore an alternative approach for selective flower removal that does not have negative effects on the trees and the environment.

### 1.2 Objectives

The main objective of this study was to develop, test and evaluate a new technique for flower removal to achieve selective blossom thinning under laboratory condition. The specific objectives were as follows:

- Investigate the efficacy of crop-load regulation using three different thinning techniques.
- Develop a laboratory approach for selective flower removal.
- Experimentally investigate the parameters, that can affect the efficacy of thinning by laser radiation.

# 2. Apple flowers and fruits

## 2.1 Principles of apple flower physiology

### 2.1.1 Pollination and fertilization of apple trees

Pollination and fertilisation are two sexual reproduction processes in fruit trees. In apple trees, sexual reproduction starts with pollination in which pollen grains are transported from an anther on the flowers to other flowers by pollinators, such as bees (Dennis, 2003; Jackson, 2003; Jahed & Hirst, 2017) (Fig. 2.1).

Fig. 2.1: A bee acts as a pollinator on apple flowers in full bloom.

Pollination can occur in two ways: a) self-pollination and b) cross-pollination. Most apple cultivars cannot self-pollinate and also require cross-pollination between different cultivars to set high-quality fruit at marketable quantities (Jackson, 2003; Jahed & Hirst, 2017; Matsumoto et al., 2008).

After pollination, pollen grains that land on the surface of the stigma begin the fertilisation process. The pollen tube is generated to transport the sperm and grows down the style to the ovary, a process known as pollen germination. After the sperm reaches the ovules in the ovary, successful fertilisation leads to fruit set and fruit development (Dennis, 2003).

After fertilisation, the petals fall and the fruit set begins. The receptacle part of the flower develops into the apple fruit. Lakso and Goffinet (2013) described the first step of fruit set in which the egg cell in each of the 10 ovules starts to develop through cell division. During the

first week after bloom until 4–5 weeks after bloom, the fruitlets or young fruits grow in size *via* both cell division and cell expansion. Subsequently, fruit growth for the remainder of the season essentially occurs through cell expansion (Fig. 2.2). A thin protective layer surrounding the ovary becomes the apple core around the seeds, whereas the outer layer develops into the exocarp or the fleshy white part of the apple. The calyx, stamens and pistils become the dry, hairy part at the bottom of the apple.

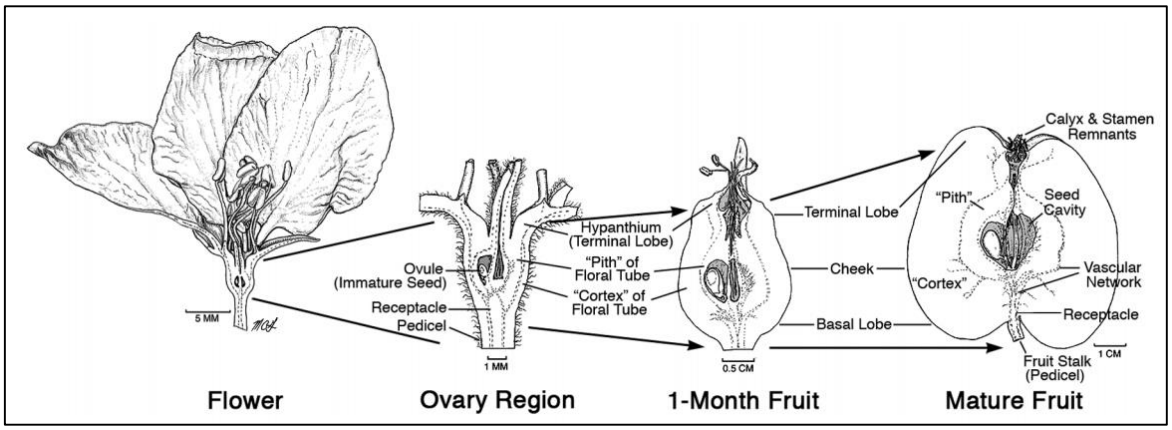



Fig. 2.2: Development of apple flower into fruit after fertilisation (Lakso & Goffinet, 2013).

### 2.1.2 Source–sink relationship

The relationship between the source and the sink is important in fruit growth regulation. The source can be defined as the photosynthesising tissue or organ, typically the mature leaves, whereas the sink refers to non-photosynthetic organs, such as the fruits, immature leaves, roots and flowers (Blanke, 2009; Fischer et al., 2012). Photosynthesis produces carbohydrates (CH), which are translocated from reserve organs (leaves) to support the growth and development of sink organs (mainly fruits) (Fischer et al., 2012).

The source–sink relationship during fruit development can be evaluated by calculating the ratio between the number of leaves and the number of fruits, which determines the carbon partitioning of photoassimilates within the tree (Friedrich & Fischer, 2000; Jackson, 2003). The optimum leaf/fruit ratio is associated with species, cultivar and geographic location. Maage (1994) reported that the optimum source/sink relationship for 'Victoria' plum under Norwegian conditions is 6–10:1 (leaves/fruit). Similarly, the suitable ratio for apricot is 7:1 (Lehner & Wurm, 2006). For apple trees, optimum source/sink relationships of 20–30:1 to 40–50:1 were reported by Friedrich and Fischer (2000).

A high fruit load in the canopy induces strong competition between the sink and the source that leads to low fruit quality, whereas a lack of fruits in the canopy causes photosynthates to accumulate in leaves. Thus, regulation of the source/sink relationship is required during fruit production to ensure high fruit quality. Meland and Kaiser (2011) reported that reducing the number of fruits per tree increases the leaf area per fruit, which means that more photo-assimilates are available to the remaining fruit. Pellerin et al. (2011) noted that effective optimal thinning not only provides good fruit size but also overcomes alternate bearing and helps maintain healthy trees. In addition, blossom thinning is more effective in encouraging consistent annual bearing compared with fruitlet thinning (Meland & Gjerde, 1993).

### 2.1.3 Alternate bearing

Alternate or biennial bearing is a major problem in fruit production. It results in fluctuating fruit yields between the 'on' years with high yields and the 'off' years with low yields (Jonkers, 1979; Monselise & Goldschmidt, 2011). Alternate bearing is common in many fruit trees, such as apple (Krasniqi et al., 2013), mango (Das et al., 2019) and citrus (Martínez-Fuentes et al., 2013). Monselise and Goldschmidt (2011) characterised two situations that lead to alternate bearing. The on-year can be caused by a lack of flowers, poor fruit set or excessive drop, whereas the off-year is due to excessive fruit set, too little fruit drop and excessively large crops. Alternate bearing is considered more widespread in apples than in other fruit trees. Baab and Lafer (2005) reported that the severity of alternate bearing depends on the cultivar of the apple tree (Table 2.1).

Table 2.1: Classification of apple cultivars according to the intensity of alternate bearing (Baab & Lafer, 2005; Jonkers, 1979).

| **Low** | **Middle** | **High** |
|---|---|---|
| Gala | Jonagold | Delbarestivale |
| Pinova | Cox Orange | Summerred |
| Golden Delicious | Braeburn | Elstar |
| Arlet | Berlepsch | Boskoop |
| Idared | Rubens | Kronprinz Rudolf |
| Topaz | Granny Smith | Fuji |

### 2.1.4 June drop

Apple trees naturally shed some flowers and fruits within three main periods: a) unfertilised flowers are discarded during weeks 1–4 after full bloom (Fig. 2.3); b) fruitlets with fewer developed seeds due to insufficient fertilisation drop 5–6 weeks after full bloom, referred to as June drop (Fig. 2.4) and c) fruits drop from ~4 weeks before harvesting, known as the pre-harvest fruit drop (Fig. 2.5) (Luckwill, 1953).

Two causes of fruitlet abscission in June drop were summarised by Bangerth (2000). First, the fruitlets are insufficiently supplied for fruit development *via* limited assimilate production. Second, many fruits drop due to a regulatory hormonal mechanism by which the plant safeguards selected fruit from limited assimilate growth later in the season. Wertheim (1973) reported that most of the dropped fruits in June drop had an average diameter of 15–32 mm and contained 3–5 seeds.

Although apple trees can regulate their fruit load *via* fruitlet abscission in June drop to efficiently use their resources (Eccher et al., 2013), this mechanism does not ensure marketable quality of the remaining fruits on the trees after June drop (Bangerth, 2000). Thus, practical thinning is required to control fruit load, e.g. by applying chemical thinning to induce fruit drop (Greene, 2012) or mechanical thinning to remove excessive flowers (Seehuber et al., 2010).

Fig. 2.3: Unfertilised flowers dropped after full bloom.

Fig. 2.4: Fruitlets dropped during the natural June drop in apple cv. ‘Rote Boskoop’.

Fig. 2.5: Apple fruits dropped ~4 weeks before harvesting.

### 2.1.5 Frost damage

Frost negatively affects fruit production in the apple-growing regions of the Northern hemisphere, such as those in Germany and Austria. Low temperature in spring causes freezing injury, which significantly damages buds, flowers (Fig. 2.6) and fruit (Fig. 2.7) during bloom and at the start of fruit development (Rodrigo, 2000). Furthermore, it causes significant damage to crops when it occurs during plant development. For example, the flowers and buds are killed by late spring frost, resulting in an unpredictable efficiency of flower thinning (Byers, 2003). Although environmental temperature has been increasing every year in late winter and early

spring since 1970 due to global warming, the risk of damaging frost has remained unchanged, as shown by the frost damage that occurred in April 2017 in Germany (Vitasse & Rebetez, 2018). Damaging spring frost has also been reported in the USA, causing significant economic losses of about €1.6 billion in 2007 (Marino et al., 2011).

Fig. 2.6: Cross-section view of an apple flower with frost injury (left) and an uninjured flower (right) (photo by John Strang, University of Kentucky; http://applescout.ca.uky.edu/frostinjury).

Fig. 2.7: Two apple fruits with frost injury (photo by Nicole Ward Gauthier, University of Kentucky; http://applescout.ca.uky.edu/frostinjury).

Murray (2020) summarised the critical temperatures that caused frost damage in apple flowers after 30 min exposures in each stage of phenological growth (Table 2.2). The damage to flower buds in late bloom was more severe than that at the early growth stage.

Table 2.2: Critical temperatures for frost damage in apple flowers at different phenological growth stages (Murray, 2020).

| **Phenological growth stages** | **Temperature (°C)** | |
|---|---|---|
| | **10% flower bud kill** | **90% flower bud kill** |
| Mouse ear | −5.0 | −9.4 |
| Green bud | −2.8 | −6.1 |
| Pink bud | −2.2 | −4.4 |
| Balloon | −2.2 | −3.9 |
| Full bloom | −2.2 | −3.9 |

## 2.2 Morphology of apple flowers

### 2.2.1 Structure of apple flowers

Apple flowers belong to the Rosaceae or rose family. They are divided into four subfamilies on the basis of fruit type: Rosoideae, Prunoideae, Spiraeoideae and Maloideae. Important fruits contained in this family are apples, strawberries, raspberries, pears, cherries, plums, apricots and pears (Folta & Gardiner, 2009). Apple flowers have a diameter of 3–4 cm and each flower has 5 sepals, 5 petals varying in colour from white to pink and many spirally arranged stamens (up to 20 stamens) with yellow anthers (Fig. 2.8) (Dennis, 1986). The pistil comprises the stigma and five united styles at the base and the styles are slightly longer than the stamens (Hancock et al., 2008). The ovary is enclosed in the receptacle, which is located under the sepals, petals and stamens (Jackson, 2003). Dennis (2003) reported that the apple flower contains five carpels, each with two or four ovules, depending on the cultivar. All flower parts, except the petals, remain attached to the fruit, which contains up to 10 seeds. The peduncle and calyx (all sepals) are usually woolly and the calyx is persistent in the fruit.

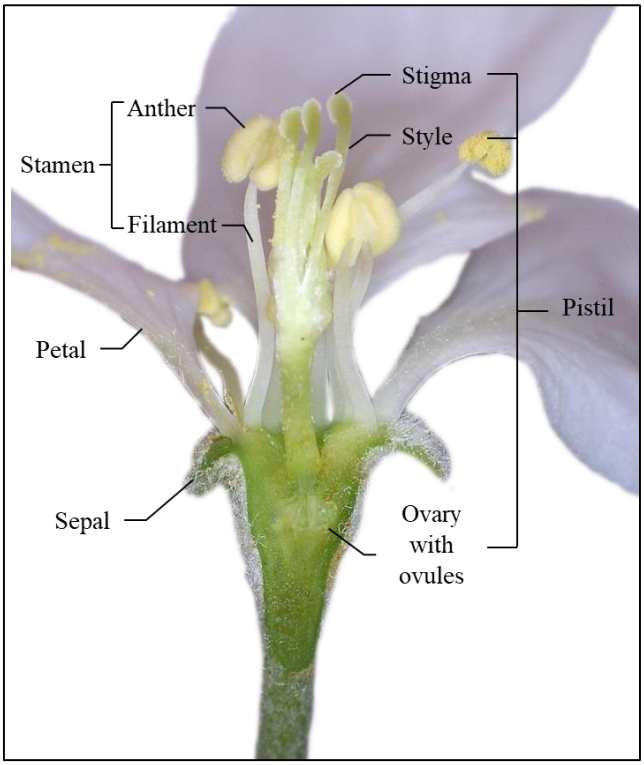


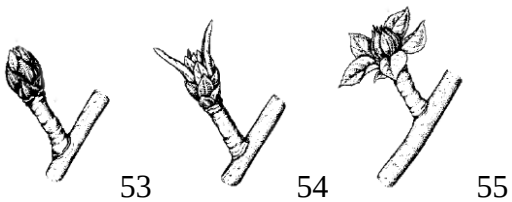

Fig. 2.8: Cross-section view of an apple flower.

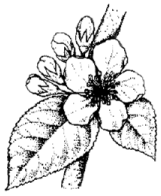
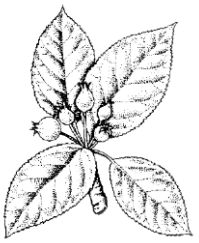
### 2.2.2 Phenological growth stages of apple flowers

The phenological growth stages of apple flowers can be described using the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie scale (BBCH), which has been widely employed to describe the principal growth stages of many types of crop as well as fruit trees, including those bearing stone and pome fruit (Meier, 2001; Pérez-Pastor et al., 2004). It consists of uniform coding with a 10-part scale (0–9); each part is further subdivided into 10 secondary stages to clearly describe and distinguish the developmental phases (Table 2.3).

Eight of the ten principal stages are used to describe the development of apple trees from sprouting/bud development (Stage 0) to senescence and the beginning of dormancy (Stage 9), except for the formation of side shoots/tillering (Stage 2) and development of harvestable vegetative plant parts or vegetatively propagated organs/booting (Stage 4) (Table 2.3).

Table 2.3: Principal growth stages of apples (Meier, 2001; Meier et al., 2009).

| Stage | Description | Diagram with BBCH code |
|---|---|---|
| 0 | Germination/ sprouting / bud development |  00 01 07 |
| 1 | Leaf development (main shoot) |  10 |
| 2 | Formation of side shoots/tillering | |
| 3 | Stem elongation or rosette growth/shoot development (main shoot) |  31 |
| 4 | Development of harvestable vegetative plant parts or vegetatively propagated organs/booting (main shoot) | |
| 5 | Inflorescence emergence (main shoot)/heading |  53 54 55 |
| | |  57 59 |

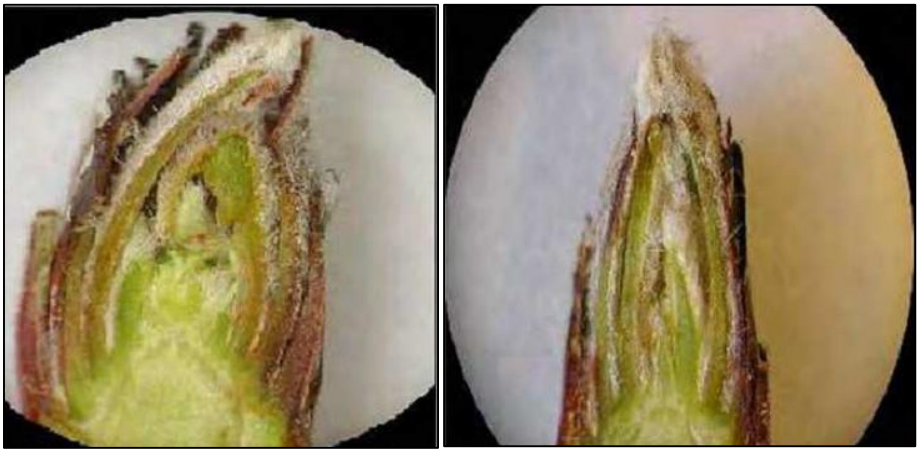
| Stage | Description | Diagram with BBCH code |
|---|---|---|
| 6 | Flowering (main shoot) |  61 |
| 7 | Development of fruit |  71  75 |
| 8 | Ripening or maturity of fruit and seed | |
| 9 | Senescence and beginning of dormancy | |

The three principal growth stages are considered to be vegetative growth, which describes bud development (Stage 0), leaf development (Stage 1) and shoot development (Stage 3), whereas two stages are allocated to flowering, describing inflorescence emergence (Stage 5) and flowering (Stage 6). Most flower induction occurs in early summer, but it can extend until early autumn under some conditions (Dennis, 2003). In addition, the flowering stage (BBCH 60–69) is barely a week in early summer. Fruit and seed development is described in the development of fruit (Stage 7) and the maturity of fruit and seeds (Stage 8) (Meier, 2001) (Table 2.3). In this study, blossom thinning, which occurs during inflorescence emergence (Stage 5) and flowering (Stage 6), was investigated.

### 2.2.3 Flower buds and clusters

Flower buds are an important initial part of fruit production and tree growth. The two types of buds on apple trees are vegetative or leaf buds, which produce leaves and/or shoots and mixed or flower buds, which produce leaves and inflorescences (Somerville, 1996) (Fig. 2.9). Buds

can be positioned on the long (extension) or short (spur) shoots and most flower buds are located at the end of shoots (apical or terminal buds) rather than at the lateral or axillary buds (Jackson, 2003; Winter et al., 2002) (Fig. 2.10).



(a) (b)

Fig. 2.9: Cross-section view of apple buds. (a) Flower bud and (b) leaf bud (Petri et al., 2012).

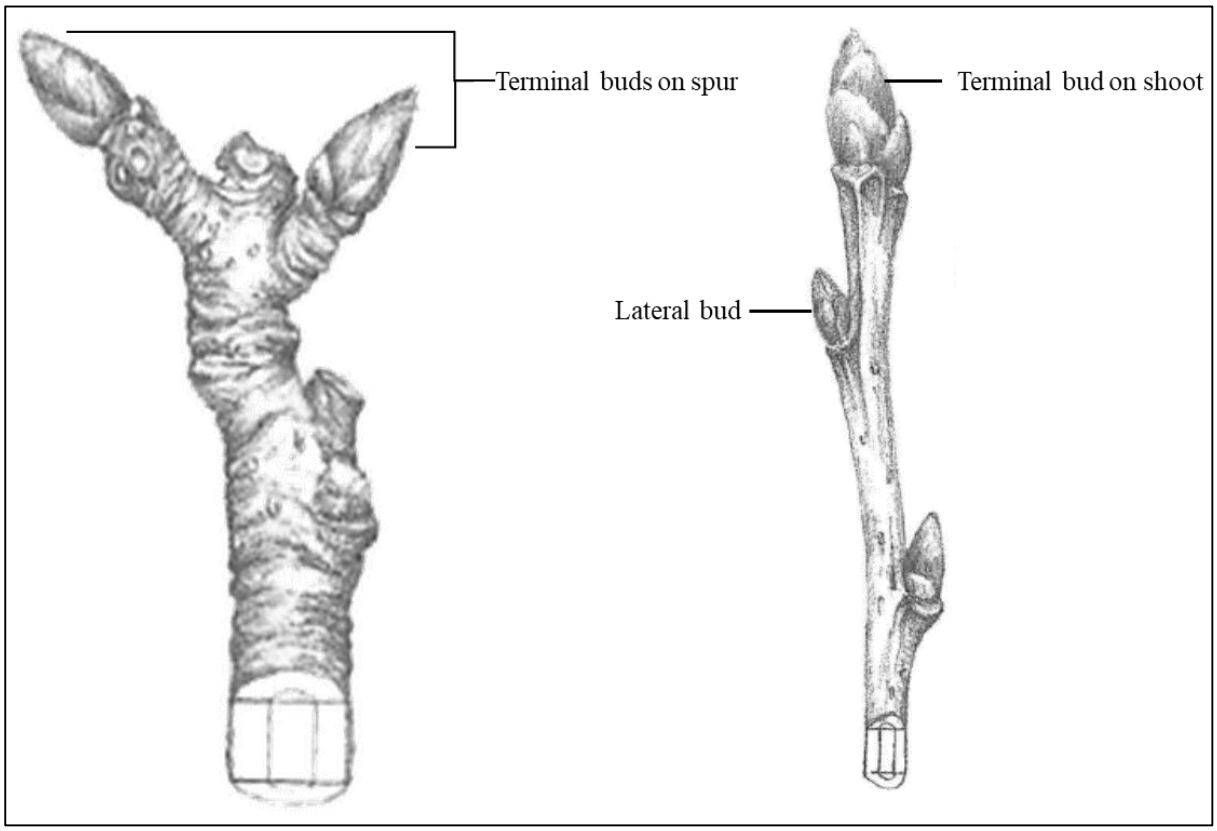



Fig. 2.10: Two types of apple buds on branches (Poland et al., 2018).

In economic fruit crop production, the flower buds that become the fruits are known as fruit buds. Both buds can be distinguished by their physical characteristics: flower buds are longer and much wider than leaf buds (Fig. 2.9). However, identifying the type of the bud at an early stage of flower development is difficult.

The structure of apple flower buds was described by Abbott (1970): the flower buds consist of nine bud scales, three transition leaves, six true leaves and three bracts (Fig. 2.11). A king flower or flower primordium is located at the end of the axis, whereas lateral flowers are in the axils of the three bracts and three distal leaves. The king flower is the first developed flower and its bloom is followed by that of the lateral flowers (Dennis, 1986; Faust, 1989) (Fig. 2.12).

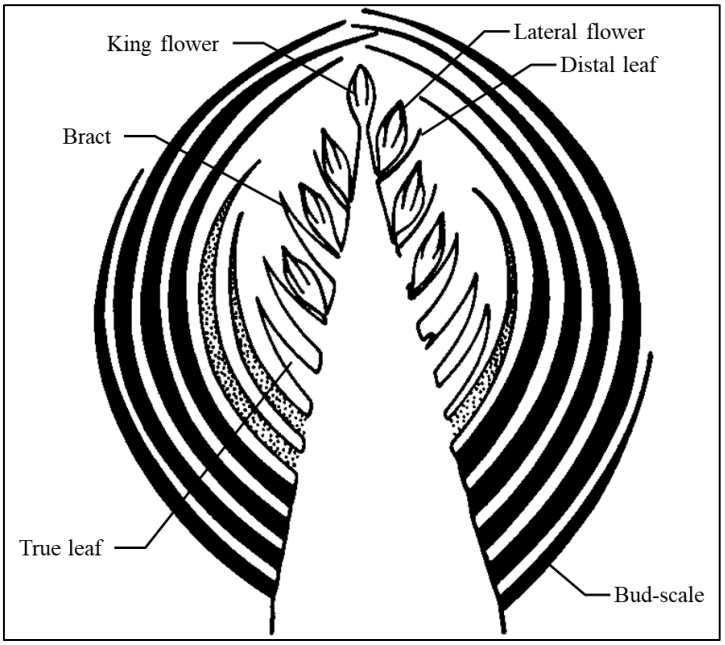



Fig. 2.11: Cross-section view of an apple flower bud (Abbott, 1970).

After the bud burst (BBCH 53), floral buds are visible and become a flower cluster. Most apple cultivars have 3–7 flowers in each flower cluster depending on the cultivar. Most frequently, five flowers appear in a cluster (Jakopic et al., 2015). Ferree et al. (2001) reported that the difference in the number of flowers was associated with the cultivar, e.g. 'Jonagold' and 'Royal Gala' have more flowers per cluster than 'Red Chief Delicious'.

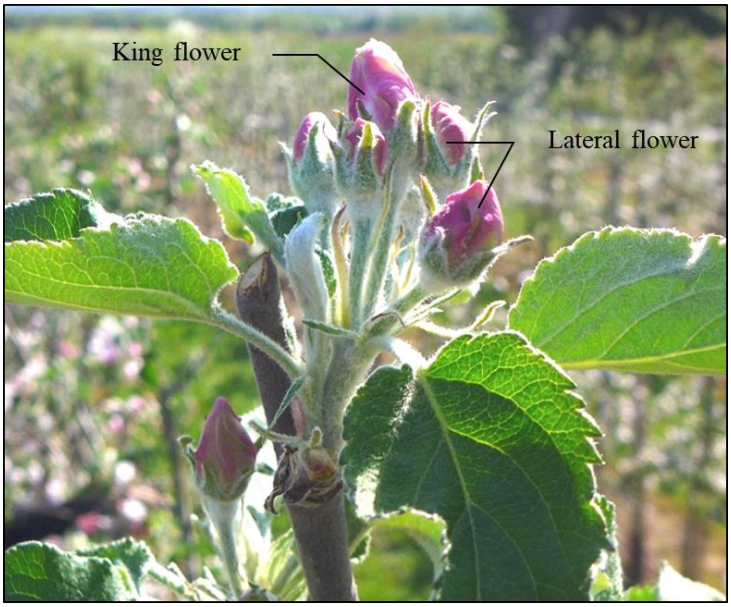



Fig. 2.12: Flower cluster with a king flower at the balloon stage surrounded by four lateral flowers at the pink bud.

## 2.3 Intensity of apple flowering

The density of apple flowers on the trees plays a significant role for farmers producing commercial fruits because the flowers become fruits. Ferree and Warrington (2003) announced that heavy flowering is not essential for economic success in fruit production, but sufficient flower density provides good fruit quality as well as benefits in terms of economic value. Tustin et al. (2012) reported that around 2,000 flowers exist on 400–500 flower clusters on apple trees, but the optimum yield with marketable fruit size is only 200–250 fruits per tree. In addition, only around 7% of flowers are necessary for apple trees to achieve sufficient yield of high-quality fruit (Costa et al., 2013; Untiedt & Blanke, 2001). In addition, Lakso and Robinson (1997) stated that both fruit yield and quality are closely related to the intensity of apple flowering. Thus, a reduction in flowering intensity due to blossom thinning can improve fruit quality (Kong et al., 2009).

Heavy crop load can inhibit flower bud initiation, which reduces flowering intensity in the subsequent year and causes alternate bearing (Jackson, 2003). Comas et al. (2019) indicated that experts are necessarily required to evaluate the level of flowering intensity. Baab and Lafer (2005) and Krasniqi et al. (2013) found that the period from the pink bud (BBCH 57) to balloon stage (BBCH 59) is most effective for the estimation of flowering intensity, which can be classified using a 9-part scale: 1 (no flowers) to 9 (white flowers). Only trees with a flowering

intensity of 7–9 should be subjected to blossom thinning to achieve a fruit yield with marketable fruit quality (Table 2.4) (Baab & Lafer, 2005).

Table 2.4: Comparison of flowering intensities and blossom thinning (Baab & Lafer, 2005).

| Level of flowering intensity | Intensity of flowering | Intensity of blossom thinning |
|---|---|---|
| 1 | No flowers | No |
| 2 | Very low | No |
| 3 | low | No |
| 4 | Low-middle | No |
| 5 | Middle | Possible |
| 6 | Middle-high | 30% flower removal |
| 7 | high | 50% flower removal |
| 8 | Very high | 67% flower removal |
| 9 | White flower | 75% flower removal |

## 2.4 Influence of flower position on fruit quality

Previous study has indicated that apple trees can have an abundance of flowers, but not all flowers have the ability to develop into fruits (Jakopic et al., 2015). Apple trees have three periods in which they regulate their load by shedding excessive flowers and fruits. In addition, several authors have reported that the positions of flowers on trees and clusters can influence flower quality and fruit development.

First, the fruits positioned in the outer part of the canopy are of a better quality than those at the inner part of the canopy due to the limited sunlight in the inner part (Damerow et al., 2007).

Second, the position of the flowers in the cluster is related to fruit set and fruit quality (Ferree et al., 2001). Due to greater sink potential, young fruit or fruitlets at the king flower position are larger in size and have an increased potential for fruit set compared with other lateral fruits in the cluster (Westwood et al., 1967). In addition, there are more dropped fruitlets in June drop from the lateral flower position than from the king flower position (Jakopic et al., 2015). However, there is no guarantee that king flowers will produce high-quality fruit because they often produce unshaped or oversized fruits after thinning (Baab & Lafer, 2005). Therefore,

reducing the number of flowers in a cluster might be a suitable mechanism for promoting fruit quality. Ferree et al. (2001) reported that the difference in quality between fruit from the king and lateral flower positions is mitigated by the regulation of the number of flowers in the cluster.

# 3. State of the art in thinning methods

## 3.1 Natural crop load control

Apple trees can naturally control their crop load by flower or fruit abscission due to hormonal changes in the pedicels of floral buds or fruits (Wertheim, 2000). In general, trees are susceptible to natural abscission in the three main periods of the growing season (Kolaric, 2010; Luckwill, 1953) (Fig. 3.1).

1) **Petal fall**

Unfertilised flowers are discarded by trees, whereas the remaining flowers develop into fruits. This process occurs 1–4 weeks after full bloom.

2) **Fruitlet drop**

Young fruits or fruitlets drop because they have fewer developed seeds, which causes by insufficient fertilization. This process occurs 5–6 weeks after full bloom and is commonly referred to as June and December drop in the Northern and Southern Hemispheres, respectively (Wouters, 2014).

3) **Pre-harvest drop**

The nearly mature fruits drop at ~4 weeks before harvest due to stress and over-cropping of the trees.

Even though the trees use the mechanisms to naturally regulate the number of fruits they produce, these processes are insufficient for the production of high-quality fruits and can have negative effects on fruit yield. Thus, farmers must use additional methods for manipulating the crop load of trees and thereby improving fruit quality and yield (Peifer et al., 2018; Wouters, 2014).

## 3.2 Crop load control methods

Crop load control methods are employed by farmers to apple trees throughout the growing season (Fig. 3.1) and have been shown to improve fruit quality and return bloom (Costa et al., 2013; He & Schupp, 2018; Robinson, 2000; Seehuber et al., 2014).

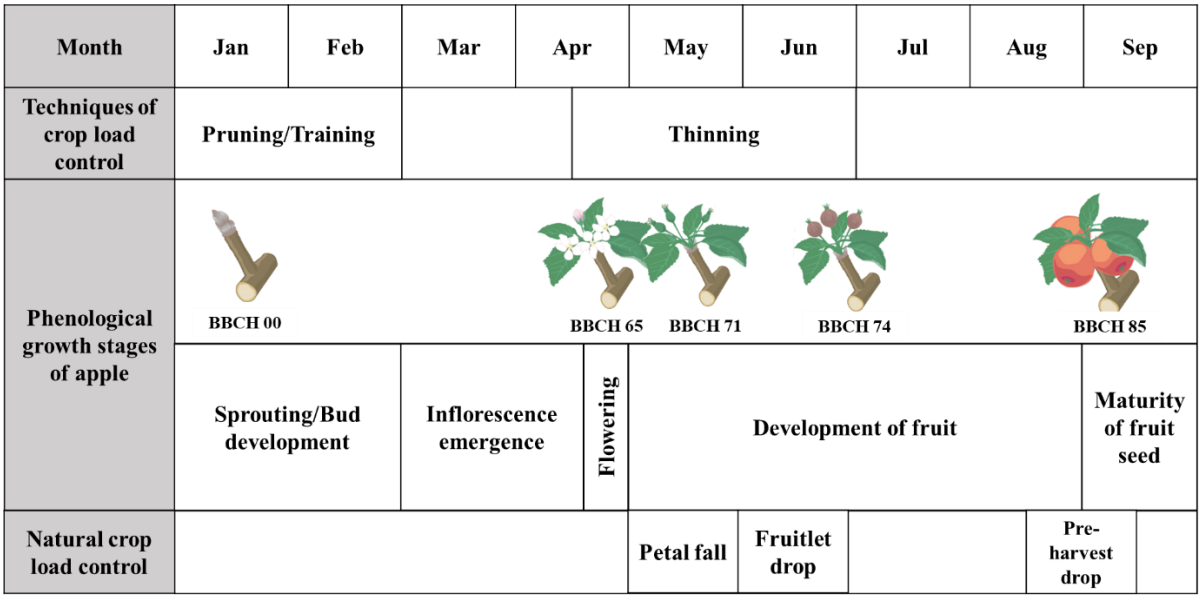
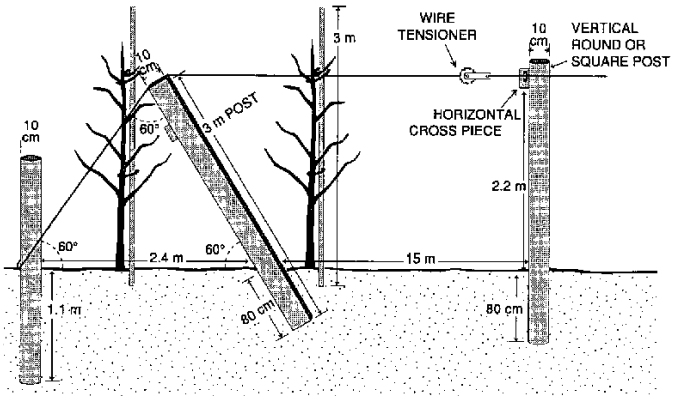


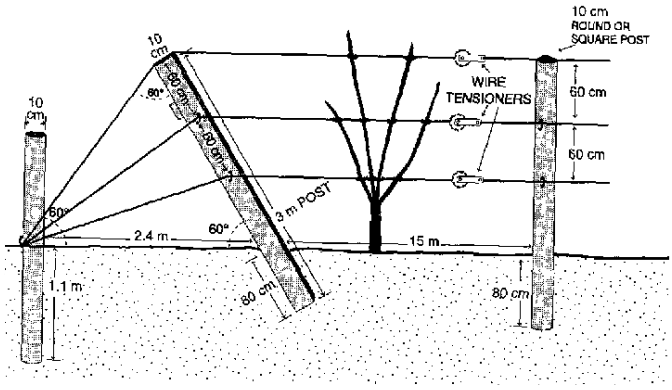

Fig. 3.1: Timeline of crop-load regulation and phenological growth stages for apple trees in Germany.

Pruning is typically applied by cutting specific branches to reduce the number of floral buds. Most farmers prune their trees during the dormant season or during winter before the beginning of active growth because it is easy to identify undesirable branches. Pruning aims to balance vegetative and reproductive growth as well as improve fruit quality (He & Schupp, 2018). However, unpredictable final fruit yield is the main disadvantage of pruning (Wouters, 2014).

Another method involves training, which is used for controlling the shape and form of trees supporting heavy crops without inflicting damage on the trees. Training is frequently applied to young trees to improve their production at an early age. In addition, it allows more sunlight and air to reach the centre of the tree. Wouters (2014) noted that vertical branches rather than horizontal branches should be removed because the former produce fewer floral buds. Two systems of training, V- and Y-shaped systems, have been popularised to train apple canopies in commercial orchards (Fig. 3.2) (Robinson, 2000). These systems have positive effects on fruit quality and yield.




(a)




(b)

Fig. 3.2: Two systems of training apple canopies. (a) V-shaped system and (b) Y-shaped system (Robinson, 2000).

Thinning is the most important crop-load regulation method used for controlling the number of flowers and fruits during the growing season (Fig. 3.1 and Fig. 3.3). It can be performed during three periods: a) early thinning is applied to remove floral buds during the late dormant and early bud break period (BBCH 51–52) (Breen et al., 2015; 2016), b) blossom thinning is used to reduce excessive flower clusters or flowers between the inflorescence and flowering stages (BBCH 57–69) (Damerow et al., 2007; Hampson & Bedford, 2011; Kong et al., 2009) and c) fruit thinning is applied to reduce misshapen fruits during the development of fruit stage (BBCH 71–72) (Bound et al., 1997; Lopez et al., 2011; Yuan, 2007; Yuan & Greene, 2000). Studies have found that thinning of pome and stone fruits improves fruit quality and ensures return bloom (Ouma, 2007; Peifer et al., 2018). Furthermore, early thinning is considered more effective than late thinning in terms of fruit quality and yield improvements (Breen et al., 2015; Costa et al., 2013; Meland, 2009).

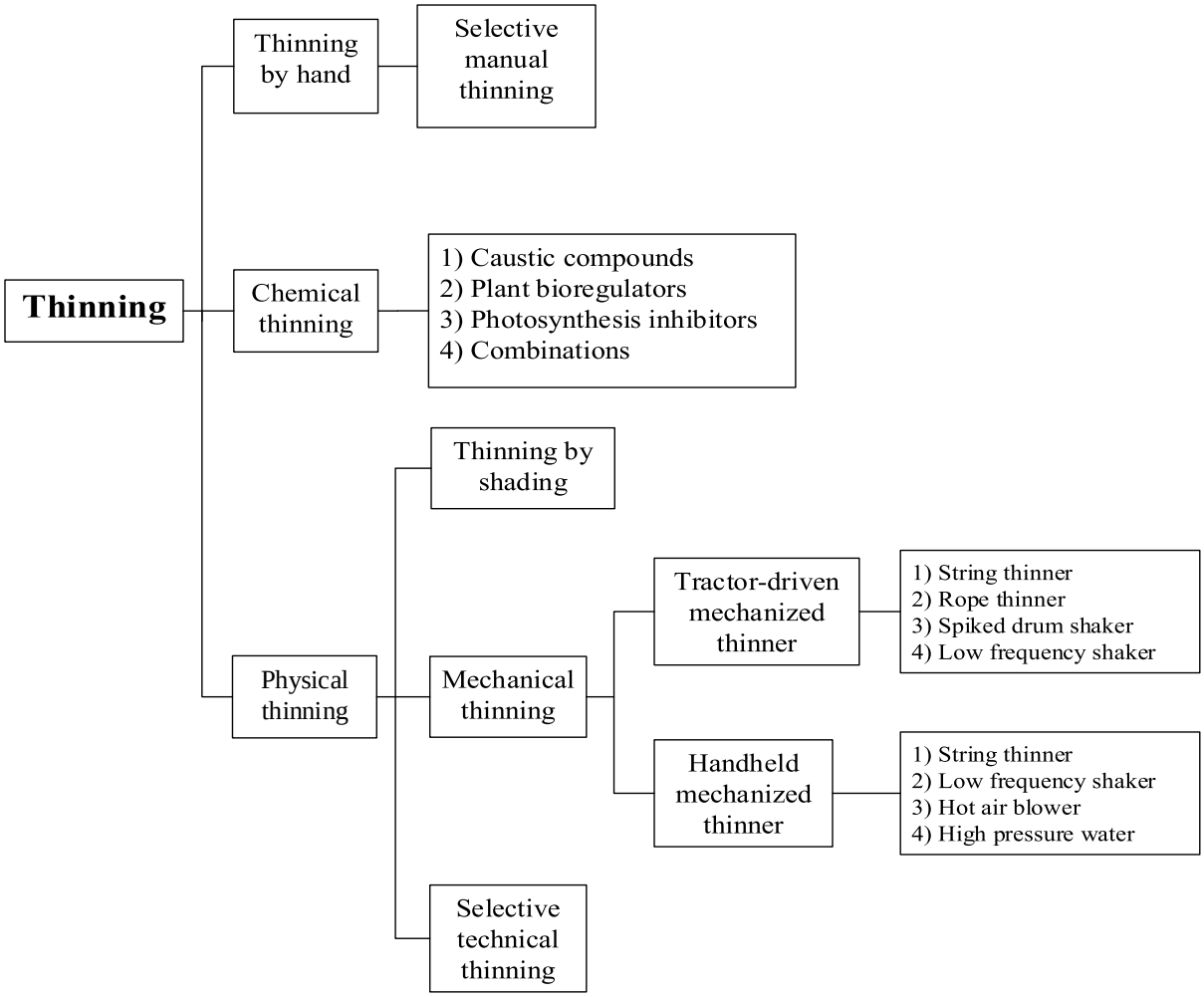



Fig. 3.3: Structure diagram showing the thinning methods used for pome and stone fruits.

### 3.3 Manual thinning

Manual thinning is a traditional crop-load regulation method widely applied to stone and pome fruits, such as peach (Sauerteig & Cline, 2013), plum (Seehuber et al., 2011), pear (Burge et al., 1991; Lopez et al., 2011) and apple (Seehuber et al., 2014). It involves the removal of flowers (Fig. 3.4a) and fruits (Fig. 3.4b) by hand and is applied to apple trees during three different vegetative growth stages. First, fruitlets are thinned after full bloom to yield single fruits per cluster and improve fruit size (Bergh, 1992). Second, flowers or flower clusters are removed at full bloom (Bergh, 1992; Breen et al., 2015), which reduces the density of flowers and flower clusters, thereby increasing carbon availability to support the remaining fruit buds and improve fruit set and development (Breen et al., 2015; Lauri & Rouanne, 1999). Third, floral buds are manually removed between late dormancy and early budbreak. This method is known as artificial spur extinction (ASE) (Breen et al., 2015; Tustin et al., 2012). By pruning during winter, floral buds at weak positions are removed and the bud density is reduced (Breen

et al., 2015). After ASE, the remaining floral buds are sufficiently supported for flower development, which improves fruit set and fruit quality (Breen et al., 2014; 2016). Manual thinning improves not only fruit quality but also prevents alternate bearing (Breen et al., 2015; Koike et al., 2003; Westwood, 1993).

Manual thinning is a highly selective method. The flowers and fruits on the tree are accurately controlled and distributed in suitable positions, which benefits fruit quality as competition among fruits on the tree for photo-assimilates is reduced (Breen et al., 2015; Palmer et al., 1991). However, removal of excess flowers or fruits from trees in commercial orchards is a labour-intensive and costly process (Damerow et al., 2007; Martin-Gorriz et al., 2012).

(a)

(b)

Fig. 3.4: Photos of manual thinning at two stages of phenological growth. (a) Blossom thinning at full bloom and (b) fruitlet thinning after full bloom.

### 3.4 Chemical thinning

Given the labour and cost requirements of manual thinning, chemical thinning is often employed as an alternative thinning method between the bloom and fruit growth stages of stone and pome fruit to control fruit load and improve fruit quality (Fig. 3.5) (Fischer et al., 2002; Link, 2000). Chemical agents can be classified by their effect on fruit trees as caustic compounds, plant bioregulators and photosynthesis inhibitors (Dennis, 2000; Wouters, 2014).

Fig. 3.5: Mechanised spraying application of chemical thinning agents in an apple orchard at the flowering stage.

### 3.4.1 Use of caustic compounds

Caustic compounds are most often sprayed during the flowering stage to prevent pollination and fruit set through damage to the reproductive organs of flowers. Ammonium thiosulfate (ATS) has become the most widely used caustic thinning compound in Europe (Greene & Lakso, 2013). It is applied during bloom to thin flowers and its effect involves burning and desiccating the style and stigma of unfertilised flowers (Fig. 3.6) (Wertheim, 2000). ATS has been found to significantly decrease fruit set and increase fruit size (Bound & Jones, 2004; Greene, 2001; Janoudi & Flore, 2005; Maas, 2007), it is most effective in thinning fully opened flowers but has no effect on closed flowers (Janoudi & Flore, 2005). Maas (2016) noted that ATS effectively inhibits fruit set when applied shortly before pollination and that the efficacy of ATS declines after pollination. The effects of ATS also depend on weather conditions. For example, Fischer et al. (2002) applying ATS during sunny days when the temperature was 17°C–25°C and the relative humidity was >60%.

Fig. 3.6: Two remaining fruitlets on a cluster at 4 weeks after ammonium thiosulfate spraying.

Liquid lime sulfur (LLS) is mainly applied for fruit thinning. McArtney et al. (2006) reported that LLS causes leaf damage and inhibits leaf photosynthesis, which reduces the transfer of carbohydrate that usually supports fruit development. In addition, LLS inhibits the formation of pollen tubes, which are used to transfer genetic material from the pollen seed to the ovules at the base of the flower after pollination (Yoder et al., 2009). However, the results are dependent on weather conditions and LLS application often has negative effects on fruit size and tree health (Cromwell et al., 2011).

### 3.4.2 Use of plant bioregulators

Hormones are the agents applied as bioregulators for thinning. They affect the complex balance between ethylene and auxin, which is responsible for the growth and natural abscission on fruit trees (Dennis, 2000; Wouters, 2014).

Ethephon is mostly used to enhance natural flower and fruit drop. It is effective for flower thinning when applied at the flowering stage after most king flowers have opened and for fruitlet thinning when the average fruitlet size is >10 mm in diameter (Meland & Kaiser, 2011). Webster (2002) noted that higher ethephon concentrations are required at the flowering stage than at the fruit development stage. The effects of ethephon depend on ambient temperature; for example, Fischer et al. (2002) reported that ethephon requires air temperatures of 18°C–22°C at the flowering stage for blossom thinning and 20°C–25°C when applied after June drop

for fruit thinning. Ethephon has no effect when applied at temperatures <15°C and the temperature during the day after application often leads to unpredictable thinning results (Baab & Lafer, 2005; Stover & Greene, 2005).

Benzyladenine (BA) is mostly applied at post-bloom for fruitlet thinning. It increases dark respiration and decreases net photosynthesis, which enhances the intensity of natural fruit abscission in June drop (Schröder et al., 2013; Yuan & Greene, 2000). In addition, benzyladenine leads to fruit drop by reducing carbohydrate levels and stimulating ethylene production (Botton et al., 2011; Eccher et al., 2013). The thinning effect of benzyladenine is maximised if it is applied when the king fruit diameter is 8–12 cm or at 10–20 days following full bloom under optimal temperature conditions of at least 15°C and with relative humidity of 42%–47% on the day of application (Bound et al., 1997; Bubán, 2000; Schröder et al., 2013).

Naphthaleneacetic acid (NAA) and Naphthaleneacetamide (NAD) are also used to achieve fruit thinning. They increase dark respiration and reduce photosynthesis, thereby enhancing fruit drop and preventing fruit set (Untiedt & Blanke, 2001). However, both chemicals are being phased out in many European countries (Veal et al., 2011).

Carbaryl is an effective fruit-thinning chemical when applied under cloudy or shady conditions (Byers et al., 1990). Despite having only minor negative side effects on fruit and trees (Wertheim, 2000), carbaryl has been banned in Europe due to its negative effects on beneficial insects, such as honeybees (Greene & Costa, 2013; Helson et al., 1994).

### 3.4.3 Use of photosynthesis inhibitors

When used for chemical thinning, photosynthesis inhibitors inhibit photosynthesis in leaves, resulting in advanced competition for carbohydrates between fruits and intensified fruit abscission.

Metamitron inhibits the photosynthesis apparatus for 7–10 days after application (McArtney et al., 2012). It is effective in fruit thinning when its application coincides with a fruitlet diameter of 10–12 mm or up to 20 mm (Lafer, 2010; McArtney et al., 2012).

Abscisic acid (ABA) is used to reduce unwanted fruits in apple and pear trees (Greene, 2012). It acts on the regulation of stomatal movement, which controls gas exchange between the leaves and environment during photosynthesis (Greene, 2010).

### 3.4.4 Combined use of chemicals

Chemical compounds may be combined to improve their chemical flower and fruit thinning performance (Dennis, 2000). Greene (2001) and Dennis (2000) each reported that multiple applications of a single chemical or a mixture of agents can be employed in cases where the fruit load is insufficiently affected by the initial application. Maas (2007) found that a combination of three ATS applications during flowering followed by an application of benzyladenine when the fruit was 13.8 mm in size obtained a thinning efficiency of 82% and achieved the target fruit load.

### 3.4.5 Limitations of chemical thinning

Chemical thinning is a practical method used by farmers for regulating fruit load and improving fruit quality and return bloom (Bangerth, 2000; Schröder et al., 2013). Indeed, Miller and Tworkoski (2010) stated that chemical thinning has a high efficacy and is capable of replacing manual thinning.

However, chemical thinning has several limitations that have been reported in previous studies. When using chemical agents, the thinning results are unpredictable and dependent on weather conditions, cultivar effects, time of application and chemical concentration (Forshey, 1976; Ouma, 2007; Wertheim, 2000). For example, the application of benzyladenine successfully controls target crop load but may be unreliable in areas with relatively low temperatures and solar radiation (Maas & Meland, 2016). In addition, ATS must be applied shortly before pollination as its efficacy on fruit set inhibition significantly declines post-pollination (Maas, 2016). Furthermore, chemical-thinning practices can have negative side effects on the environment, tree health and the health of human labourers (Wouters, 2014). For example, although carbaryl is a mild chemical relative to trees, it has negative side effects on honeybees (Helson et al., 1994). Wouters (2014) also stated that chemical thinning is not effective on individual trees, unlike manual thinning.

## 3.5 Physical thinning

Due to the limitations of chemical agents in agriculture, physical thinning is also employed for controlling fruit load. Several studies on physical thinning have been conducted at the laboratory and commercial levels (Damerow & Blanke, 2009; Kon et al., 2013; Lyons et al., 2015; Seehuber et al., 2016). Physical thinning can be classified into three categories: thinning by shading, mechanical thinning and selective thinning (Fig. 3.3).

### 3.5.1 Thinning by shading

Shading is an environmentally friendly thinning method in which the availability of trees to sunlight is reduced using shadow or hail nets (Fig. 3.7). This process interrupts photosynthesis at the leaves, resulting in reduced carbohydrate production. These effects enhance fruit abscission due to the side effect of carbon starvation (Aliev et al., 2012; Byers et al., 1990). Thinning by shading can positively affect fruit quality and alleviate alternate bearing (Aliev et al., 2012; Zibordi et al., 2009). In apple trees, thinning by shading should be performed 30 days after full bloom because the trees lose their reserve of carbohydrates, thus increasing the effect of shading (Lakso et al., 1999). However, determining the optimal duration of shading and preventing over-thinning are difficult (Zibordi et al., 2009). Peifer et al. (2018) applied shading for 8 days in a shading experiment and the shaded trees had the lowest fruit set, with 1 fruitlet per 100 flower clusters, indicating the occurrence of over-thinning.

Fig. 3.7: Thinning by shading with a 3-m-wide net that reduces photosynthetically active radiation by 74% in an apple orchard (Kockerols et al., 2008).

### 3.5.2 Mechanical thinning using a handheld mechanised thinner

Portable thinners are designed to enable labourers to work from the ground to remove excess flowers or fruitlets. Their various designs and applications are discussed below.

#### 1) String thinner

Electric handheld fruit remover (Volpi, Davide e Luigi Volpi S.p.A., Casalromano, Italy) consists of a head with six rotating fingers (Fig. 3.8). It is powered by a 12-V electric motor and work at two rotor speeds of 714 and 833 rpm. Martin-Gorriz et al. (2011) invented the electric handheld fruit thinner prototype (Fig. 3.9). This device works at rotor speed of 250 rpm. It consists of a rotating cylinder with 10 flexible cords, a 12-V and 0.12-kW DC motor. Commercial electric handheld flower thinner (Electrocoup, Infaco S.A., Cahuzac sur Vere, France) (Fig. 3.10) has a rotary head with a four-fingered comb and a rotor speed of 770 rpm and is powered by a 48-V electric motor with a portable battery bag.

Fig. 3.8: Electric handheld fruit remover (Volpi, Davide e Luigi Volpi S.p.A., Casalromano, Italy) (Martín et al., 2010).

Fig. 3.9: Electric handheld fruit thinner prototype named Electrocoup flower thinner (Martin-Gorriz et al., 2011).

Fig. 3.10: Commercial electric handheld flower thinner (Electrocoup, Infaco S.A. Cahuzac sur Vere, France) (Martin-Gorriz et al., 2011).

**2) Low-frequency shaker**

A pneumatic handheld shaker (Campagnola P.E.S. Bologna, Italy) can be used to disjoin fruits by branch shaking. This device, which has a mass of 1.9 kg (Fig. 3.11), functions with a vibratory frequency of 10–14 Hz and provides a 3-cm stroke. An air compressor is installed with this thinning shaker to restrict its mobility when working in orchards. Martín et al. (2010) used this thinning shaker in an experiment to remove fruits from peach trees at post-bloom; they reported that the pneumatic handheld shaker led to over-thinning.

Fig. 3.11: Commercial handheld shakers used for fruit thinning (Campagnola P.E.S.Bologna, Italy) (Martín et al., 2010).

### 3) Hot air blower

Hot air can be applied to damage flowers thermally and affect fruit sets in apple and plum trees (Webster, 1993). An air temperature of 60°C is released onto the flowers; the efficacy of thinning is positively correlated with air temperature and exposure time. This type of thinning has the highest efficacy when the air temperature is >80°C or the exposure time is >3 s. However, the flowers and blower must be in close proximity to reduce energy loss between the hot air and ambient air.

### 4) High-pressure water

A high-pressure stream of water can also be employed to remove flowers. For example, Byers (1990) applied pressurised water (3 MPa) to peach trees. A flow rate of 4.5–5.7 Litres per minute is required for full-sized trees. Cline (2017) applied water with a pressure of 1,378 kPa and a flow rate of 7.6 Litres per minute to remove flowers from peach trees at full bloom, with a distance of 1.5 m used between the nozzle and the tree limb (Fig. 3.12). A thinning time of 60–70 seconds per tree with a flow rate of 7.6–9.5 Litres per tree provided the highest final fruit quality and reduced the intensity of manual thinning. However, bark injury occurred when the distance between the nozzle and the limb was <1 m (Fig. 3.13).

Fig. 3.12: Manually applied high-pressure water thinning to peach trees (Cline, 2017).

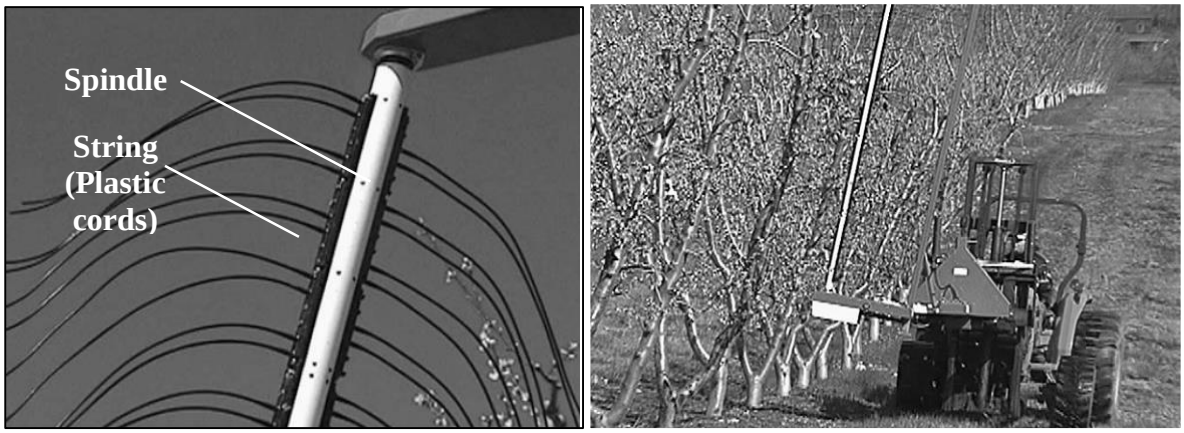
Fig. 3.13: Bark injuries incurred after the application of high-pressure water thinning (Cline, 2017).

### 3.5.3 Mechanical thinning using a tractor-driven mechanised thinner

Tractor-driven thinners have been developed to achieve flower or fruit thinning in commercial orchards. They are discussed below in detail.

**1) String thinner**

The string thinner (Darwin 300, Fruit-Tec, Deggenhausertal, Germany) was developed to remove excessive apple flowers (Bertschinger et al., 1998). It consists of a 3-m-long spindle with 50-cm-long flexible plastic cords attached to the spindle at the right angles (Fig. 3.14a). The spindle is driven by a hydraulic motor with an adjustable rotational speed provided by a proportional flow control valve. The thinner can be adjusted using a tractor hitch and a frame device to match the tree canopy's height and inclination (Fig. 3.14b). This device has been tested in peach and nectarine orchards, which are trained to have a narrow canopy with a 60–75-cm tree height in a perpendicular V system during the flowering stage (Baugher et al., 2010; Schupp et al., 2008). It has been reported that the string thinner reduces the thinning time to 51% that of manual thinning. However, the efficacy of the string blossom thinner was lower at the pink-bud stage than at the other stages during flowering.




(a) (b)

Fig. 3.14: Darwin string thinner. (a) The 3-m-long spindle with 50-cm-long flexible plastic cords. (b) Application of the thinner to peach and nectarine orchards, which are trained to form a perpendicular V system (Baugher et al., 2010).

The Baum string thinner was developed at the University of Bonn, Germany, to remove excess flowers from apple trees (Damerow et al., 2007). This thinner consists of three adjustable spindles with 0.35-m-long stiff plastic filaments. The spindles are separately rotated by three hydraulic motors (Fig. 3.15). With rotor speeds of 260–480 rpm, this thinner is mounted on the front hitch of a tractor operated at 3–7 km $h^{-1}$ to remove flowers and floral buds from stone and pome fruit trees. The three flexible spindles can change position in terms of height and angle depending on the tree size and shape.

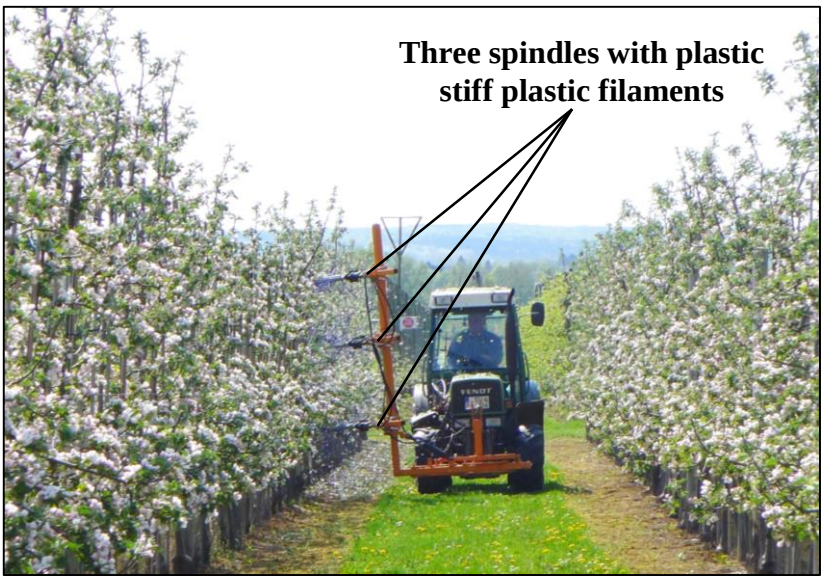



Fig. 3.15: Tractor-mounted Baum string thinner used for blossom thinning in apple trees at the flowering stage.

**2) Rope thinner**

The rope curtain thinner is mounted on a tractor and used to remove flowers from peach and nectarine trees (Fig. 3.16) (Baugher et al., 1988; 1991). Using a tractor speed of 3.2 km $h^{-1}$, this device is applied at the flowering stage when 80%–100% of flowers are open. The rope thinner reduces the manual thinning time by 40% and increases the final fruit weight by 10%–20%. However, the thinning efficiency depends on the position of the flowers on the tree; the device mostly removes flowers at the top and periphery of the tree.

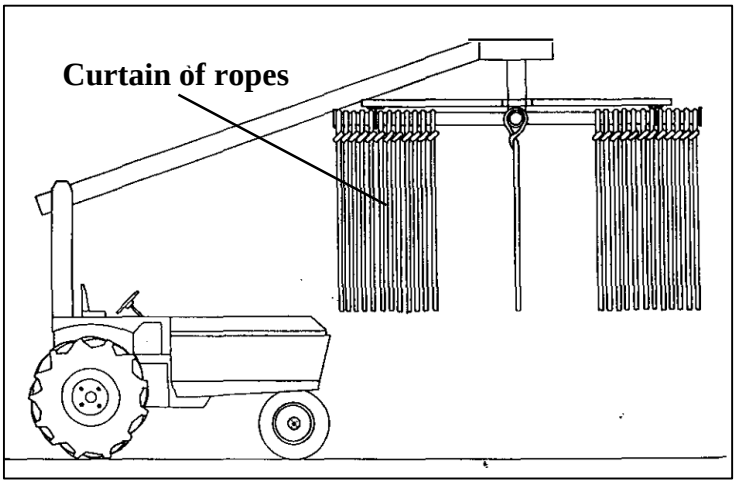



Fig. 3.16: Tractor-mounted rope thinner used for flower thinning in nectarine and peach trees (Baugher et al., 1991).

**3) Spiked-drum shakers**

Spiked-drum shakers are used for mechanical harvesting in citrus trees and for thinning (Fig. 3.17). Glenn et al. (1994) and Schupp et al. (2008) demonstrated that the mechanical spiked-drum shaker could effectively remove peaches on Y- and V-trained trees at the early green-fruit stage. These devices are single- or double-spiked, depending on the number of drums used. The double-spiked-drum shaker consists of 6 whorls with 16 rods, whereas the single-spiked-drum type has 24 rods. The shaker is mounted on a tractor-towed trailer or attached to a tractor hitch.

The drums are rotated by a hydraulic pump that generates an oscillating motion of 3.6–5.0 Hz in the horizontal plane. The drums can be adjusted in a vertical direction and at angles to accommodate the plane of the trees' canopy. Fruitlets are removed by the shaking energy, which is transferred to the branches through their contact with the rods (Miller et al., 2011).

However, this is non-selective thinning device as it removes both large and small fruits (Berlage & Langmo, 1982).


Fig. 3.17: Spiked-drum shaker (USDA prototype single-spiked drum shaker) uesd for thinning peaches (Miller et al., 2011).

### 3.5.4 Selective thinners

Selective thinning is employed to improve the efficacy of thinning for precision crop load management. Numerous studies have reported the adjustment of thinning devices that can increase thinning performance. For example, Damerow et al. (2007) and Hehnen et al (2012) adjusted the amount or position of strings in the Baum string thinner (Fig. 3.15). From these adjustments, their devices were able to remove excess flowers in the inner part of the canopy, which is less exposed to sunlight and provides lower-quality fruit.

In other studies, the detachment force required to remove flowers or fruits from branches has been investigated. Wouters (2014) studied the detachment forces required to pick flower buds or flowers from pear branches in different phenological growth stages; the detachment forces and diameter of the fracture surfaces in 2 years were 6.65 N with 3.24 mm and 9.95 N with 3.88 mm, respectively. The phenological growth stage is the main factor influencing the fracture strength of the pedicel. The green cluster stage is the most viable stage at which to begin the removal of flower buds or flowers by mechanical thinning. Romano et al. (2019) investigated a vibratory device used as a thinning shaker to detach flower buds, flowers and green fruits from mandarin branches. They reported that the amplitude, frequency and phenological stage significantly affected the efficacy of removal. The removal percentage

when using an amplitude of 30 mm was 30% higher than that achieved using a 15-mm amplitude. In addition, vibrating with a 37.8-Hz frequency led to a higher percentage of removal (48%) compared with the percentage achieved at 34.8 Hz (33%). From flowering to the beginning of the fruit development stage (BBCH 72) is a suitable period in which to remove flower buds, flowers and fruitlets using low-retention traction forces. In addition to pome fruit, the condition of flower and fruit detachment has been investigated in stone fruit. Lyons et al. (2015) examined the normal and tangential forces required for peach blossom removal, reporting that a normal force of 0.44–0.57 N and tangential force of 0.49–0.71 N could remove peach flowers from a shoot.

Several techniques are applied when using thinning devices to locate the target position for precise removal. In recent years, autonomous or robotic systems have been used during orchard management, e.g. during pruning, thinning and harvesting (Zhang et al., 2019).

Stereo vision system has also been used for automated blossom thinning on peach trees with a perpendicular V-shaped system (Nielsen et al., 2010; 2012) (Fig. 3.18). These studies provided a good starting point for target detection for automated selective blossom thinning applications. Aasted et al. (2011) invented an autonomous mechanical thinner consisting of a system using LIDAR to sense the canopy and automatically control the position of a modified Darwin string thinner depending on the positions of trees and branches. This laser control system was able to rapidly control the string thinner and provide a removal rate of ~50% when applied with a tractor speed of 1.6 km $h^{-1}$ and spindle rotation of 240 rpm.

Fig. 3.18: Stereo vision system for automated blossom thinning on peach trees (Nielsen et al., 2010).

A multi-spectral camera system has also been used with a pneumatic flower removal system, which consists of a pneumatic nozzle and air compressor that generate sufficient air flow at supply pressures of 1.2–1.4 MPa (Wouters et al., 2013; Wouters, 2014) (Fig. 3.19). This device achieved thinning rates of 94% and 53% at the green bud and fruitlet stages, respectively. The distance between the nozzle and bud and also the age of branches were identified as the two main factors affecting thinning efficiency. The effective distance between the nozzle and floral bud was 21.34 cm. Furthermore, the efficacy of flower-bud removal was reduced in older branches as a 2-year-old branch had the ability to absorb kinetic energy from the pressurised air.

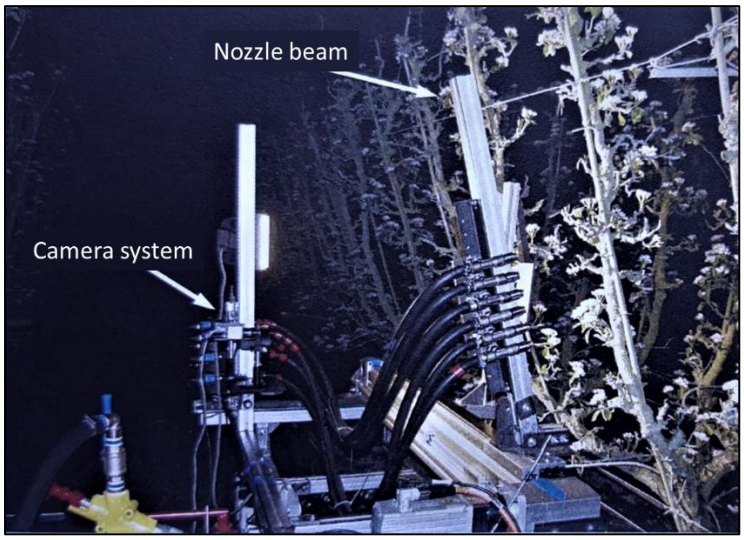



Fig. 3.19: Mechatronical system for blossom thinning on pear (Wouters, 2014).

In addition, laboratory equipment can be used to apply robotic systems for flower and fruit removal. For example, Yang (2012) and Lyons et al. (2015) applied robotic systems for peach flower removal using a table-top robotic arm (Fig. 3.20). A clamp-type device containing dual rollers with a brush end-effector was installed on the robotic arm to brush off the flowers.

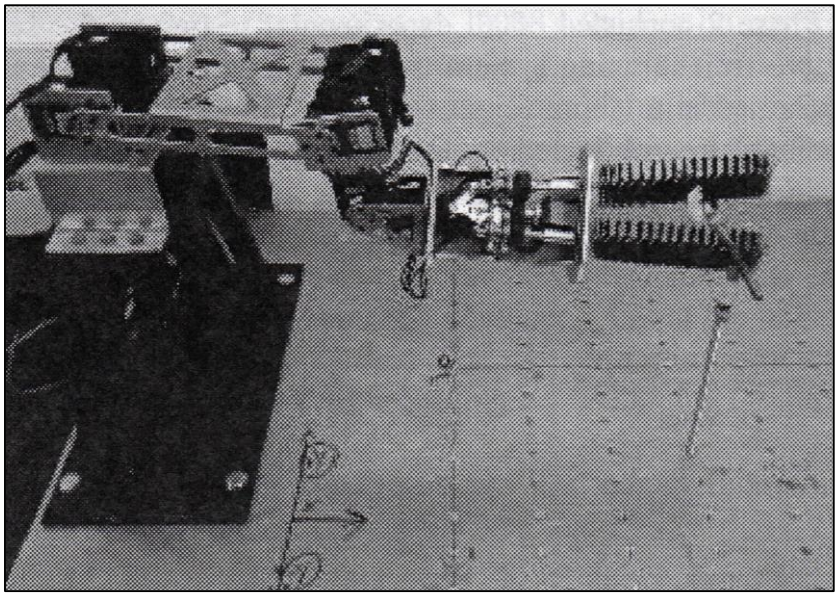


Fig. 3.20: Robotic arm for flower removal on peaches (Lyons et al., 2015).

As detailed in the descriptions of numerous thinning devices mentioned above, blossom or fruit thinning techniques have limitations, such as unpredictable results for chemical thinning and limited selective thinning for mechanical thinning. Therefore, the methods used for flower or fruit removal require further development to improve the precision and accuracy of selective thinning without negatively affecting the trees and environment.

## 4. Materials and methods

Two experiments were conducted in this research. First, practical thinning methods were studied in a field experiment to compare their efficacy as well as the effects of thinning on the reduction and improvement of fruit set and fruit quality, respectively. Second, the feasibility of laser radiation as a method for flower removal applied for selective thinning was investigated.

### 4.1 Practical thinning experiment conducted in 2018

#### 4.1.1 Treatment and location of trees

Six-year-old apple trees, cv. 'Roter Boskoop' in M9 rootstock, were studied at the Klein-Altendorf field laboratory (50° N, 6° E) of the University of Bonn, Germany. A total of 67 trees (2.3-m tall at a planting distance of 3.5 × 1 m) had been trained as slender spindles and produced a large blossom intensity in 2018 (8 on a scale of 1–9 for blossom intensity: 1 = no flowers, 9 = white blossom; Peifer et al., 2018) after the spring frost in April 2017. The treatments consisted of chemical or mechanical thinning and flower cluster removal by hand; control trees were not treated (Table 4.1).

Table 4.1: Crop load management (CLM) in 2018.

| Type of CLM | Treatment number/ CLM description | Flower stage/ fruit development |
|---|---|---|
| 1. Unthinned control | U1: all flowers and cluster leaves remaining | n.a. |
| 2. Flower cluster removal by hand | H1: 25% flower cluster removal<br>H2: 50% flower cluster removal<br>H3: 75% flower cluster removal | Balloon and flowering stage (BBCH 59–61) |
| 3. Mechanical thinning | M1: 320 rpm rotor speed<br>M2: 380 rpm rotor speed<br>(with a tractor speed of 5 km $h^{-1}$) | Balloon stage (BBCH 59) |

| Type of CLM | Treatment number/ CLM description | Flower stage/ fruit development |
|---|---|---|
| 4. Chemical thinning | C1: ATS (15 L ha$^{-1}$) + ethephon (0.3 L ha$^{-1}$)<br>C2: ATS (15 L ha$^{-1}$) + ethephon (0.3 L ha$^{-1}$) and 6-BA (7.5 L ha$^{-1}$) | Full bloom (BBCH 65) for ATS and Flordimex 420; fruit size of 10–12 mm (BBCH 71) for 6-BA |

n.a.: not applicable

### 4.1.2 Counting flower clusters and fruit and assessing return bloom

Apple flower clusters on the trees were counted on 19$^{th}$ April 2018 at the balloon stage (BBCH 59) (Meier, 2001) before CLM (Fig. 4.1). The fruit set was calculated based on the number of fruits per 100 flower clusters before and after the June drop in 2018. Return bloom in the subsequent year (2019) was expressed using the blossom intensity scale evaluated on 10 detached branches (100%) per treatment at a temperature of 20°C from December 2018 to February 2019 until flowering (Bertschinger et al., 2000).

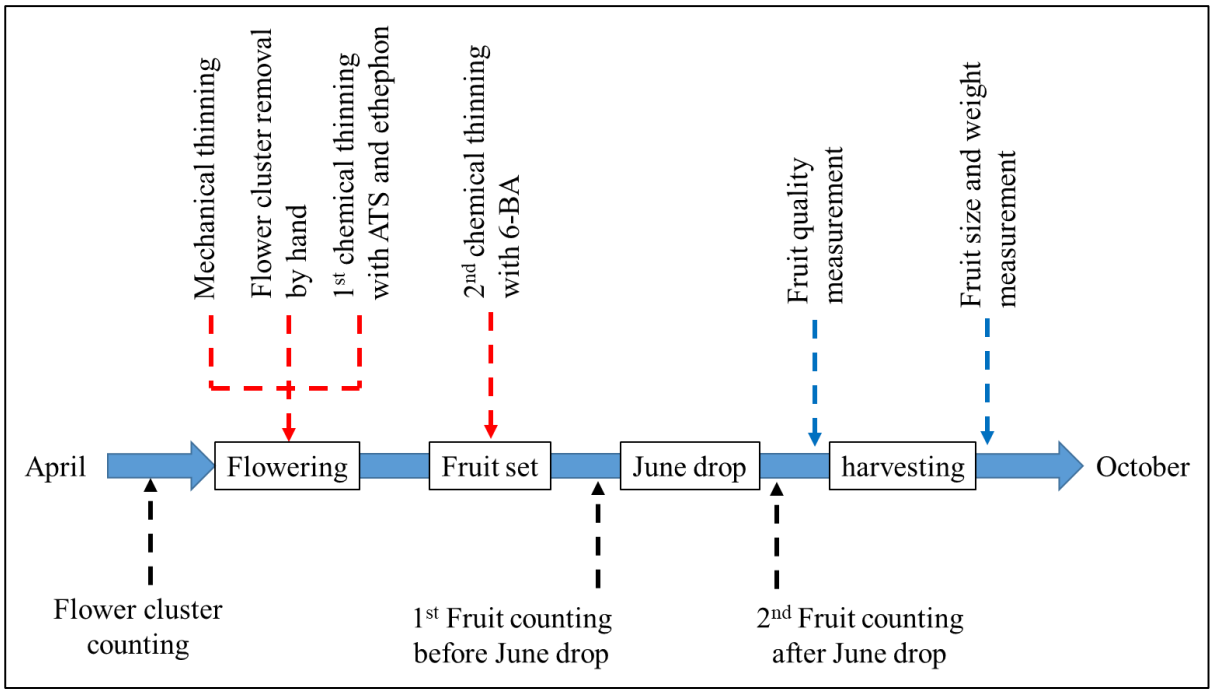



Fig. 4.1: Schedule of flower cluster and fruit counting on whole and thinned trees in 2018.

### 4.1.3 Flower cluster removal by hand

Flower clusters were manually removed at the beginning of flowering (BBCH 59–61) with three different thinning intensities of 25% (treatment H1), 50% (treatment H2) and 75% (treatment H3) applied to flower clusters (Fig. 4.2).

Fig. 4.2: Flower cluster removal by hand at the beginning of flowering (BBCH 59–61).

### 4.1.4 Mechanical thinning

The Bonner thinning device (Damerow et al., 2007) (Fig. 4.3) was used with three adjustable horizontal rotors mounted on the front of a tractor. It was operated at a tractor speed of 5 km $h^{-1}$ and rotor speed of 320 rpm (Treatment M1), resulting in an integrated coefficient of thinning (ICT) of 3.6 (Equation 1), or 380 rpm with an ICT of 6.2 at the balloon stage (BBCH 59) on 20th April 2018 (Table 4.1; Treatment M2). The ICT was developed to devise critical thresholds and aid future decision-making processes (Solomakhin & Blanke, 2010); it is expressed as follows:

$$ICT = \frac{M \; x \; S^2}{FS \; x \; V \; x \; R} \qquad (1)$$

where *FS* denotes fruit set (%); *M*, mass of the rope in the brush (3 g); *S*, rotor speed (rpm); *R*, radius (m; i.e. length of the rope in the brush = 0.3 m) and *V*, vehicle speed or velocity of tractor (km $h^{-1}$).

(a)


(b)

Fig. 4.3: Mechanical thinning. (a) The Bonner thinning device used in an apple orchard at the balloon stage (BBCH 59). (b) The tractor mounted with the Bonner thinning device.

### 4.1.5 Chemical thinning

ATS (15 L $ha^{-1}$ application rate) was combined with ethephon (Flordimex 420; 420 g $L^{-1}$ active ingredient; application rate of 0.3 L $ha^{-1}$) to produce a spray volume of 1,000 L $ha^{-1}$ for the first

chemical thinning, which was employed to remove blossoms at full bloom (BBCH 65) (Fig. 4.4) on 24$^{th}$ April 2018 at 10 am (15°C, 56% relative humidity and 3 m s$^{-1}$ wind speed) in treatment C1. At the onset of fruitlet development (BBCH 71), on 4$^{th}$ May 2018 when the air temperature was 19°C and the relative humidity was 35%, 6-benzyladenine (Exilis; 7.5 L ha$^{-1}$ application rate) was also applied with an air-blast sprayer (S1000; Hans Wanner GmbH, Germany) as the second chemical thinning, which was used to remove fruitlets in treatment C2 (Fig. 4.4).

(a)


(b)

Fig. 4.4: Chemical thinning. (a) Applying chemical thinning in an apple orchard at full bloom (BBCH 65). (b) The tractor trailed by an air-blast sprayer.

### 4.1.6 Fruit quality and maturity assessment

One week before regular harvesting, apple fruits from the trees in each CLM treatment were examined for fruit quality and maturity using an ART system (UP Co., Osnabrück, Germany) (Fig. 4.5). The Streif index (Equation 2) was calculated based on fruit firmness measured using a penetrometer with a 10-mm$^2$ plunger, total soluble solid concentration measured using a digital refractometer (type PR 32; Atago Co., Tokyo, Japan) and starch breakdown after iodine–potassium staining assessed on a scale of 1–10 (1 = no starch breakdown; 10 = complete starch breakdown) (Peirs et al., 2000; Solomakhin & Blanke, 2010; Streif, 1989). In addition, 15 apple fruits per treatment were randomly picked from example trees in each treatment to evaluate the internal fruit quality on 15$^{th}$ September 2018. The remaining apple fruits were harvested on 22$^{nd}$ September 2018. Fruit size was represented by the average size of apples from 10 trees per treatment, which was calculated using an automatic grading machine (type Greefa MSE 2000; Geldermalsen, Holland).

$$Streif\ index = \frac{Firmness}{Total\ soluble\ solids \times Starch\ breakdown} \quad (2)$$

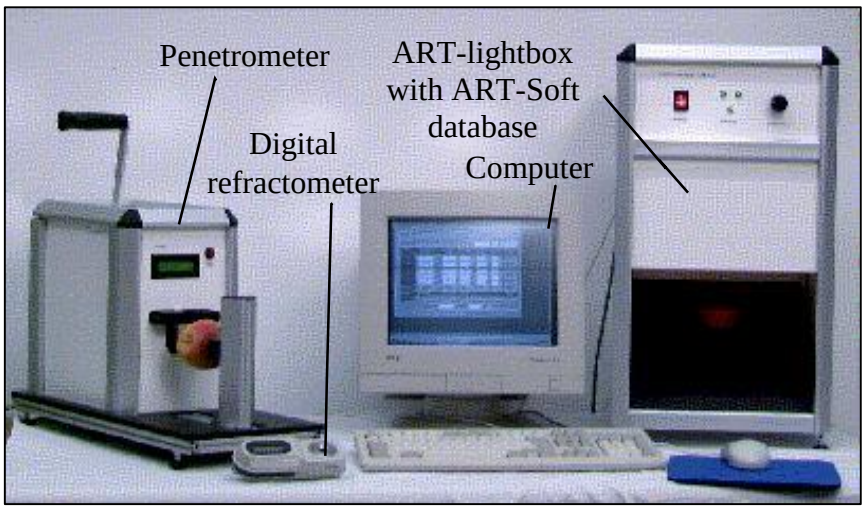



Fig. 4.5: Fruit quality was measured using an ART system (www.wetter.rlp.de).

### 4.1.7 Experimental design and statistical analysis

The orchard layout for blossom thinning in 2018 is presented in Fig. 4.6. Manual thinning treatments (Treatments H1–H3) were randomly performed on individual trees in rows 1–3, whereas both mechanical (Treatments M1 and M2) and chemical (Treatments C1 and C2)

treatments were performed on 10 adjacent trees in a row. The unthinned control treatment was randomly performed on individual trees in row 4 and in 10 adjacent trees in row 5. Fruit set, determined by the number of remaining apple fruit before and after June drop and fruit quality, was statistically evaluated using the SPSS software version 24 (SPSS Co., USA). Levene's test was employed to determine the homogeneity of variances. A Dunnett T3 test was used to determine the differences between the group means and the unthinned control at the 95% confidence level, whereas least significant differences (LSDs) were used to determine differences between the group means in cases where homogeneous variance was observed.

| Row1 | Row2 | Row3 | Row4 | Row5 | Row6 | Row7 | Row8 |
|---|---|---|---|---|---|---|---|
| H1 | H2 | H3 | - | M1 | - | C1 | - |
| - | - | - | - | M1 | - | C1 | - |
| - | - | - | U1 | M1 | - | C1 | - |
| - | - | - | - | M1 | - | C1 | - |
| - | - | H3 | - | M1 | - | C1 | - |
| H1 | H2 | - | U1 | M1 | - | C1 | - |
| - | - | - | - | M1 | - | C1 | - |
| - | - | - | - | M1 | - | C1 | - |
| H1 | H2 | H3 | U1 | M1 | - | C1 | - |
| - | - | - | - | M1 | - | C1 | - |
| - | - | - | - | - | M2 | - | - |
| - | H2 | - | - | - | M2 | - | - |
| H1 | - | H3 | U1 | - | M2 | - | - |
| - | H2 | - | - | - | M2 | - | - |
| - | - | - | U1 | - | M2 | - | - |
| H1 | - | H3 | - | - | M2 | - | - |
| H1 | H2 | - | U1 | - | M2 | - | - |
| - | - | - | - | - | M2 | - | - |
| - | - | H3 | - | - | M2 | - | - |
| - | - | - | - | - | M2 | - | - |
| - | - | - | U1 | U1 | - | - | C2 |
| - | - | - | - | U1 | - | - | C2 |
| H1 | H2 | H3 | - | U1 | - | - | C2 |
| - | - | - | - | U1 | - | - | C2 |
| - | - | - | - | U1 | - | - | C2 |
| H1 | H2 | H3 | U1 | U1 | - | - | C2 |
| - | - | - | - | U1 | - | - | C2 |
| - | - | - | - | U1 | - | - | C2 |
| H1 | H2 | H3 | U1 | U1 | - | - | C2 |
| - | - | - | - | U1 | - | - | C2 |

**U1**= Unthinned control
**H1**= 25% flower cluster removal
**H2**= 50% flower cluster removal
**H3**= 75% flower cluster removal
**M1**= Mechanical thinning with 320 rpm rotor speed
**M2**= Mechanical thinning with 380 rpm rotor speed
**C1**= ATS + ethephon
**C2**= ATS + ethephon and 6-BA
- = Border tree

Fig. 4.6: Orchard layout used for blossom thinning in 2018.

## 4.2 Flower removal by laser radiation

The materials and methods in this section adapted from Netsawang et al. (2021a, 2021b) (see list of publications).

### 4.2.1 Laser setup and energy measurement

A blue (450 nm) diode laser with 4-W optical power was applied as a prototype laser flower remover. The laser system was installed on an aluminium frame (Fig. 4.7). An apple branch was placed in front of the laser device to obtain a focal length of 0.15 m and a constant laser spot area of 3.92 $mm^2$. Two low-power line lasers were used to target the laser spot position on the flower clusters and buds. The laser diode was operated in continuous mode emitting a laser beam with a Gaussian profile to transfer energy horizontally toward the flower cluster. An Arduino Uno microcontroller board was connected to a laser driver by an interface to adjust the exposure time.

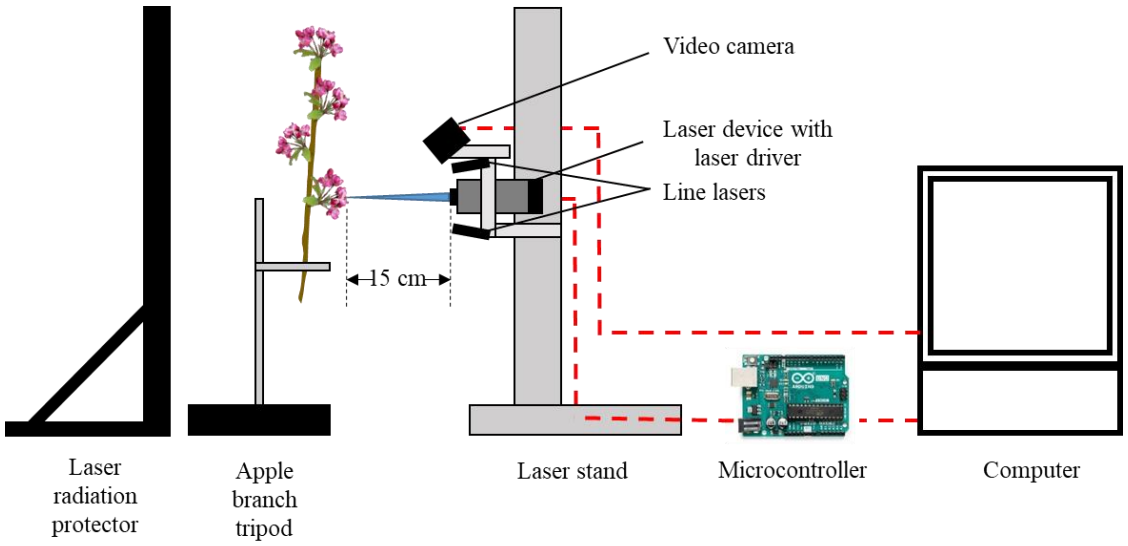



Fig. 4.7: Experimental setup used to apply laser radiation for flower removal.

The optical power of the laser was measured using a laser power meter (PM100A; Thorlabs GmbH., Dachau, Germany) with a thermal power sensor (S425C-L; Thorlabs GmbH., Dachau, Germany) (Fig. 4.8) and the laser energy was calculated using Equation (3). The beam profile was measured using a beam diagnostic system (Fig. 4.9) with beam view software (Coherent Inc., USA) to determine the laser spot area on the flower tissue. The laser energy density (Table

4.2) was determined based on the laser energy and laser spot area using Equation (4) (Mathiassen et al., 2006).

$$E = P \times T \tag{3}$$

and

$$I = \frac{E}{A} \tag{4}$$

where $E$ denotes the laser energy (J); $P$, the laser power (W); $T$, the exposure time (s); $A$, the laser spot area (3.92 mm$^2$) and $I$, the laser energy density (J mm$^{-2}$).

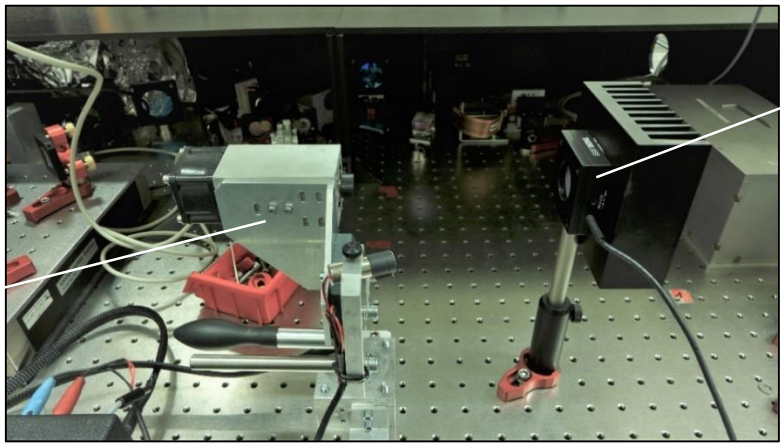



Fig. 4.8: Measurement of optical power using a laser power meter with a thermal power sensor.

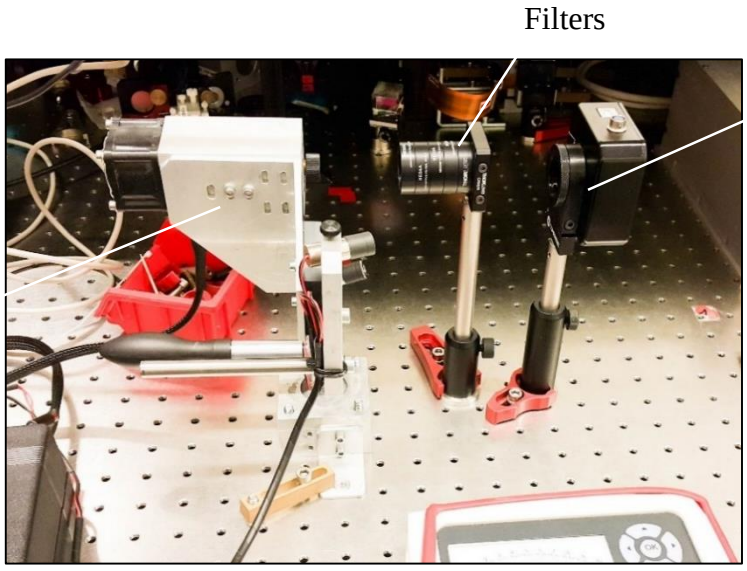



Fig. 4.9: Beam diagnostic system used for laser beam profile measurement (www.coherent.com).

Table 4.2: Energy density of a 4-W laser at different exposure times.

| Exposure time (ms) | Energy (J) | Density of laser energy ($J\ mm^{-2}$) |
|---|---|---|
| 500 | 2 | 0.50 |
| 1,000 | 4 | 1.02 |
| 1,500 | 6 | 1.53 |
| 2,000 | 8 | 2.04 |
| 2,500 | 10 | 2.55 |
| 3,000 | 12 | 3.06 |

### 4.2.2 Apple flower clusters

The apple cv. 'Hilieri' flower cluster of one-year-old branches with 1m length from trees at the Klein-Altendorf Research Centre, University of Bonn, Germany (50°37', 51 N, 6°59', 32 E) were cut in April 2020 to preserve the flower clusters for subsequent experiments. All apple branches were submerged in water in buckets for storage before being tested in the laser laboratory at the Institute of Agricultural Engineering, University of Bonn. Four phenological growth stages of apple flowers, namely, the mouse ear (BBCH 54) (Fig. 4.10), pink bud (BBCH 57) (Fig. 4.11), balloon stage (BBCH 59) (Fig. 4.12) and full bloom (BBCH 65) (Fig. 4.13) stages, were studied to assess the efficacy of flower removal.

### 4.2.3 Experimental design

Each treatment, including an untreated control, consisted of 25 flower clusters (1 flower cluster = 1 replicate). For the untreated control, 25 flower clusters per phenological growth stage were used. Different positions of the laser spot and untreated controls were randomly set up on five or six flower clusters per branch at the middle of the branch. Two laser spot positions from the side at the bottom of the flower cluster (FSC) and from the front of the flower bud (FFB) were tested at the mouse ear stage (Fig. 4.10). Two laser spot positions were tested at pink bud with a) from the side at the bottom of the flower cluster (FSC) and b) from the front of the flower (FFF) (Fig. 4.11). At balloon (Fig. 4.12) and full bloom (Fig. 4.13) stage, four laser spot positions were assessed as a) from the side at the bottom of the flower cluster (FSC), b) from the front of the flower cluster (FFC), c) from the side of the flower at the ovary (FSF) and d) from the front of the flower (FFF). The effect of laser energy density (Table 4.2) on flower

damage was further investigated by using 10 flower clusters per treatment at the laser spot position from the front of the flower cluster (FFC). All the experimental parameters and variables are presented in Table 4.3.

(a) (b)

Fig. 4.10: Photographs taken from (a) the front of the flowers and (b) the side of flowers at the **mouse ear stage** (BBCH 54). Two laser targeting positions are shown (green point: positioned in the front of the flower bud; FFB and red point: positioned at the side of the flower cluster; FSC) (Netsawang et al., 2021a).

(a) (b)

Fig. 4.11: Photographs taken from (a) the front of the flowers and (b) the side of flowers at the **pink bud stage** (BBCH 57). Two laser targeting positions are shown (green point: position at the front of the flower; FFF and red point: positioned at the side of the flower cluster; FSC) (Netsawang et al., 2021a).

(a) (b)

Fig. 4.12: Photographs taken from (a) the front of the flowers and (b) the side of the flowers at the **balloon stage** (BBCH 59). Four laser targeting positions are shown (green point: positioned at the front of the flower; FFF, yellow point: positioned at the front of the flower cluster; FFC, white point: positioned at the side of the flower at the ovary; FSF and red point: positioned at the side of the flower cluster; FSC) (Netsawang et al., 2021a; 2021b).

(a) (b)

Fig. 4.13: Photographs taken from (a) the front of the flowers and (b) the side of the flowers at the **full bloom stage** (BBCH 65). Four laser targeting positions are shown (green point: positioned at the front of the flower; FFF, yellow point: positioned at the front of the flower cluster; FFC, white point: positioned at the side of the flower at the ovary; FSF and red point: positioned at the side of the flower cluster; FSC) (Netsawang et al., 2021b).

Table 4.3: Experimental parameters and variables used in the study of flower removal by laser radiation conducted in 2020.

| Phenological growth stages of apple flowers | Position of laser spot | Laser energy density |
|---|---|---|
| **Part 1** | | |
| Mouse ear (BBCH 54) | From the front of the flower bud (FFB)<br>From the side of the flower cluster (FSC) | 1.02 J $mm^{-2}$ |
| Pink bud (BBCH 57) | From the front of the flower (FFF)<br>From the side of the flower cluster (FSC) | 1.02 J $mm^{-2}$ |
| Balloon stage (BBCH 59) | From the front of the flower (FFF)<br>From the front of the flower cluster (FFC)<br>From the side of the flower (FSF)<br>From the side of the flower cluster (FSC) | 1.02 J $mm^{-2}$ |
| Full bloom (BBCH 65) | From the front of the flower (FFF)<br>From the front of the flower cluster (FFC)<br>From the side of the flower (FSF)<br>From the side of the flower cluster (FSC) | 1.02 J $mm^{-2}$ |
| **Part 2** | | |
| Balloon stage (BBCH 59)<br>Full bloom (BBCH 65) | From the front of the flower cluster (FFC) | 0.50 J $mm^{-2}$<br>1.02 J $mm^{-2}$<br>1.53 J $mm^{-2}$<br>2.04 J $mm^{-2}$<br>2.55 J $mm^{-2}$<br>3.06 J $mm^{-2}$ |

### 4.2.4 Flower damage assessment

After laser treatment, apple branches were submerged in water and evaluated in a laboratory with a temperature of 20°C–25°C. To assess damage, flowers were divided into two categories depending on the position of the damage. Damage at the stigma, style and ovary was classified as ‘damaged flowers’, whereas damage at other parts of the flower, such as the petal, was classified as ‘undamaged flowers’. Damage to flowers after laser treatment was visually

evaluated every other day and until the untreated flowers showed damage, which accounted for the effect of natural damage/deterioration during flower assessment. The number of damaged flower clusters was counted after emitting laser radiation at the position from the side (FSC) and the front (FFC) of flower clusters, while the number of damaged single flowers was collected for the positions from the side (FSF) and the front (FFF) of the flower and from the front of flower bud (FFB).

### 4.2.5 Statistical analysis

The number of damaged flowers or flower buds was statistically evaluated using SPSS Statistics (SPSS Co., USA). The LSD test was employed to determine the differences between the group means at the 95% confidence level.

# 5. Results

In this chapter, the results of the first experiment, i.e. the effects of three different thinning methods on fruit set regulation, June drop, return bloom, fruit quality, fruit yield and the source–sink relationship and second experiment, i.e. the effects and efficacy of selective flower removal by laser radiation, are presented.

## 5.1 Results of the practical thinning experiment

### 5.1.1 Effect of CLM on fruit set before and after June drop

The fruit set and/or thinning efficiency determined as the number of apple fruitlets before June drop expressed per 100 flower clusters (100%) following mechanical, chemical and flower cluster removal by hand is presented in Fig. 5.1. The fruit set before June drop defines the efficiency of the thinning procedure in terms of reducing the number of flowers, whereas the fruit set after June drop indicates the relationship between the thinning efficiency and source–sink relationship in apple trees. The number of fruitlets before June drop was counted on 6$^{th}$ June 2018.

In terms of fruit set reduction, CLM was successful when 50% or 75% of flower clusters were removed compared with the unthinned control, as 56% and 46% fruit sets were achieved (Fig. 5.1; Treatments H2 and H3). The faster rotor speed (380 rpm) used for mechanical thinning with an ICT of 6.2 (M2) removed more flowers and thinned more effectively compared with the slower rotor speed (320 rpm) with an ICT of 3.6 (M1) (46.5% and 56.5% fruit sets, respectively). Both rotor speeds were as efficient or more efficient than chemical treatment C1 (ATS + ethephon: 65.6% fruit set) but similar to chemical treatment C2 (ATS + ethephon with 6-benzyladenine: 60.0% fruit set). Only treatment H1, i.e. 25% flower cluster removal, resulted in a larger fruit set (83.3%) than that of the unthinned control.

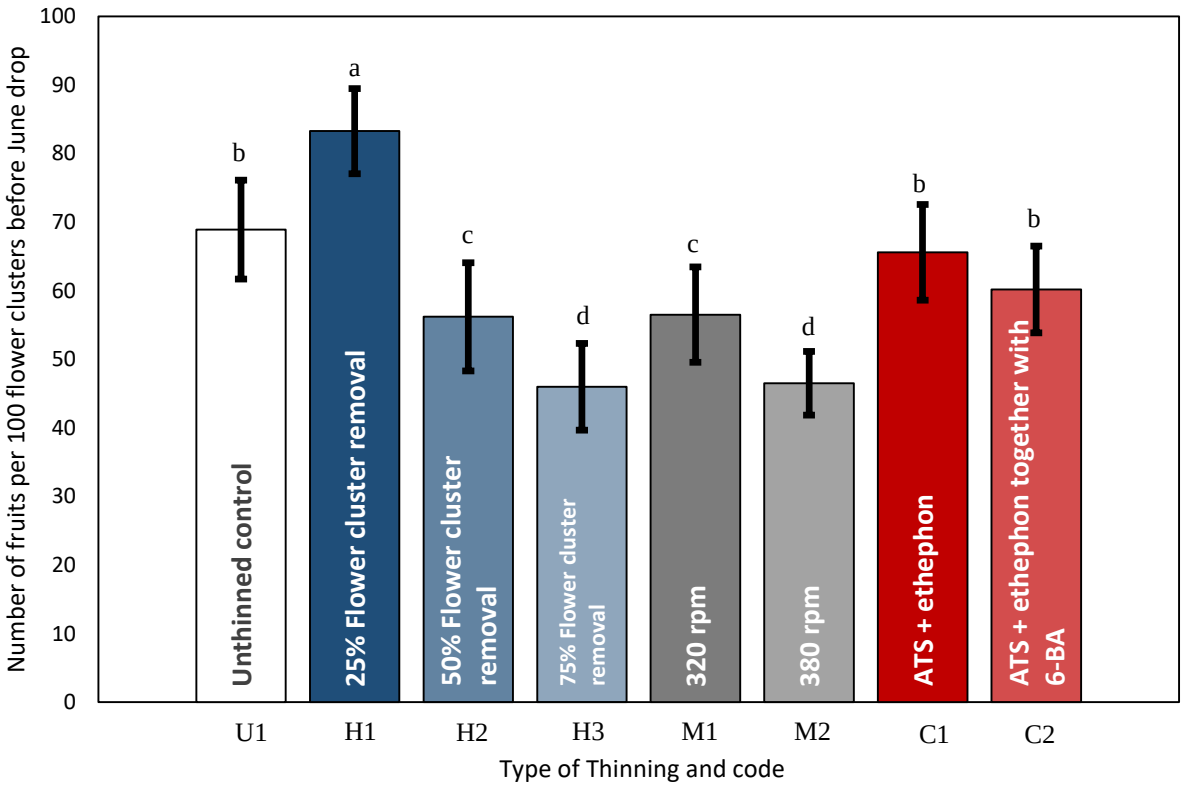



Fig. 5.1: Effect of practical thinning methods on the number of apple fruitlets before June drop per 100 flower clusters (White, unthinned control; blue, thinning by hand at flowering; grey, mechanical blossom thinning; red, chemical thinning).

In Fig. 5.2, the effects of practical methods on fruit set after June drop, which was calculated based on the number of fruits per 100 flower clusters, are presented. The number of fruits was counted on 4$^{th}$–6$^{th}$ July 2018 after the trees had compensated for excessive fruitlet removal during June drop. Fruit set after June drop indicates the relationship between the thinning efficiency and the source–sink relationship in apple trees.

The trend in the number of fruitlets per 100 flower clusters after June drop for all treatments (Fig. 5.2) was similar to that in the number of fruits before June drop (Fig. 5.1). The removal of 75% of flower clusters (H3) achieved a significantly smaller fruit set after June drop (38.4%) compared with that of the unthinned control (56%) (U1) (Table 5.1).

In addition, the number of fruitlets per 100 flower clusters significantly declined with the application of more extreme CLM treatments (Fig. 5.2). Chemical thinning using ATS + ethephon (C1) had a negligible effect (56%) on either June drop or total fruit drop relative to

the unthinned control trees (U1). Two CLM treatments, namely, hand removal of 50% (H2) and 75% (H3) of flower clusters, resulted in the intended reduction of fruitlets per 100 flower clusters (45.5% and 38%, respectively) (Fig. 5.2). Similarly, both rotor speeds of the mechanical thinning device successfully reduced fruit set (39% for M2 and 47% for M1). Furthermore, the example trees in treatment H1 (25% flower cluster removal) abscised their excessive fruitlets, resulting in a fruit set (63%) similar to that of unthinned control trees (U1). The application of 6-benzyladenine (C2) for fruitlet thinning after the first chemical thinning using ATS + ethephon reduced fruit set (50.4%) to a similar level to that achieved with hand removal of 25% of flower clusters (H1), the first chemical thinning treatment (C1) and unthinned control (U1).

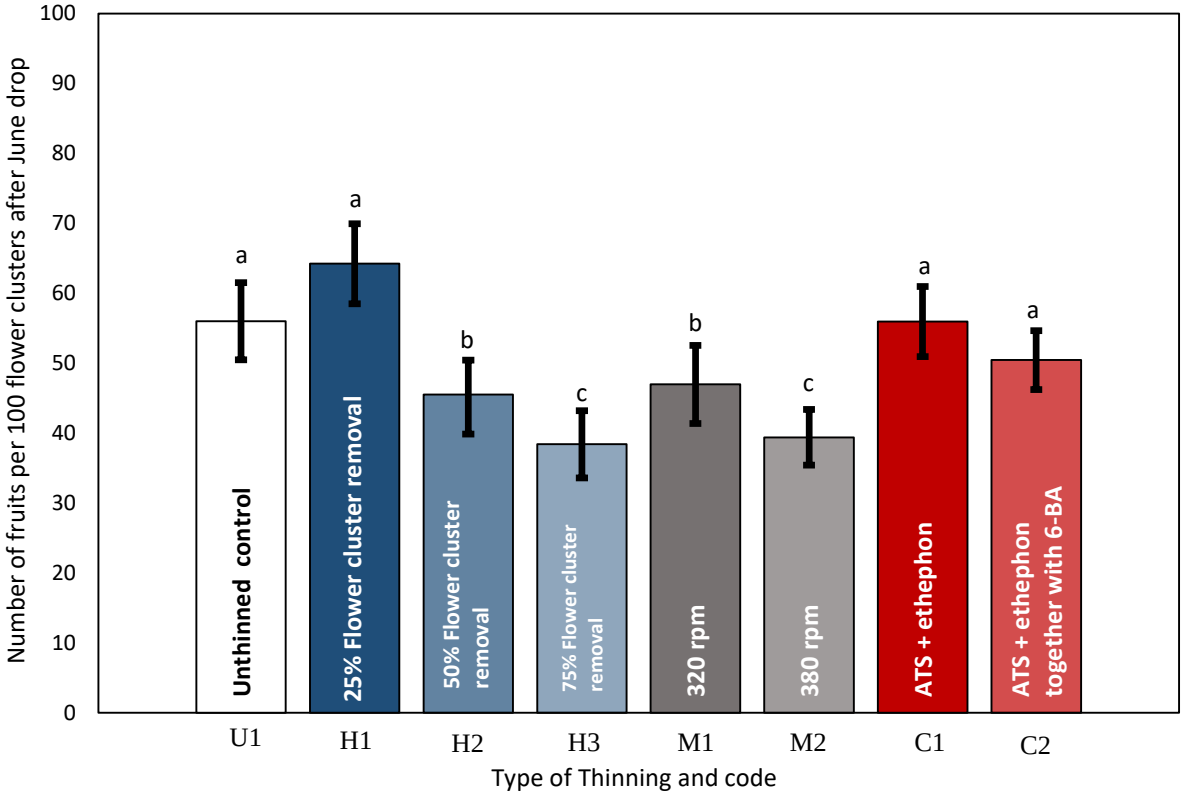



Fig. 5.2: Effect of practical thinning methods on the number of apple fruitlets after June drop per 100 flower clusters (same colour coding as that used in Fig. 5.1).

### 5.1.2 Effect of CLM on June drop

Excess fruitlets with fewer developed seeds due to insufficient fertilisation generally drop at 5 to 6 weeks after full bloom as June drop. The intensity of the natural June drop is an important

parameter indicating the relationship between the thinning efficiency and the source–sink relationship in apple trees.

The intensity of the natural June drop was reduced to different extents by the application of CLM at flowering. After severe flower cluster removal (more than 50% flower cluster removal: H2 and H3), June drop was reduced relative to that observed after slight flower cluster removal (H1) (Fig. 5.3). All treatments except 25% flower cluster removal (H1) lessened the reduction of fruitlets in June drop relative to that in the unthinned control.

Mechanical thinning with the faster rotor speed (380 rpm; M2) was the strongest manipulation with a close source–sink relationship and the lowest June drop reduction of 14%–15%, similar to both types of chemical thinning (Fig. 5.3). The 25% flower cluster removal (H1), which resulted in a higher number of fruitlets before and after June drop relative to the unthinned control, exhibited the greatest reduction in June drop (22%; Table 5.1).

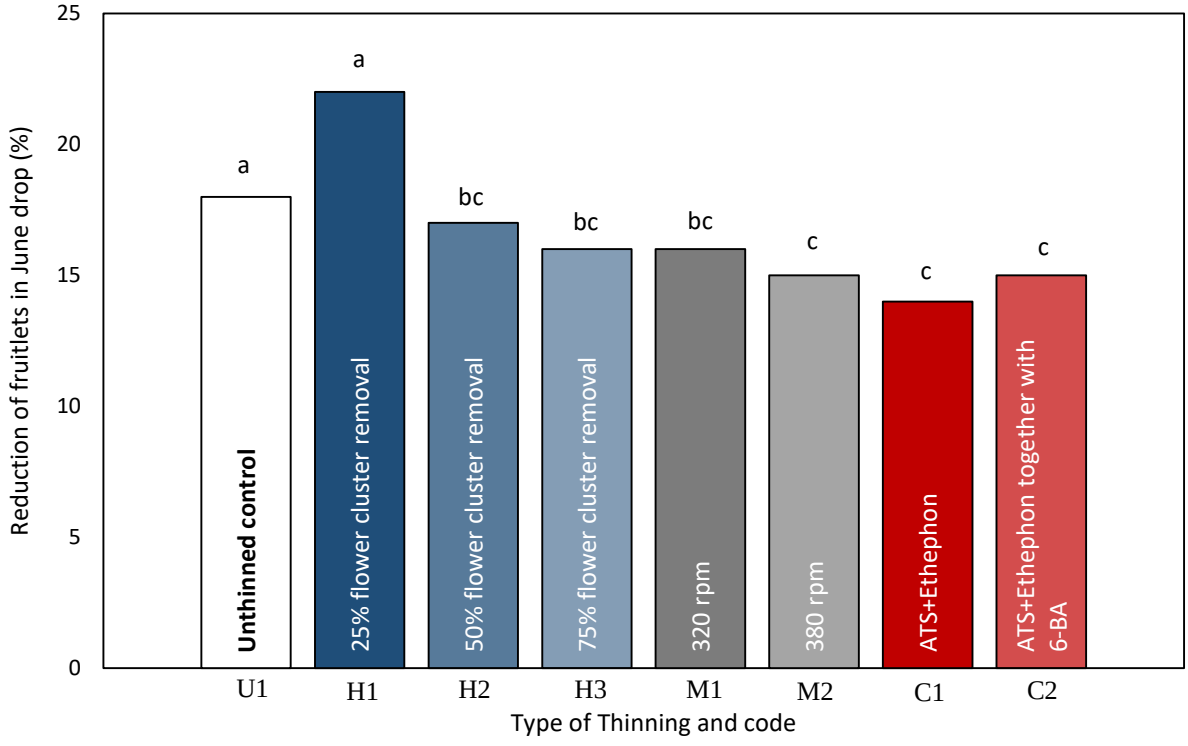



Fig. 5.3: Effect of practical thinning methods on the reduction of fruitlets in June drop expressed as the difference in fruitlets before and after June drop (colour coding is the same as that presented Fig. 5.1).

Table 5.1 presents the effect of CLM on the number of fruitlets before and after June drop and the percentage of fruit reduction in June drop; this table includes the extended results from Fig. 5.1, Fig. 5.2 and Fig. 5.3.

Table 5.1: Effects of crop load management (CLM) on the number of fruitlets before and after June drop and fruit reduction in June drop.

| Treatment code | Type of CLM | Number of fruitlets per 100 flower clusters before June drop | Number of fruitlets per 100 flower clusters after June drop | Reduction in June drop* (%) |
|---|---|---|---|---|
| U1 | Unthinned control | 69[b] | 56[a] | 18[a] |
| | Thinning by hand | | | |
| H1 | 25% flower cluster removal | 83.3[a] | 63[a] | 22[a] |
| H2 | 50% flower cluster removal | 56.2[c] | 45.5[b] | 17[bc] |
| H3 | 75% flower cluster removal | 46[d] | 38.4[c] | 16[bc] |
| | Mechanical thinning | | | |
| M1 | 320 rpm | 57.3[c] | 46.9[b] | 16[bc] |
| M2 | 380 rpm | 46.4[d] | 39.2[c] | 15[c] |
| | Chemical thinning | | | |
| C1 | ATS + ethephon | 65.9[b] | 55.9[a] | 14[c] |
| C2 | ATS + ethephon and 6-BA | 60.2[b] | 50.4[a] | 15[c] |

[a, b] and [c]: Significant differences according to Dunnett T3 and LSD tests with $P < 0.05$.

* Percentages are relative to the number of fruits per tree before June drop (100%).

### 5.1.3 Effects of CLM on fruit quality and yield

The internal fruit quality of apples cv. ‘Roter Boskoop’ in all treatments is presented in Table 5.2. Apple fruits were evaluated for fruit maturity using an ART system (see Section 4.1.6).

The internal quality of apples in all treatments was within or exceeded the recommended range at fruit harvest as follows: fruit firmness = 8.6–9.0 kg $cm^{-2}$; sugar content = 14.9–15.9 °Brix; Streif index = 0.18–0.24 (Table 5.2). However, the starch breakdown of all treatments (2.6–

3.7) was lower than the recommended range. Höhn et al. (1999) recommended that the following fruit quality for cv. 'Roter Boskoop' apples suitable for harvesting: fruit firmness = 8–9 kg $cm^{-2}$; sugar content = 11–12 °Brix; starch breakdown = 4–5; Streif index = 0.15–0.20.

Except for sugar content, no significant differences were observed in fruit quality (Table 5.2). The greatest sugar content was observed with the extreme thinning treatments, i.e. 75% flower cluster removal by hand (H3; 15.9 °Brix) and the mechanical thinning with the higher rotor speed (M2; 15.8 °Brix). The lowest sugar content (14.9 °Brix) was observed with 25% flower cluster removal by hand.

Table 5.2: Effect of thinning treatments on the internal quality of apples cv. 'Roter Boskoop' in 2018 and blossom intensity in 2019.

| **Treatment code** | **Type of CLM** | **Firmness (kg $cm^{-2}$)** | **Sugar (ºBrix)** | **Starch breakdown (1-10)** | **Streif index** |
|---|---|---|---|---|---|
| U1 | Unthinned control | 8.6 | 15.1[bc] | 3 | 0.19 |
| | Thinning by hand | | | | |
| H1 | 25% flower cluster removal | 9.0 | 14.9[c] | 2.6 | 0.24 |
| H2 | 50% flower cluster removal | 8.9 | 15.7[ab] | 2.9 | 0.20 |
| H3 | 75% flower cluster removal | 8.9 | 15.9[a] | 3.7 | 0.18 |
| | Mechanical thinning | | | | |
| M1 | 320 rpm | 9.0 | 15.6[ab] | 2.7 | 0.23 |
| M2 | 380 rpm | 9.0 | 15.8[a] | 2.8 | 0.22 |
| | Chemical thinning | | | | |
| C1 | ATS + ethephon | 8.8 | 15.1[bc] | 2.7 | 0.22 |
| C2 | ATS + ethephon and 6-BA | 8.8 | 15.5[ab] | 3.2 | 0.19 |

[a, b] and [c]: Significant difference according to LSD with $P < 0.05$.

Fruit size and weight were averaged from the apples of 10 trees per treatment using an automatic grading machine after harvest on 22nd September 2018. The effects of CLM treatments on the fruit size percentage relative to the standard marketable fruit size in 2018

according to the Bundesanstalt für Landwirtschaft und Ernährung scale (70–90 mm fruit diameter) are presented in Fig. 5.4.

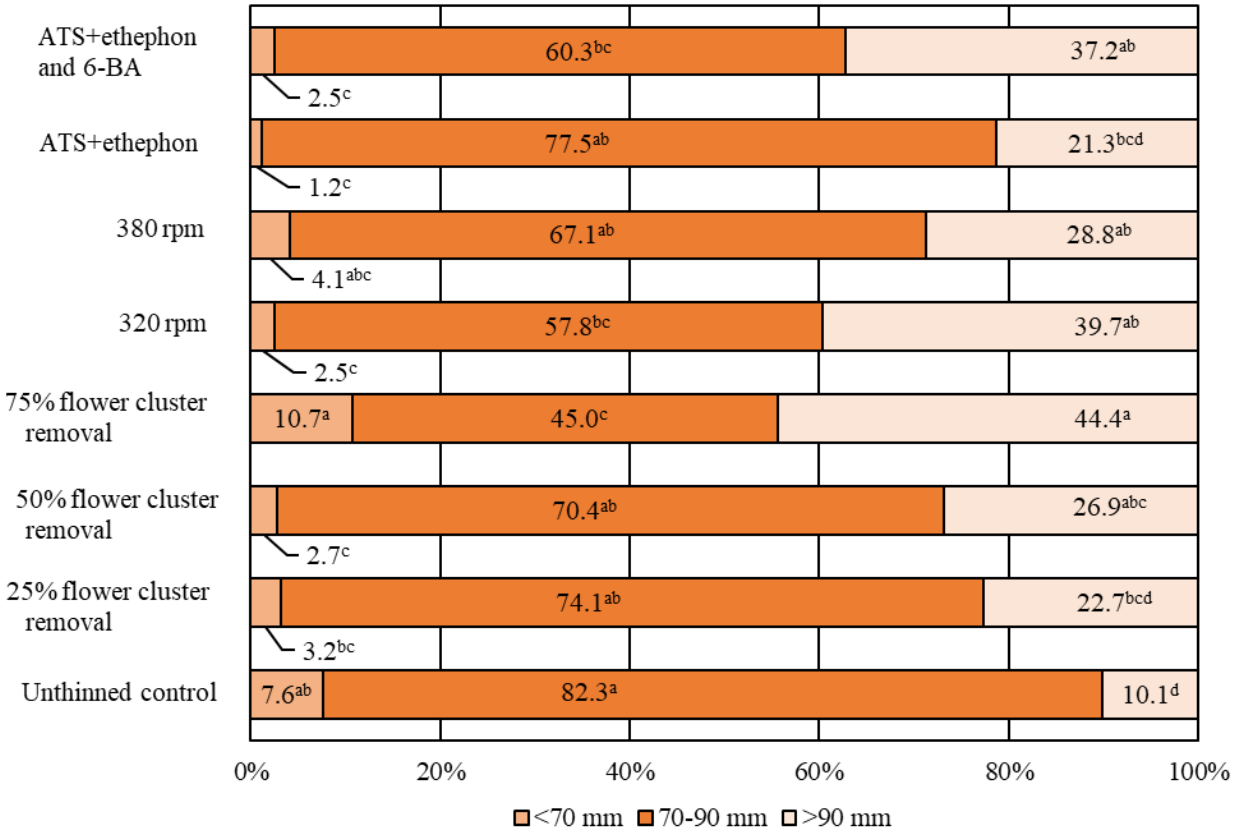



Fig. 5.4: Fruit size percentage in all treatments relative to marketable fruit size (70–90-mm diameter). [a, b] and [c]: Significant difference according to Dunnett T3 tests with $P < 0.05$.

Most CLM treatments significantly improved fruit size compared with that in the unthinned control according to the percentage of large fruits (>90-mm diameter) and reduced percentage of small fruits (<70-mm diameter). The percentage of large fruits was significantly increased with most CLM treatments, except for 25% flower cluster removal (H1) and chemical thinning using ATS + ethephon (C1). The most severe flower cluster removal by hand with the 75% flower cluster removal (H3) had the most substantial effect on fruit size improvement, leading to the highest percentage of fruit with >90-mm diameter (44.4%; Fig. 5.4). Both rotor speeds of the mechanical thinning device successfully improved fruit size (fruits with >90-mm diameter: 39.7% for M1 and 28.8% for M2), similar to the 50% flower cluster removal treatment (H2: 26.9%). In addition, chemical thinning using ATS + ethephon and 6-

benzyladenine (C2) led to 37.2% of fruits having a >90-mm diameter, similar to both mechanical thinning treatments.

However, the unthinned control produced the largest proportion of fruit (82.3%), with the optimum size being 70–90-mm diameter (Fig. 5.4). The smallest percentage (45%) of optimally sized fruit was observed with the 75% flower cluster removal treatment. Four treatments had similar proportions of optimally sized fruit: 25% (H1: 74.1%) and 50% (H2: 70.4%) flower cluster removal, mechanical thinning with the higher rotor speed (M2: 67.1%) and chemical thinning with ATS + ethephon (C1: 77.5%). However, no significant difference was observed in the percentage of optimally sized fruits between mechanical thinning with the lower rotor speed (M1: 57.8%) and chemical thinning using ATS + ethephon and 6-benzyladenine (C2: 60.3%).

All CLM treatments except 75% flower cluster removal (H3) and mechanical thinning with the higher rotor speed (M2) significantly reduced the proportion of small fruit (<70-mm diameter) in comparison with the fruit from the unthinned control (Fig. 5.4). The lowest percentages of small fruit size were observed with 50% flower cluster removal (H2: 2.7%), mechanical thinning with the lower rotor speed (M1: 2.5%) and both chemical thinning methods (C1: 1.2%; C2: 2.5%) (Fig. 5.4).

Improved fruit weight was achieved with all CLM treatments, which significantly increased fruit weight compared with that of the fruit from the unthinned control. Table 5.3 presents the effects of thinning treatments on fruit weight and yield per tree. All CLM treatments improved fruit weight by at least 25 g per fruit. The 75% flower cluster removal treatment (H3) led to the production of the heaviest fruit (293.6 g per fruit), whereas the unthinned control trees (U1) produced the lightest fruit (228.3 g per fruit).

Fruit yield was reduced with most CLM treatments in comparison with the yield of the unthinned control trees (U1). Specifically, reduced fruit yield occurred with flower cluster removal by hand and mechanical thinning. The removal of 50% of flower clusters (H2) significantly reduced fruit yield (18.2 kg per tree), similar to reductions due to both mechanical thinning methods (M1: 15.9 kg per tree; M2: 18.5 kg per tree). The removal of 75% of flower clusters (H3) provided the significant smallest fruit yield with 14.7 kg per tree. In contrast, the 25% flower removal (H1), chemical thinning using ATS + ethephon (C1) and chemical

thinning using ATS + ethephon and 6-benzyladenine (C2) did not reduce fruit yield (21.3, 22.9 and 22.3 kg per tree, respectively) relative to the yield from the unthinned control trees (U1: 21.1 kg/ tree).

Table 5.3: Effects of thinning treatments on fruit weight and yield per tree (cv. 'Roter Boskoop') in 2018.

| Treatment code | Type of CLM | Fruit weight (g per fruit) | Yield (kg per tree) |
|---|---|---|---|
| U1 | Unthinned control | 228.3[d] | 21.1[a] |
| | Thinning by hand | | |
| H1 | 25% flower cluster removal | 253.2[c] | 21.3[a] |
| H2 | 50% flower cluster removal | 259.6[bc] | 18.2[b] |
| H3 | 75% flower cluster removal | 293.6[a] | 14.7[c] |
| | Mechanical thinning | | |
| M1 | 320 rpm | 280.2[ab] | 15.9[bc] |
| M2 | 380 rpm | 256.9[bc] | 18.5[b] |
| | Chemical thinning | | |
| C1 | ATS + ethephon | 262.3[bc] | 22.9[a] |
| C2 | ATS + ethephon and 6-BA | 277[ab] | 22.3[a] |

[a, b] and [c]: Significant differences according to Dunnett T3 and LSD tests with $P < 0.05$.

### 5.1.4 Effects of CLM on return bloom

In 2018, apple trees benefited from CLM in terms of improved or similar return bloom and less alternate bearing in 2019.

Table 5.4 presents the effects of crop load management on return bloom in 2019. The highest return bloom (score 4) occuerred after 75% flower cluster removal (H3). Treatments H2 and H1, 50% and 25% flower cluster removal, scored only 3 and 2, respectively. Mechanical thinning at the lower rotor speed (M1) scored 3, whereas that at the higher rotor speed (M2) scored 2. The two chemical thinning treatments using ATS + ethephon with or without 6-benzyladenine at 10–12 mm fruit diameter (C1 and C2, respectively) each scored 2, which was the score of the unthinned control.

Table 5.4: Effects of thinning treatments on blossom intensity in 2019.

| Treatment code | Type of CLM | Blossom intensity (scales 1–9)* in 2019 |
|---|---|---|
| U1 | Unthinned control | 2[c] |
| | Thinning by hand | |
| H1 | 25% flower cluster removal | 2[c] |
| H2 | 50% flower cluster removal | 3[b] |
| H3 | 75% flower cluster removal | 4[a] |
| | Mechanical thinning | |
| M1 | 320 rpm | 3[b] |
| M2 | 380 rpm | 2[c] |
| | Chemical thinning | |
| C1 | ATS + ethephon | 2[c] |
| C2 | ATS + ethephon and 6-BA | 2[c] |

[a, b] and [c]: Significant differences according to LSD tests with $P < 0.05$.

* 1 = no flowers; 9 = white blossom.

## 5.2 Results of the experiment of applying laser radiation for flower removal

In this experiment, the use of lasers was evaluated as an alternative approach for selective flower removal. Directing lasers at flowers was conducted under laboratory conditions to evaluate the efficacy of the method for flower deterioration based on three different factors: the phenological growth stage of the apple flower, laser spot position and laser energy density. The results in this section are adapted from Netsawang et al. (2021a, 2021b) (see list of publications).

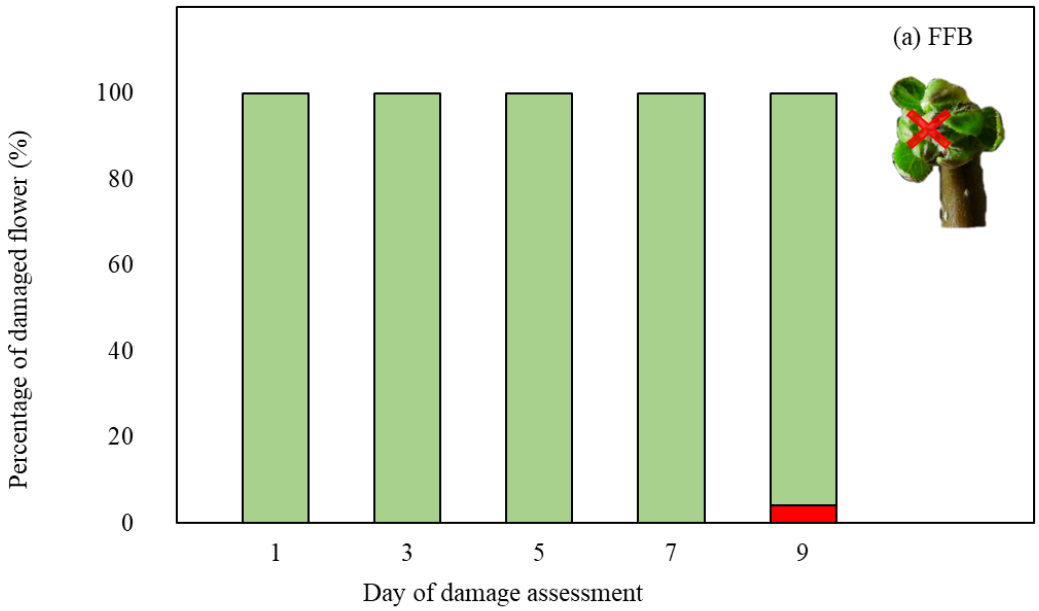
### 5.2.1 Effect of the flower's phenological growth stage on the efficacy of flower removal by laser radiation

In this experiment, a new method of flower removal by laser for blossom thinning was investigated at different flowering stages. Specifically, different phenological growth stages of apple flowers, namely, the mouse ear (BBCH 54), pink bud (BBCH 57), balloon (BBCH 59) and full bloom (BBCH 65) stages, were studied in relation to the effects of lasers on flower

removal. The efficacy of flower removal, defined as the percentage of damaged flowers and flower clusters, is presented in Fig. 5.5–Fig. 5.8.

After the application of laser radiation with an energy density of 1.02 J $mm^{-2}$, damaged flowers were visually evaluated and recorded every other day. Natural damage to the flower clusters in the untreated control appeared on different days after application (DAA) for each of the phenological growth stages. Therefore, to control for the effect of natural damage on the assessment of apple flowers, the damage assessment period differed according to the phenological growth stage as follows: 9 DAA for the mouse ear stage (Fig. 5.5), 7 DAA for the pink bud stage (Fig. 5.6) and 5 DAA for the balloon and full bloom stages (Fig. 5.7 and Fig. 5.8, respectively). These findings indicate that the phenological growth stage affects the damage resistance of flowers, which relates to the duration of assessment after thinning.

Two laser spot positions were tested at the mouse ear stage with the position from the front of flower bud (FFB) and from the side of flower cluster (FSC). Damage to flowers (4%) appeared 9 days after laser application in the FFB position (Fig. 5.5a), whereas flowers were not damaged by lasers applied in the FSC position (Fig. 5.5b).



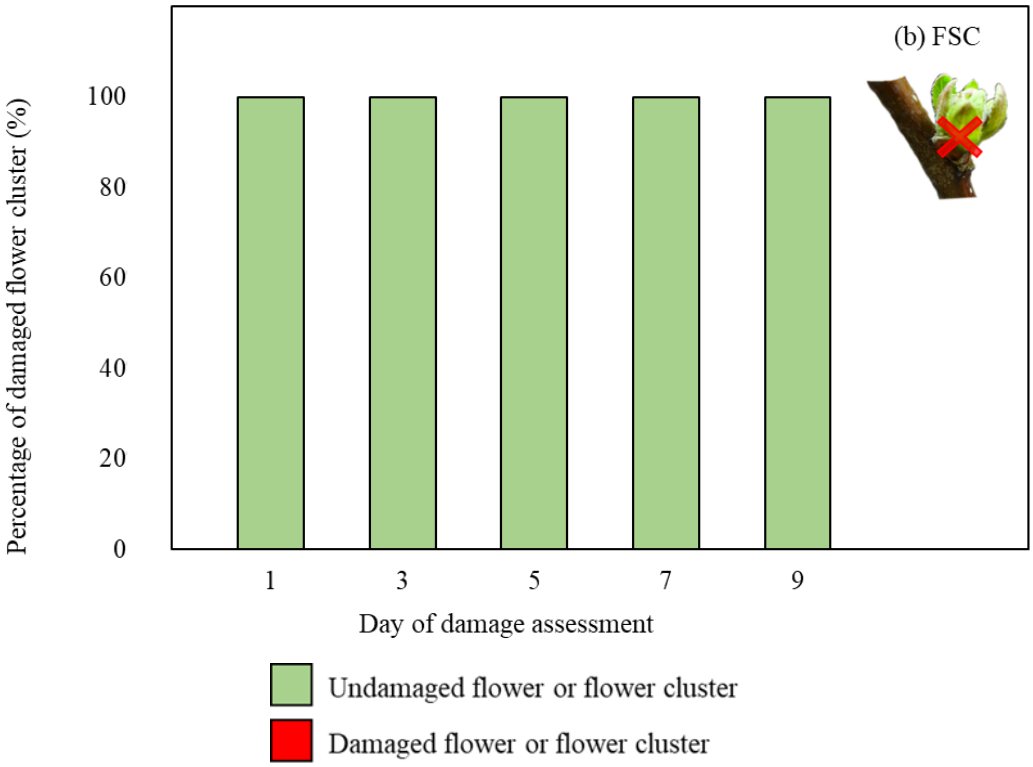



Fig. 5.5: Percentage of laser-damaged flower clusters and flowers at the **mouse ear** stage (BBCH 54). Laser spots were positioned at the laser spot position from the front of flower bud (FFB) (a) and from the side of flower cluster (FSC) (b).

Similar to the mouse ear stage (BBCH 54), two laser spot positions, namely, from the front of flower (FFF) and from the side of flower cluster (FSC) were used to evaluate the effects of laser at 1.02 J $mm^{-2}$ during the pink bud stage (BBCH 57). Damaged flowers appeared on 3 and 5 DAA in the FFF position (4%) and the damage increased to 12% at 7 DAA (Fig. 5.6a). In contrast, damage was not observed on flower clusters due to laser radiation applied in the FSC position (Fig. 5.6b).

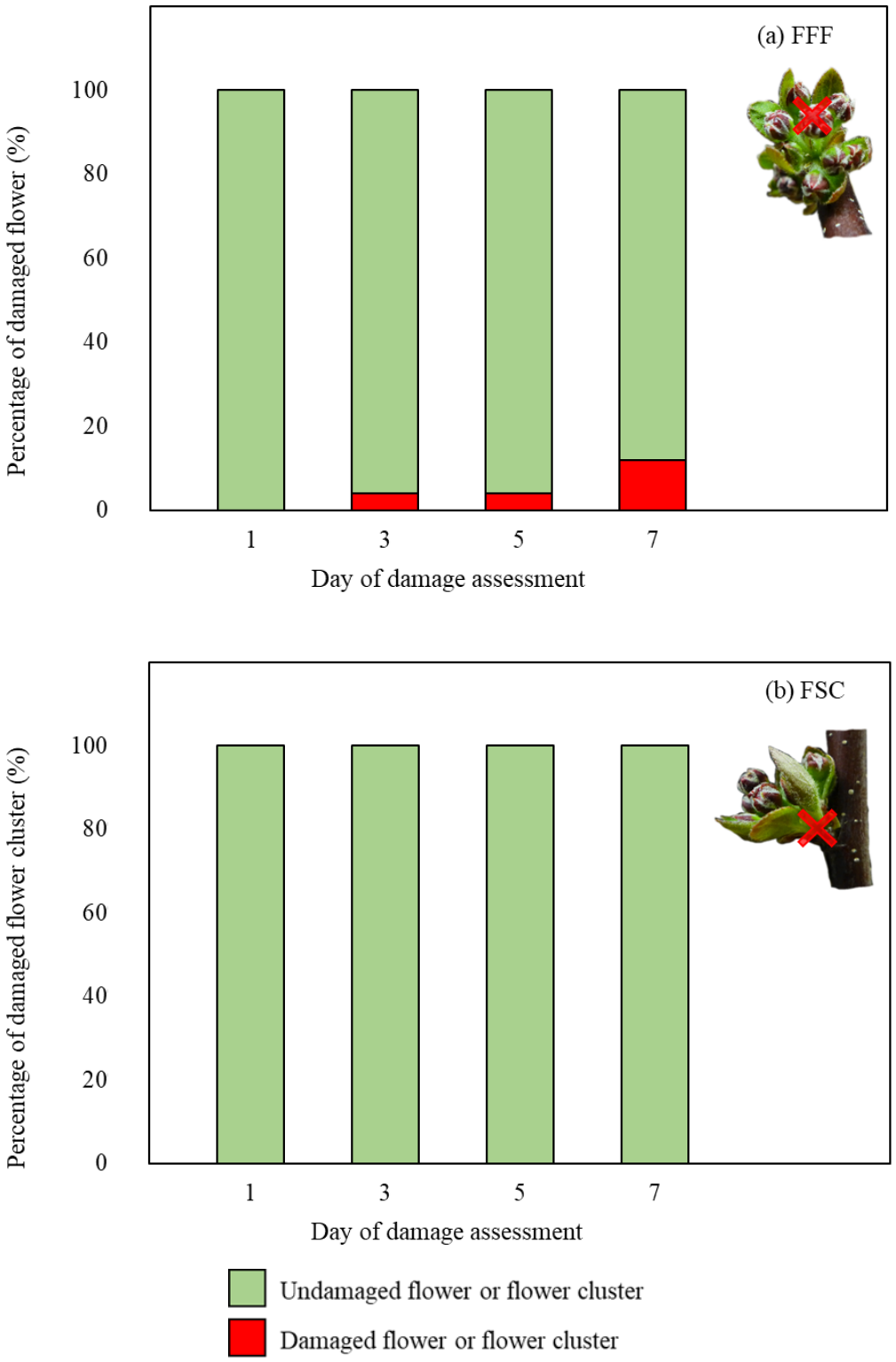
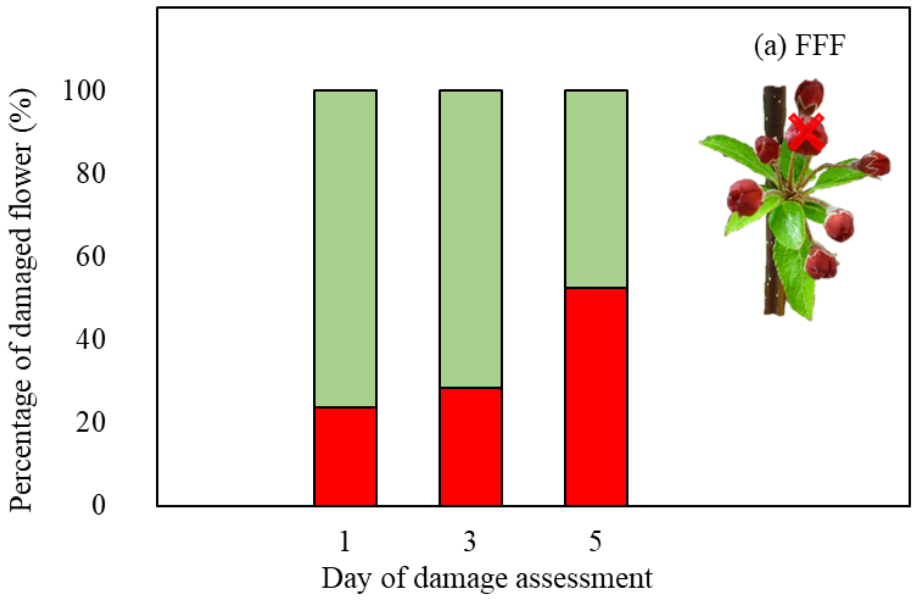
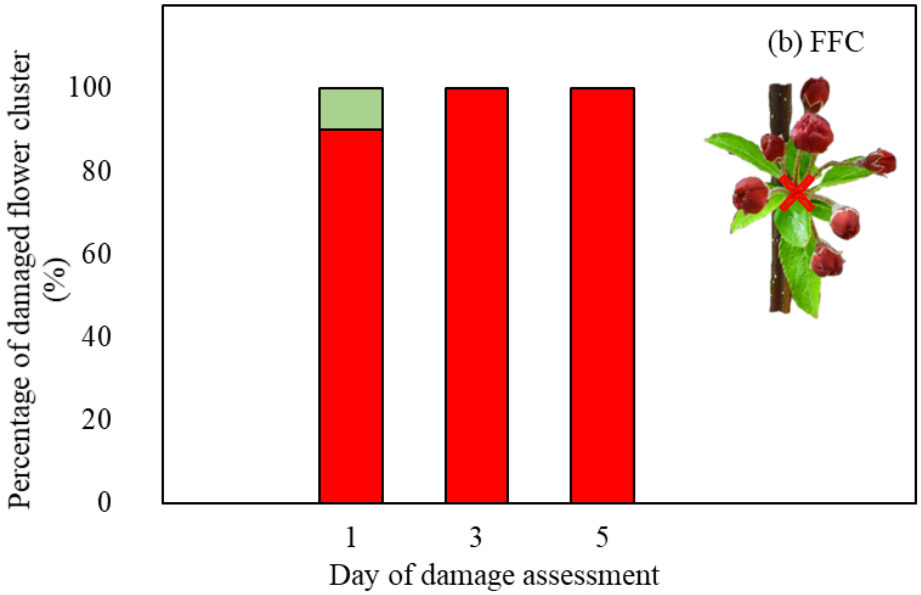


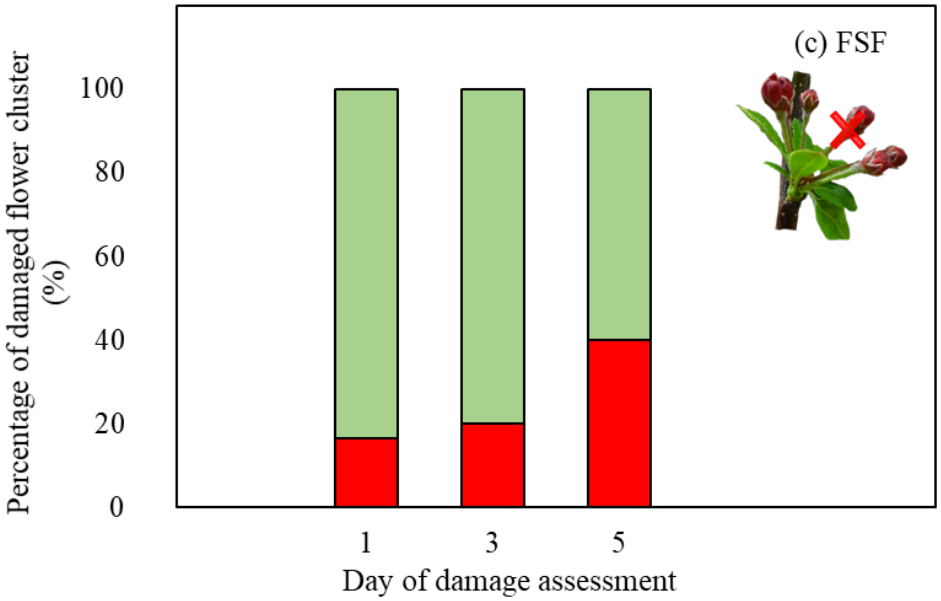

Fig. 5.6: Percentage of laser-damaged flower clusters and flowers at the **pink bud** stage (BBCH 57). Two laser spot positions were tested at the laser spot position from the front of the flower (FFF) (a) and from the side of the flower cluster (FSC) (b).

Four laser spot positions were tested during the balloon stage (BBCH 59) with the position from the front of flower (FFF), from the side of flower (FSF), from the front of flower cluster (FFC) and from the side of flower cluster (FSC). The results appeared that the application of laser radiation with a laser energy density of 1.02 J $mm^{-2}$ successfully reduced the number of flowers at the FFF, FSF and FFC laser spot positions. Fig. 5.7 presents the effect of laser radiation during the balloon stage on the percentage of damaged flowers and flower clusters.

In the FFF position, the application of laser radiation resulted in 23.8% and 28.6% damage to flowers at 1 and 3 DAA, respectively (Fig. 5.7a); at 5 DAA, the flower damage increased to 52.4%. In contrast, laser radiation applied in the FFC position caused 90% damage at 1 DAA (Fig. 5.7b). Strikingly, 100% of flower clusters were damaged at 3 and 5 DAA when lasers were applied in the FFC position. In the FSF position, laser application induced 15%, 20% and 40% damage to flowers at 1, 3 and 5 DAA, respectively (Fig. 5.7c). In contrast, no damage appeared on flower clusters due to lasers applied in the FSC position during the balloon stage (Fig. 5.7d).




(b) FFC
Percentage of damaged flower cluster (%)
100
80
60
40
20
0
1
3
5
Day of damage assessment


(c) FSF
Percentage of damaged flower cluster (%)
100
80
60
40
20
0
1
3
5
Day of damage assessment

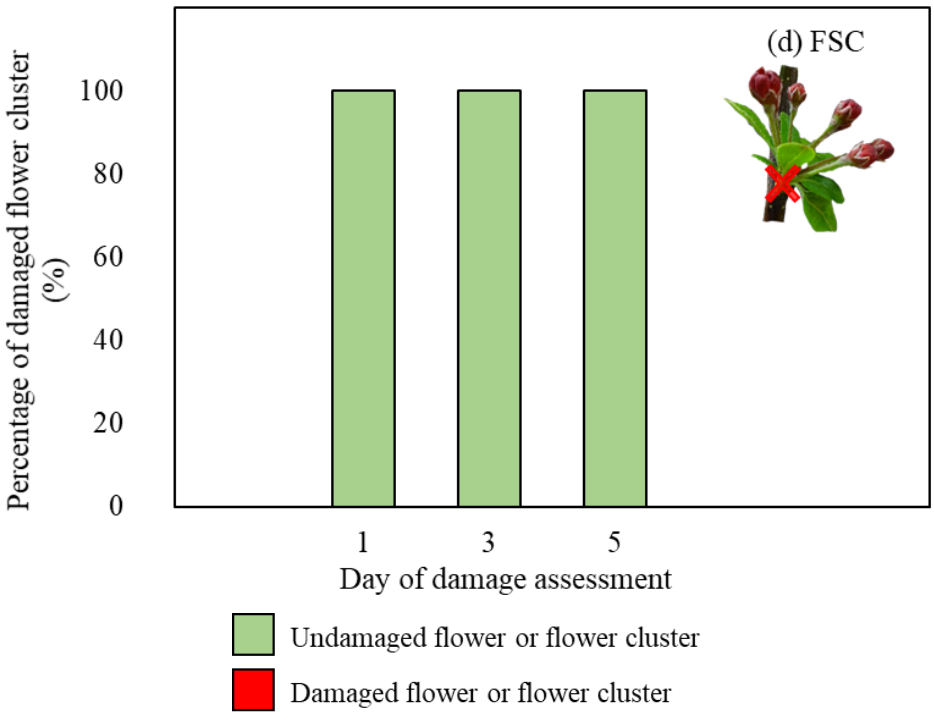
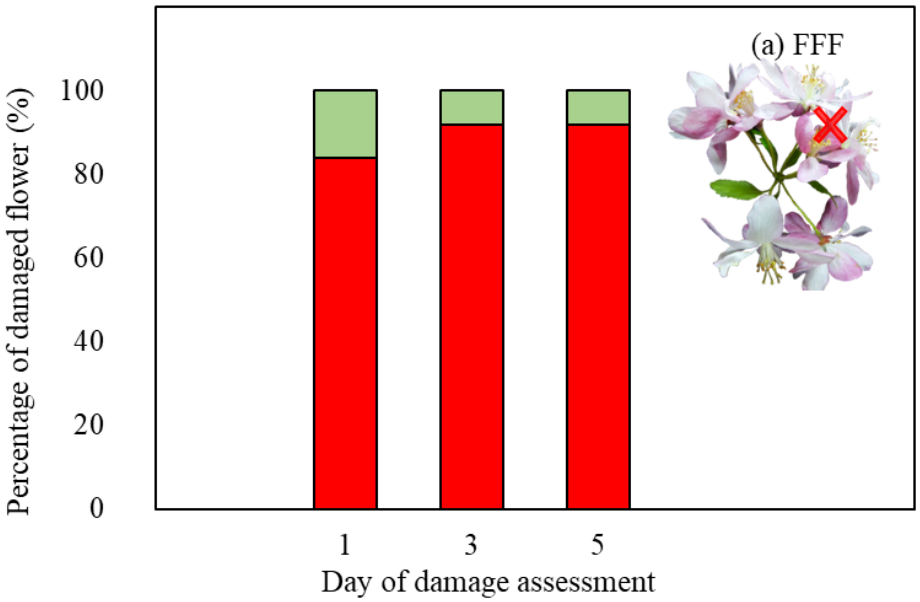


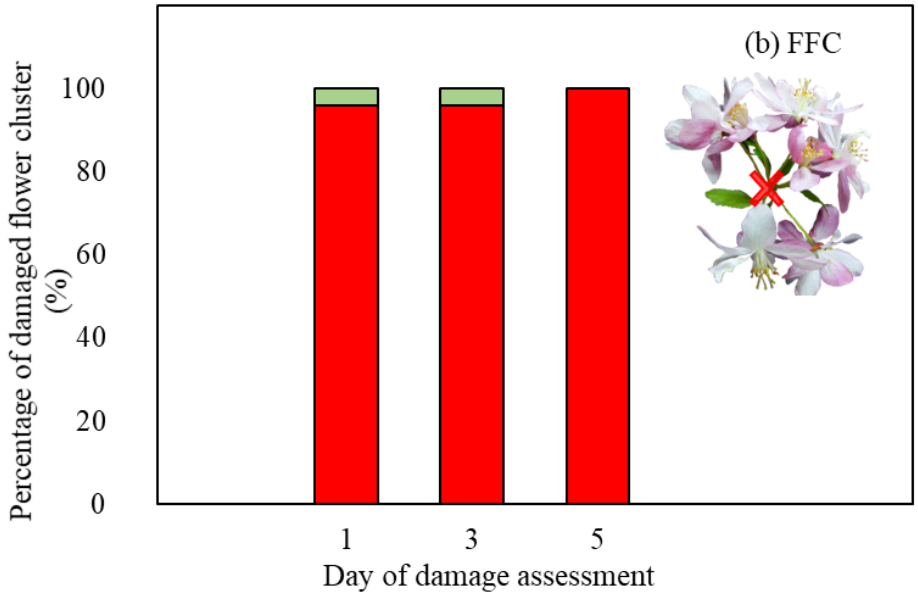

Fig. 5.7: Percentage of laser-damaged flower clusters and flowers at the **balloon** stage (BBCH 59). Four laser spot positions were used at the laser spot position from the front of the flower (FFF) (a), from the front of the flower cluster (FFC) (b), from the side of the flower (FSF) (c) and from the side of the flower cluster (FSC) (d).

Similar to the results for the balloon stage, the application of laser radiation at full bloom also led to positive effects on flower removal. Laser radiation applied at the laser spot position from the front of the flower (FFF), from the side of the flower (FSF) and from the front of the flower cluster (FFC) successfully removed flowers, as presented in Fig. 5.8a–c.

In the FFF position, 84% of flowers were laser-damaged on 1 DAA (Fig. 5.8a), which increased to 92% damage at 3 and 5 DAA. In the FFC position (Fig. 5.8b), 96% of flower clusters were damaged at 1 and 3 DAA and 100% of flower clusters were damaged at 5 DAA, similar to the effects of lasers at the balloon stage.

In contrast, the application of laser radiation in the FSF position resulted in only 4% and 8% of damaged flowers at 1 and 3 DAA, respectively (Fig. 5.8c); however, the damage increased to 24% at 5 DAA. Similar to the other stages of phenological growth, the application of lasers in the FSC position caused no damage to flower clusters at full bloom (Fig. 5.8d).


(a) FFF
Percentage of damaged flower (%)
100
80
60
40
20
0
1
3
5
Day of damage assessment


(b) FFC
Percentage of damaged flower cluster (%)
100
80
60
40
20
0
1
3
5
Day of damage assessment

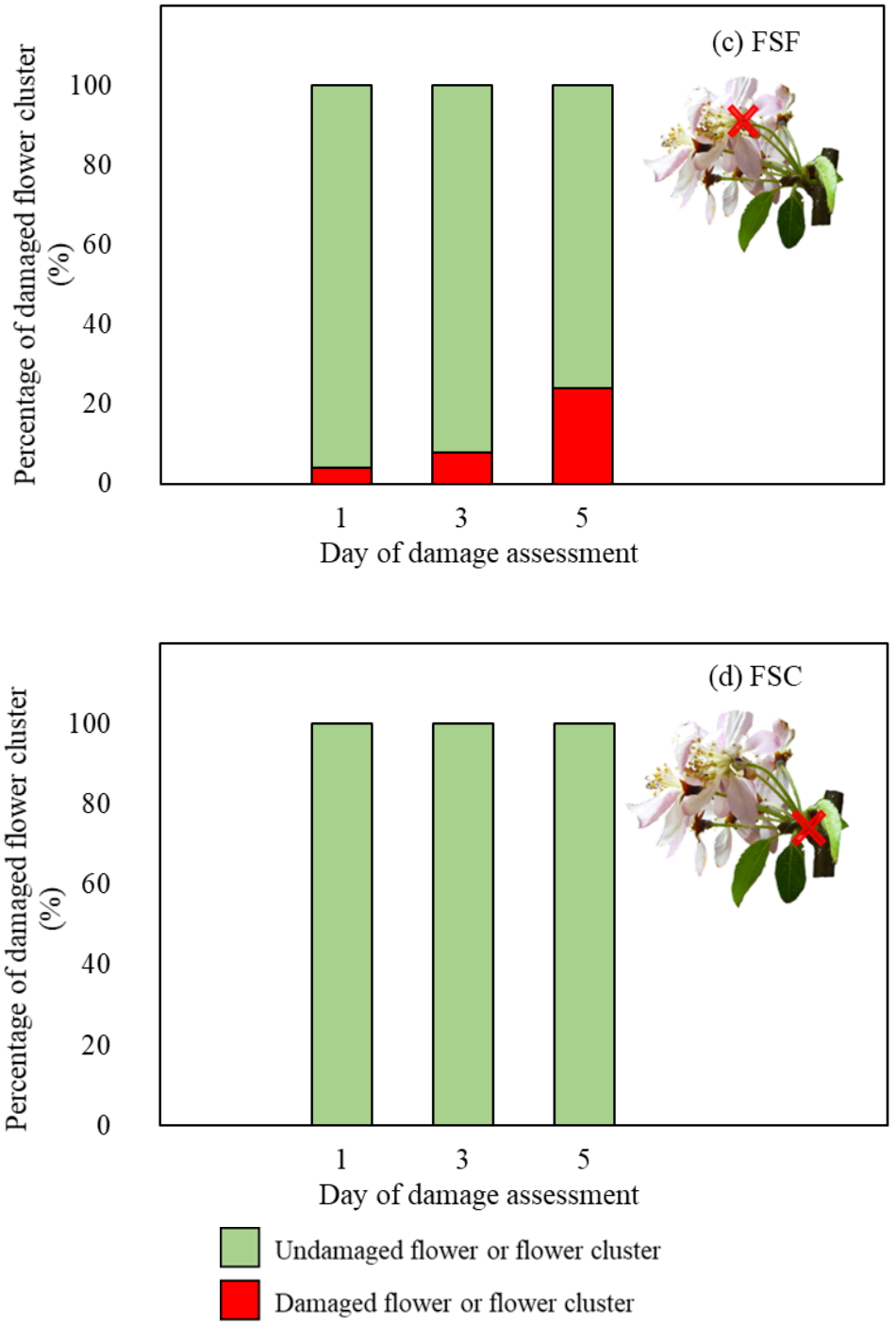



Fig. 5.8: Percentage of laser-damaged flower clusters and flowers at full bloom (BBCH 65). Four laser spot positions were used at the laser spot position from the front of the flower (FFF) (a), from the front of the flower cluster (FFC) (b), from the side of the flower (FSF) (c) and from the side of the flower cluster (FSC) (d).

In all phenological growth stages, the highest percentage of flower and flower cluster damage was observed on the last day of damage assessment. Therefore, the results of these days are summarized in Table 5.5 with indications of statistical differences.

As presented in this table, the efficacy of laser radiation for removing flowers or flower clusters at the balloon (BBCH 59) and full bloom (BBCH 65) stages was significantly increased relative to its efficacy at the mouse ear (BBCH 54) and pink bud (BBCH 57) stages. Indeed, no significant damage to flowers or flower clusters was detected at the mouse ear stage and only slight damage to flowers was observed at the pink bud stage.

Table 5.5: Efficacy of flower removal by laser radiation with a laser energy density of 1.02 J $mm^{-2}$ on the last day of damage assessment. Four different laser spot positions (see footnote) were tested at the mouse ear, pink bud, balloon and full bloom stages.

| **Position of laser spot** | **Percentage of damaged flower clusters and flowers** | | | |
|---|---|---|---|---|
| | **Mouse ear (BBCH 54)** | **Pink bud (BBCH 57)** | **Balloon stage (BBCH 59)** | **Full bloom (BBCH 65)** |
| FFB | $4^{a}$ | - | - | - |
| FFF | - | $12^{a}$ | $52.4^{b}$ | $92^{a}$ |
| FFC | - | - | $100^{a}$ | $100^{a}$ |
| FSF | - | - | $40^{b}$ | $24^{b}$ |
| FSC | $0^{a}$ | $0^{b}$ | $0^{c}$ | $0^{c}$ |

[a, b and c]: Significant differences according to the LSD tests with a 95% confidence level.

FFB: at the position from the front of the flower bud

FFF: at the position from the front of the flower

FFC: at the position from the front of the flower cluster

FSF: at the position from the side of the flower

FSC: at the position from the side of the flower cluster.

The application of laser radiation at 1.02 J $mm^{-2}$ in the FFC laser spot position, both at the balloon and full bloom stages, resulted in damage to all flower clusters; thus, these laser applications had the greatest flower removal efficacy (Table 5.5). In addition, the application of laser radiation in the FFF position at full bloom improved the efficiency of flower removal compared with that at the balloon stage (92% and 52.4%, respectively). In contrast, the

application of laser radiation in the FSF position during the balloon stage was more effective for flower removal than that applied during full bloom (40% and 24%, respectively).

In summary, these results indicate that flower removal by laser radiation is affected by the laser spot position and phenological growth stage of the flower. The balloon and full bloom stages were found to be suitable periods for flower removal. In particular, the application of laser radiation with an energy density of 1.02 J $mm^{-2}$ to remove flowers was successful during both stages when the laser spot was in the FFC, FFF and FSF positions.

### 5.2.2 Effect of laser spot position on the appearance of flower damage

The laser spot position is expected to play a significant role in the efficacy of flower removal and the damage to flower clusters and flowers. As mentioned in section 4.2.3, the five different positions of laser spot were studied in this experiment by the emitting of 4-W diode laser with 1,000 ms exposure time (1.02 J $mm^{-2}$ density of laser energy) on flowers and flower clusters. The two laser spot positions at the front and side of flower clusters, i.e. FFC and FSC, respectively, were hypothesized to reduce the number of flowers on the cluster or remove all flowers from the cluster, whereas the three laser spot positions directing lasers onto flowers from the front (FFF) and side (FSF) and to the front of flower bud (FFB) were predicted to damage individual flowers.

The application of lasers with an energy density of 1.02 J $mm^{-2}$ in the FFC position induced the highest percentage of damaged flower clusters at the balloon and full bloom stages (Table 5.5). Indeed, lethal damage was caused to the flowers, and the partial flower buds on inflorescences were successfully reduced (Fig. 5.9).


Fig. 5.9: Two damaged flowers on a cluster at full bloom following the application of lasers at the position from the front of the flower cluster (FFC) during the balloon stage.

In contrast, emitting laser radiation with the laser energy density of 1.02 J $mm^{-2}$ at the position from the side of flower clusters (FSC) had no effect on flower removal in all phenological growth stages of flower. It did, however, result in a burned spot on the bark under the flower cluster (Fig. 5.10 and Fig. 5.11).


Fig. 5.10: Burned spot on the bark under flower clusters at pink bud stage. This spot was the result of laser radiation applied in a position from the side of the flower clusters (FSC) during each stage, respectively.

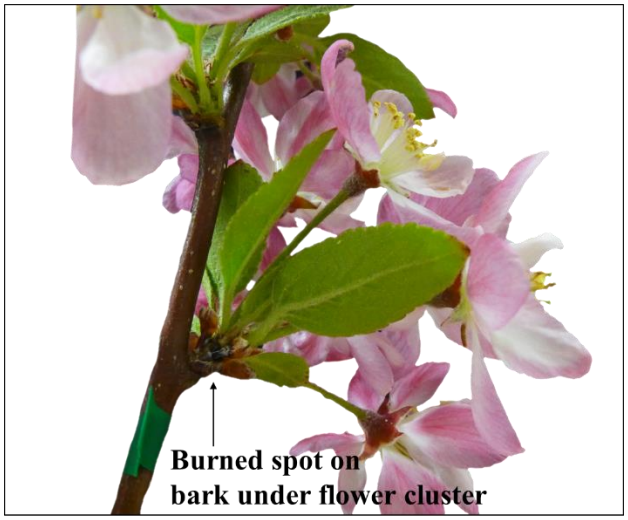



Fig. 5.11: Burned spot on the bark under flower clusters at pink bud (a) and full bloom (b) stages. This spot was the result of laser radiation applied in a position from the side of the flower clusters (FSC) during each stage, respectively.

In relation to laser application intended to remove single flowers, the application of a laser with an energy density of 1.02 J $mm^{-2}$ in the FFB position during the mouse ear stage and in the FFF position during the pink bud stage slightly damaged the bud scales and flower. Specifically, a burned spot appeared on the flower and at the distal part of the bud scales (Fig. 5.12). As presented in Fig. 5.5 and Fig. 5.6, 4% and 12% of the flower were damaged at the mouse ear and pink bud stages, respectively.

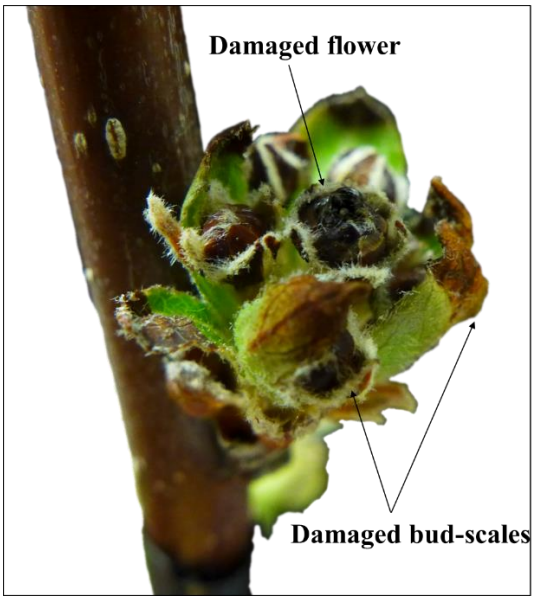



Fig. 5.12: Damage to the flower and bud scales caused by the application of laser radiation in a laser spot position at the front of the flower bud (FFB) during the mouse ear stage.

The efficacy of laser radiation on flower removal in the FFF position was significantly increased and accounted for 52.4% and 92.0% of damaged flowers at the balloon and full bloom stages, respectively (Table 5.5). Flower damage could clearly be distinguished at 5 DAA by burns on the stigma and style (Fig. 5.13). After laser application at the balloon stage, many flowers were considered undamaged because burned spots were found only on petals without damage to the stigma and style (Fig. 5.14).

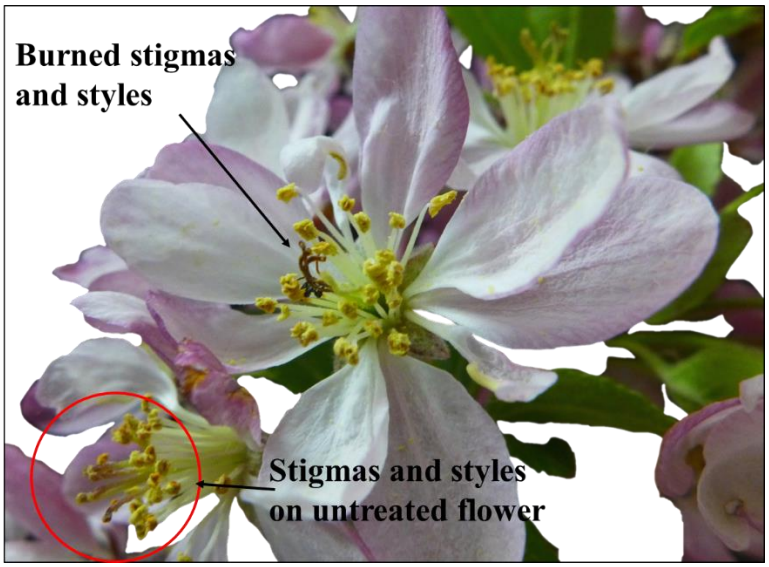



Fig. 5.13: Damage to the stigmas and styles caused by the application of laser radiation at a laser spot at the front of the flower (FFF) during the balloon and full bloom stages. For comparison, the stigmas and styles of an untreated flower are indicated in the red circle.

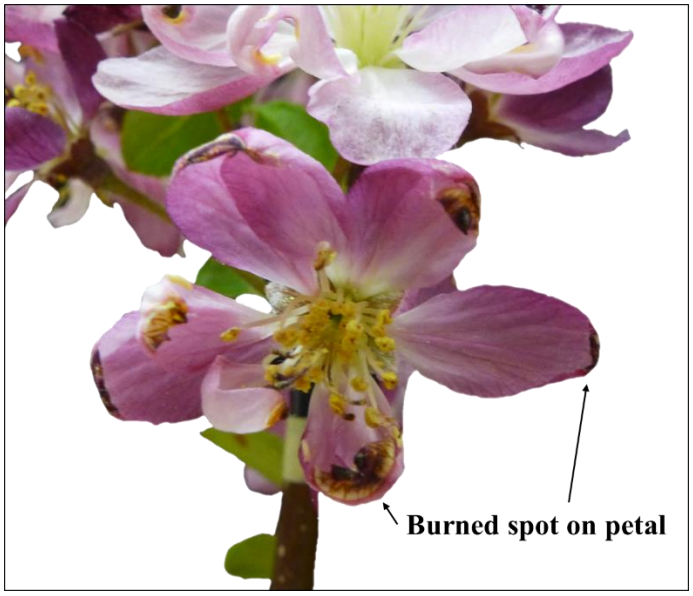



Fig. 5.14: Partial damage to the petals at full bloom caused by the application of laser radiation at a laser spot positioned at the front of the flower (FFF) during the balloon stage.

The application of laser radiation in the FSF position was intended to remove single flowers by damaging flower buds at the ovary. Laser application in this position is applicable during the balloon and full bloom stages because the flower buds are separated, which helps ease targeting; during these stages, 40% and 24% of flowers were damaged, respectively (Table 5.5). Lethal damage was caused by laser application from a position at the side of the flower bud (Fig. 5.15). There were burned spots on the bark under the sepals, which did not indicate damaged flowers but affected the growth of the petals located above the burned spot, which grew in an unusual manner (Fig. 5.16).

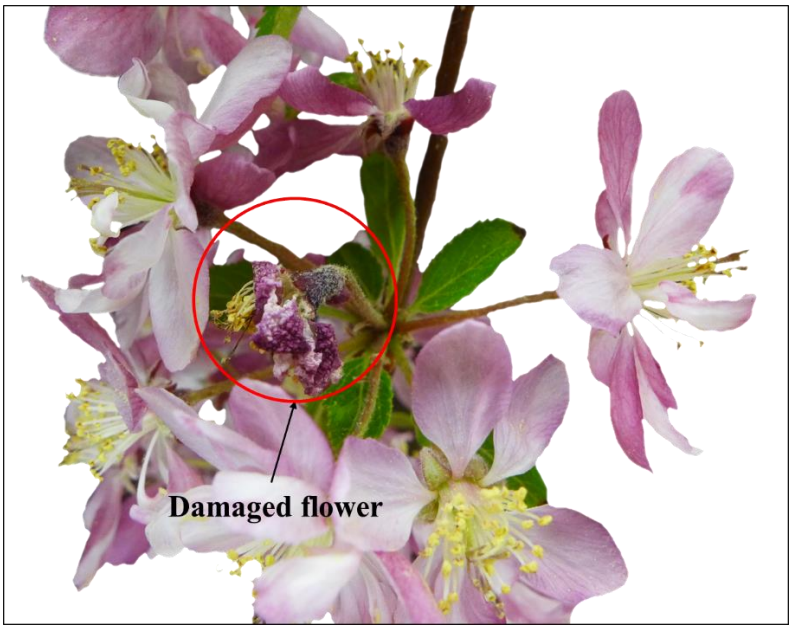



Fig. 5.15: Damaged flower bud at the full bloom stage caused by the application of laser radiation in a position at the side of the flower (FSF) during the balloon and full bloom stages.


Fig. 5.16: Burned spot on the bark under the sepal at full bloom due to the application of laser radiation in a position at the side of the flower (FSF) during the balloon stage.

According to these results, two conditions are recommended to achieve efficient results when using laser radiation for flower removal: positioning the laser spot at the front of the flower cluster and at the front of the flower (i.e. the FFC and FFF positions, respectively).

### 5.2.3 Effects of laser energy density on the efficacy of flower removal

The most successful laser treatment, i.e. applied at the laser spot position from front of flower cluster (FFC) during balloon and full bloom stages, was further investigated to evaluate the effects of laser energy density on the efficacy of flower removal. The average number of damaged flowers in this experiment is presented in Table 5.6.

The efficacy of flower removal was strongly related to the laser energy density. The number of damaged flowers increased with the increase in the density of laser energy. The lowest laser energy density of 1.02 J $mm^{-2}$ (4-W laser power with a 1,000-ms exposure time) efficiently removed around one or two flowers in a cluster at the balloon and full bloom stages, as indicated in Table 5.6. While the highest laser energy density of 3.06 J $mm^{-2}$ (4-W laser power with a 3,000-ms exposure time) removed three or four flowers on average, i.e. 50% of the flowers on the cluster. There was no significant difference in the number of damaged flowers between the balloon and full bloom stages.

Table 5.6: Effects of different laser energy densities on the number of damaged flowers in flower clusters when the laser spot was positioned at the front of the flower cluster (FFC) during the balloon and full bloom stages.

| **Energy density of laser (J mm$^{-2}$)** | **Number of damaged flowers in a cluster** | |
|---|---|---|
| | **Balloon stage (BBCH 59)** | **Full bloom (BBCH 65)** |
| 0.51 | 0.20$^{e}$ | 0.20$^{e}$ |
| 1.02 | 2.55$^{d}$ | 1.96$^{d}$ |
| 1.53 | 2.60$^{cd}$ | 2.60$^{bc}$ |
| 2.04 | 2.80$^{bc}$ | 2.60$^{bc}$ |
| 2.55 | 3.20$^{ab}$ | 3.10$^{ab}$ |
| 3.06 | 3.30$^{a}$ | 3.20$^{a}$ |

$^{a, b, c, d \text{ and } e}$: Significant differences according to the LSD tests with a 95% confidence level.

As the number of damaged flowers was increased by increasing the density of laser energy, it would be possible to remove all flowers in a cluster using a specific level of laser radiation. Fig. 5.17 presents the estimated number of damaged flowers caused by different laser energy densities during blossom thinning by laser radiation when the laser spot is positioned at the front of the flower cluster (FFC) during the balloon and full bloom stages.

Curve fitting by linear regression was used to develop a mathematical model describing the relationship between laser energy density (I) and the number of damaged flowers (N), as presented in Fig. 5.17. This model was based on the results of an experiment with at least 10 repetitions per each treatment. In addition, the results could be fitted by the linear regression with a log transformation, which provided two semi-log modals as follows: $N = 1.5961 \ln(I) + 1.7662$ with $R^2 = 0.8602$ (balloon stage) and $N = 1.623 \ln(I) + 1.5898$ with $R^2 = 0.9401$ (full bloom). Therefore, all flowers in a cluster (i.e. seven flowers) could be removed by applying laser radiation at the front of the flower cluster with a laser energy density of at least 21 J mm$^{-2}$ (4-W laser power with a 21,000 ms exposure time). In this experiment, the laser energy density was increased by extending the exposure time. The laser energy density could also be increased by increasing laser power, which would also increase

the accuracy of targeting but lower the applicability of laser application in orchards due to stricter user safety requirements.

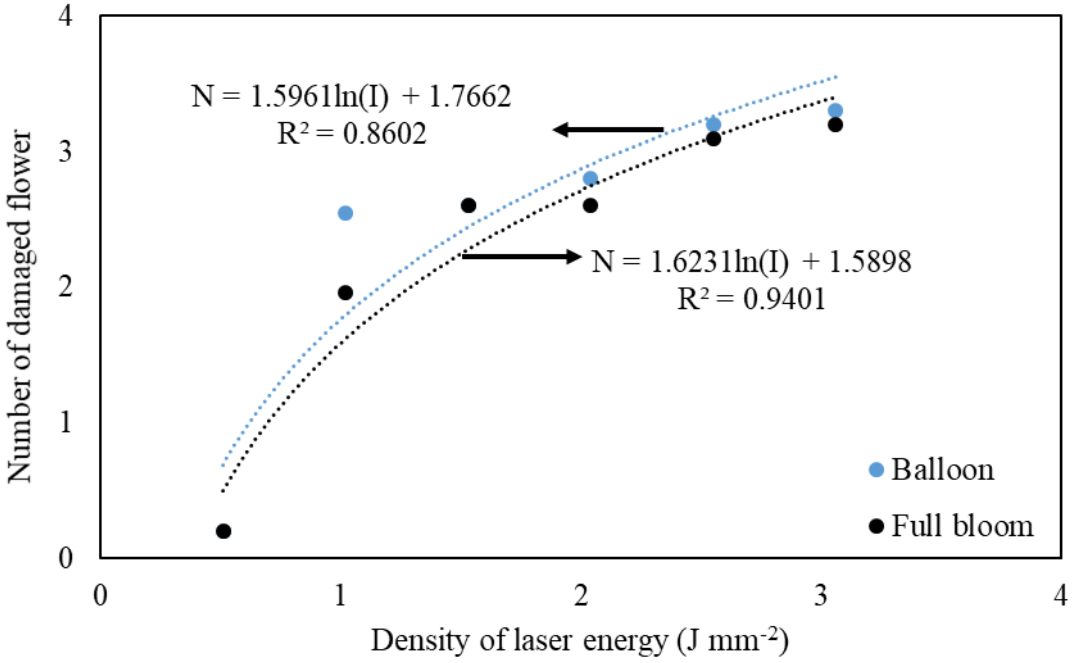



Fig. 5.17: Semi-log equations and regression curves based on the analysis of laser energy density and the number of damaged flowers in a cluster after the application of laser radiation at the front of the flower cluster (FFC) during the balloon and full bloom stages.

# 6. Discussions

## 6.1 Practical thinning experiment conducted in 2018

This research aimed to determine the effects of three state-of-the-art CLM methods on flower reduction. Specifically, hand, mechanical and chemical thinning techniques were employed and the fruit set, June drop, return bloom, fruit quality and yield were evaluated as well as the optimum source–sink relationship. The results reported here should aid the development of more precise and selective thinning methods. The experiment was conducted in 2018 following a frost in April 2017 across Europe, which caused an 80% loss of flowers and fruitlets. Consequently, apple trees showed strong flowering in April 2018. In addition, heavy June drop and weak fruit set resulted from the hot and dry spring and summer in 2018 throughout Europe.

### 6.1.1 Efficacy of mechanical thinning and ICT

In this study, a Bonner thinning device was used to remove flowers at 320 and 380 rpm with a tractor speed of 5 km $h^{-1}$. The increase in rotor speed was found to substantially improve the efficacy of mechanical thinning.

The improved flower removal effectiveness of mechanical thinning with a faster rotor speed (Table 5.1) is consistent with the findings of Kong et al. (2009) and Solomakhin and Blanke (2010). In their experiments, a rotor speed of 420 rpm removed excess apple flowers more effectively than a rotor speed of 300 rpm. These authors created the ICT score considering the impact of increasing rotor speed and the inverse relationship to tractor speed and fruit set. An optimum ICT of 10–40 was found for a tractor speed of 5 or 7.5 km $h^{-1}$, which resulted in a post-thinning fruit set of 50%–70% (Solomakhin & Blanke, 2010). In addition, Hehnen et al. (2012) reported a lower ICT value of 4–10 at a tractor speed of 2.5 km $h^{-1}$ in Washington State, USA, without considering the number of fruit removed per cluster, as presented in Equation (2).

In the present study, an ICT value of 6.2 with the higher rotor speed of 380 rpm during mechanical thinning was similar to that reported by Solomakhin and Blanke (2010) (ICT = 6.1) who tested rotor and tractor speeds of 420 rpm and 5 km $h^{-1}$, respectively. Kong et al. (2009) used the same machine at a 420-rpm rotor speed and 5-km $h^{-1}$ tractor speed and reported ICT values of 6.0 and 6.4. The lower rotor speed of 320 rpm used in the current study resulted in

an ICT value of 3.6, which is in ICT range (2.5–5.0) reported by Kong et al. (2009) when they used a rotor speed of 300–360 rpm. Although mechanical thinning is an effective thinning method, the control and adjustment of the settings is unsatisfactory and the effects on flowers are unselective.

### 6.1.2 Efficacy of chemical thinning

Chemical treatments including ATS and ethephon (Fig. 4.4a) at full bloom (BBCH 65) as well as 6-benzyladenine at a fruit size of 10–12 mm (BBCH 71) were applied after a strong spring frost in 2017. Consequently, a heavy bloom occurred in 2018. No significant difference was observed in the number of fruitlets per 100 flower clusters before (fruit set) and after June drop when chemical thinning was compared with the unthinned control (Table 5.1). The negligible effect of chemical thinning in the present study was likely caused by the unfavourable weather condition during and after the application of 6-benzyladenine and flower development, which caused unpredictable fruit set responses and poor fruit set reduction (Breen et al., 2016; Maas, 2007). During the 6-benzyladenine application, the temperature was 19°C and dropped to 12°C in the subsequent days, which is lower than the optimum temperature of 20°C–25°C.

ATS was applied for blossom thinning at full bloom (BBCH 65) at the optimum stage when most flowers had opened (Janoudi & Flore, 2005). As described in section 3.4.1, ATS mainly prevents pollination of the flower by burning out the stigma. However, in the current study, ATS only slightly reduced fruit set in comparison with that of the unthinned control. This result is consistent with the model of Maas (2016), in which ATS inhibits pollen tube growth and does not affect the already-pollinated flowers; thus, the efficacy of ATS is reduced by 50% when it is applied ~32 h after pollination.

Ethephon was applied in the present study to reduce excessive flowering in conjunction with ATS at the full bloom stage when the temperature was ~15°C. It is effective in thinning as it reduces excess flowers when applied at full bloom after most king flowers have opened. However, contrary to expectations, the application of ethephon in the current study had negligible thinning efficacy in relation to excess flower reduction and fruit set inhibition, likely because the ambient temperature on the day of application was below the optimum temperature. Ethephon requires an air temperature of 18°C–22°C at the flowering stage for an effective blossom thinning (Fischer et al., 2002). Moreover, it has no effect when applied at

temperatures <15°C (Stover & Greene, 2005). The current results confirm, therefore, chemical thinning is highly dependent on weather conditions. Thus, regardless of its environmental impact, chemical thinning using this method cannot be considered a precise method.

### 6.1.3 Efficacy of source–sink modification *via* flower cluster removal by hand

The source–sink relationship has a significant effect on fruit growth regulation. In this study, 25% flower cluster removal produced a leaf/fruit ratio of 17:1 and did not reduce the number of fruitlets before June drop compared with that in the unthinned control group (leaf/fruit ratio = 18:1 (Table 5.1). However, the fruit set before and after June drop was reduced by 50% and 75% flower cluster removal, which produced leaf/fruit ratios of 21:1 and 29:1, respectively. These ratios are close to the optimum source–sink relationship and the results are consistent with those of Blanke (2009) who reported that CLM and a lower fruit number reduce competition between sinks in terms of partitioning for photo-assimilates. In addition, the removal of 75% of flower clusters in the present study provided a source–sink relationship close to the optimal leaf/fruit ratio, which has been reported at between 20–30:1 and 40–50:1 (Friedrich & Fischer, 2000) or 25–30 apple leaves supporting a 160-g fruit with photo-assimilates (Hansen, 1969).

Breen et al. (2015) suggested that the final fruit number under frost-free weather conditions in the apple-growing region of New Zealand can be determined by artificial spur extinction (ASE) between dormancy and early bud break (BBCH 51–52) or flower cluster thinning at the pink bud stage (BBCH 57). Both methods improve fruit set, which is consistent with the manual removal of flower clusters (BBCH 59–61) in the present study (data not shown). In both cases, the removal and uniform spatial distribution of buds had a positive effect on the irradiance of fruiting spurs and increased the photosynthates available to developing fruit. As an early thinning method with a positive effect on fruit quality and alternate bearing (Tustin et al., 2012), ASE might not be appropriate in areas such as Canada and Bonn, where spring frost reduces the number of floral buds, flowers or fruitlets (Rodrigo, 2000; Vitasse & Rebetez, 2018). When selecting crop-load regulation strategies, the possibility of a spring frost should be considered to ensure consistent fruit yield.

### 6.1.4 Effects of CLM on June drop and return bloom

Apple trees are susceptible to fruit abscission, which can be controlled by CLM within three main periods (Luckwill, 1953): a) when unfertilised flowers are discarded by trees 1–4 weeks after full bloom; b) 5–6 weeks after full bloom with June drop of fruitlets with fewer developed seeds due to insufficient fertilisation and c) ~4 weeks before harvesting, known as the pre-harvest fruit drop. All three fruit falls have a negative effect because they decrease fruit yield, as described in section 2.1.4.

In the current research, the majority of CLM by blossom thinning, which reduced fruit set and altered the source–sink relationship, positively affected June drop in comparison with that of the unthinned control trees (Table 5.1). All CLM treatments except for manual thinning with 25% flower cluster removal reduced June drop. This is in accordance with the findings of Peifer et al. (2018) who reported that blossom thinning successfully reduced the intensity of natural June drop. In addition, no difference was observed between the two mechanical thinning techniques (lower and higher rotor speeds) used in this study in terms of their effect on June drop. These results contradict those of Seehuber et al. (2010) and Peifer et al. (2018), who applied Bonner thinning devices to remove flowers from pear and apple trees. They found that the intensity of natural June drop could be reduced by increasing the rotor speed.

The apple cv. ‘Roter Boskoop’, which was studied here, is susceptible to alternate bearing (Fischer et al., 2002; Winter et al., 2002). Consequently, in unthinned control trees, the flowering intensity in 2019 was low (Table 5.4; score value = 2) after the high flowering intensity in 2018 [score value = 8 (maximum)]. However, the effect of alternate bearing was partly mitigated by the CLM treatments and fewer blossom buds developed compared with those in normal years due to the hot summer and autumn in 2018. Manual removal of ≥50% of flower clusters improved the return bloom, reaching levels similar to those achieved using mechanical thinning with the lower rotor speed (Table 5.4). Embree et al. (2007) and Meland (2009) suggested that crop-load reduction enhances flower formation, whereas higher crop load results in lower return bloom.

### 6.1.5 Effects of CLM on fruit quality and fruit yield

In the current research, all CLM treatments led to the production of high-quality fruits in terms of its firmness, sugar level, starch breakdown and ripeness (Table 5.2). Moreover, all CLM treatments substantially enhanced fruit weight in comparison with that of the fruit produced by unthinned control trees (228 g per fruit) (Table 5.3).

Most CLM treatments improved fruit size relative to that from the unthinned control by increasing the percentage of large fruits (>90-mm diameter) and reducing the percentage of small fruits (<70-mm diameter) without overly compromising internal fruit quality (Fig. 5.4). This result is consistent with the findings of Hehnen et al. (2012), Henriod et al. (2011), Kong et al. (2009), Seehuber et al. (2014), and Solomakhin and Blanke (2010).

Severe thinning treatment by the manual removal of 75% of flower clusters produced a higher proportion of fruit that was larger than the optimum size (i.e. >90-mm diameter). This was likely due to the relatively hot and dry weather conditions in spring 2018, which resulted in a smaller fruit set after June drop. However, this would have been more balanced in normal years. By regulating flower intensity, CLM can improve fruit weight and size by reducing fruit set and improving the source–sink relationship (Seehuber et al., 2011).

In the current study, the yield progressively decreased when 50% or 75% flower cluster removal was applied. Fruit yields of 14–18 kg per tree are acceptable for 6-year-old apple trees at 50° N if the fruit size and quality are appropriate (Seehuber et al., 2014). Both the mechanical thinning techniques used here had a positive effect on the regulation of fruit yield. Therefore, ≥50% flower cluster removal and mechanical thinning as CLM techniques produced the optimum fruit yield and improved fruit quality in terms of fruit weight and size.

As already mentioned in the previous paragraph, it is maintained that the fruit quality, as well as the optimal fruit yield, can be attained by the effective thinning method. Besides, selective blossom thinning has an important role to improve the efficacy of thinning in comparison with other conventional thinning. Thus, developing a novel flower removal was necessary to produce a precise result of thinning. The possible method of flower removal for selective blossom thinning will be addressed in the subsequent section.

## 6.2 Applying laser radiation as a novel flower removal technique

In 2020, an experiment was conducted to investigate an alternative approach for selective flower removal, namely, the application of a laser beam to flowers under laboratory conditions. The efficacy of this method was evaluated in terms of flower deterioration according to three different factors: the phenological growth stage of the apple flower, position of the laser spot and density of laser energy.

### 6.2.1 Effects of phenological growth stage on the efficacy of laser-induced flower removal

Four different stages of phenological growth between inflorescence emergence and flowering were investigated. These included two pre-bloom stages, the mouse ear stage (BBCH 54; the first stage in which a difference emerges between floral and leaf buds) and the pink bud stage (BBCH 57; the stage in which the flower petals are elongating and sepals are slightly open) and two later stages, the balloon stage (BBCH 59; the last stage of pre-bloom in which most flowers with petals form as a hollow ball) and full bloom stage (BBCH 65; the stage in which at least 50% of flowers are open).

Applying lasers at the two early stages, the mouse ear and pink bud stages, was less effective in removing flowers than applying them at the later balloon and full bloom stages (see Section 5.2.1). In the early stages, laser radiation may not be effective as a thinning technique as the structure of apple flowers is characterised by overlapping layers of bark covering the internal reproductive organs. Flowers are damaged by lasers at the surface; thus, the reproductive organs are not affected by laser energy at these early stages. This finding is supported by the study conducted by Wöltjen et al. (2008a) in which a high absorption of diode laser energy led to almost complete absorption at the surface compared with a lack of absorption in deeper layers. Moreover, at the balloon and full bloom stages, targeting the laser spot at the reproductive organs of the flowers is easier (see Section 4.2.3).

As reported by Breen et al. (2015) and Tustin et al. (2012) in blossom thinning, the early stages of phenological growth led to constant fruit yield between seasons. However, this application may not be appropriate in apple-growing regions that experience frost conditions, e.g. those in the Northern hemisphere (see Section 6.1.3). Thus, laser radiation could be applied to blossom thinning as it results in successful flower removal starting from the balloon stage.

### 6.2.2 Effects of laser spot position on flower damage

The position of the laser spot should play a role in the efficacy of flower removal in terms of the effects on flower and flower cluster damage. In the present study, when the laser spot was positioned on flower clusters from the front (FFC) and side (FSC), the aim was to reduce the number of flowers in a cluster or remove all flowers from the cluster. When the laser spot was positioned on the flowers from the front (FFF) and side (FSF) or on the flower bud from the front (FFB), the aim was to remove single flowers (see Section 4.2.3). The laser spot positions tested in this study were all selected as possible target sites as no previous research existed on the application of laser radiation for flower removal.

As mentioned in section 5.2.2, the position of the laser spot significantly affected the appearance and lethality of damage caused by the laser to flowers. The application of lasers in the FFC position caused lethal damage to flowers and successfully removed single flowers on inflorescences as the laser energy was absorbed by the tissue at the base of the pedicel. In contrast, applying lasers in the FSC position had no effect on flower removal in all phenological growth stages; however, it did produce a burned spot on the bark under the flower cluster.

The removal of single flowers was achieved by directing laser radiation at positions FFF and FSF during the balloon and full bloom stages. However, a limitation may reduce the efficacy of flower removal in these cases. Applying laser radiation in positions at the front of flowers might be suitable only at full bloom when flowers have opened because the laser beam can directly affect the stigma and style. Furthermore, a highly precise system of targeting is required because the target size is very small.

Removal of single flowers was also achieved by applying laser radiation at the FSF position during the balloon and full bloom stages. However, an increase in laser energy is necessary to damage the deeper layer at the ovary.

According to these findings, applying laser radiation at the position of laser spot from front of flower cluster (FFC) during the balloon and full bloom stages is most effective in terms of flower removal as it provides the highest percentage of damaged flowers. Furthermore, the number of damaged flowers in the cluster may vary according to the density of laser energy

(Table 5.6). This result is important for selective blossom thinning which is the object of this study. The influence of laser energy density is discussed on the next section.

### 6.2.3 Effects of laser energy density on the efficacy of flower removal

The influence of laser energy density at the position from the front of the flower cluster (FFC) was investigated in terms of thinning efficacy when applied at the balloon and full bloom stages. No significant difference was observed in the results between the two stages of phenological growth; however, the density of laser energy affected the efficacy of thinning.

Flower removal was achieved only by applying a laser beam with an energy density of at least 1.02 J $mm^{-2}$ (4-W laser power with a 1,000 ms exposure time), which caused lethal damage one or two flowers in a cluster on average. Moreover, the number of flowers removed from a cluster increased as the density of the laser energy applied also increased (Table 5.6). Thus, the efficacy of flower removal could be increased by extending the laser exposure time, which increases the laser energy density. This finding is in line with the work of Marx et al. (2012).

To the best of our knowledge, the removal of flowers by irradiation with laser beams has not previously been reported in the literature. Some research exists, however, on the application of laser radiation for weed control and marking labels on fruit surfaces (Bauer et al., 2020; Gude, 2012; Marx et al., 2013; Sood et al., 2009; Wöltjen et al., 2008a). The current results are consistent with those of Mathiassen et al. (2006) who applied a diode laser for weed control. They found that the efficacy of laser weed control was related to wave length, exposure time, spot size and laser power. In addition, Wöltjen et al. (2008b) and Mathiassen et al. (2006) found that the density of laser energy in a range of 0.5–2.0 J $mm^{-2}$ was sufficient to slightly damage weed plants, which is of the same order of magnitude as the lowest density of laser energy (1.02 J $mm^{-2}$) found to have meaningful effects in the present study.

However, it must be noted that applying lasers for flower removal in apple farming is challenging due to technical problems, such as flower recognition and laser targeting, which have yet to be resolved. In addition, the adverse effects of laser radiation on fruit development and other nearby flowers may also arise as well as difficulties with the approval of laser technology use in the field, given the potentially harmful effects of lasers on humans and animals.

# 7. Summary and Conclusions

## 7.1 General conclusions

Crop-load regulation is necessary for apple production to improve the fruit quality and promote a constant fruit yield during the growing season. Blossom thinning is an efficient method to regulate the fruit yield by removing excessive flowers in apple orchards. Unwanted flowers are generally reduced by three conventional techniques. First, hand thinning provides a precise result of thinning, but requires extensive labour and is therefore expensive. Chemical thinning has been found to improve fruit quality, but its efficacy is unpredictable and dependent on weather conditions and cultivars. Third, mechanical thinning as the environmentally friendly method was developed to reduce labour and cost requirement. However, negative effects of mechanical blossom thinning have been reported that it causes tree diseases and requires subsequent chemical and/or hand thinning to be conducted at a later stage to fine-tune the fruit set. Therefore, the improvement of mechanised techniques for blossom thinning is essential to increase the thinning selectivity and to prevent unnecessary tree damage.

To achieve the aforementioned goals, three objectives were set up with two experiments. The first experiment was set out to determine the effects of three different practical thinning methods on fruit set regulation, June drop, return bloom, fruit quality, fruit yield and the source–sink relationship. The second experiment was undertaken to explore the effects and efficacy of selective flower removal by laser radiation.

## 7.2 Effect of blossom thinning on apple quality with practical methods

This experiment presents the effect of three different practical thinning methods on the regulation of fruit set, June drop, return bloom, fruit quality, fruit yield and the source–sink relationship. Three practical methods of thinning were studied in this work at the apple orchard of the Klein-Altendorf field laboratory of the University of Bonn, Germany. First, flower clusters were manually removed at the beginning of flowering with three different intensities of thinning, 25%, 50% or 75%. Second, mechanical thinning was applied at the balloon stage by the Bonner thinning device with two rotor speeds of 320 and 380 rpm under the tractor speed of 5 km $h^{-1}$. Third, chemical thinning consisted of two treatments. ATS was combined with ethephon in a spray volume of 1,000 L $ha^{-1}$ for the first chemical thinning to remove

blossoms at the full bloom stage. At the onset of fruitlet development, 6-benzyladenine (6-BA) was also applied for the second chemical thinning to remove the fruitlets.

All methods of crop-load regulation in this experiment provided the evidence of improvement in fruit quality in terms of fruit size and weight. This result clearly demonstrated that fruit production benefits from crop load management by blossom thinning. Moreover, it improved the return bloom on the sequent growing season.

The efficacy of 50% flower cluster removal on the reduction of fruit set resembled the mechanical thinning with lower rotor speed (320 rpm). Besides, there was no difference in the thinning efficacy between 75% flower cluster removal and mechanical thinning with the higher rotor speed (380 rpm). The fruit yield progressively decreased when ≥50% of flower cluster was removed with manual thinning and for both rotor speed for mechanical thinning. They provided a fruit yield of 14–18 kg per tree with acceptable fruit size and quality. Moreover, manual removal of ≥50% of flower clusters improved the return bloom, reaching levels similar to those achieved using mechanical thinning with the lower rotor speed.

The relevance of unpredictable results of chemical thinning is clearly supported by this study and weather conditions are a major cause of thinning ineffectiveness. Chemical thinning benefited the fruit size and weight, but it did not have a positive effect on the reduction of fruit yield and return bloom.

Summarising, the mechanical blossom thinning with rotor speed of 320 rpm was demonstrated to be the practical approach for the farmers. It would be the third-best CLM and comparable with the manual removal of 50% of flower clusters in this experiment. Moreover, this treatment successfully improved the fruit quality and return bloom.

It is demonstrated that the fruit quality, as well as the optimal fruit yield, can be attained by effective methods of crop-load regulation. Besides, selective blossom thinning is expected to improve the efficacy of the thinning in comparison with other practical thinning methods. Thus, further research is essential to determine the extent of the precise method of flower removal for selective blossom thinning.

### 7.3 Study on applying laser radiation for flower removal

This study was performed under laboratory conditions to assess the efficacy of flower removal by applying laser radiation based on three different factors: the phenological growth stage of the apple flower, laser spot position and laser energy density. One of the significant findings to emerge from this study is that the laser radiation can be used as an alternative technique for selective flower removal.

Starting with the balloon stage, a diode laser with 4 W and at least 1.02 J $mm^{-2}$ laser energy density successfully removed flowers on three different laser spot positions, a) from the front of the flower cluster (FFC), b) from the side of the flower (FSF) and c) from the front of the flower (FFF).

Applying laser radiation at the laser spot position from the front of the flower cluster (FFC) was the most effective in terms of flower removal as it provided the highest percentage of damaged flowers. There was no difference on the thinning efficacy between the balloon and full bloom stages. The lowest applicable laser energy density of 1.02 J $mm^{-2}$ reduced two flowers in a flower cluster on average. The enhancement of thinning efficacy was related to the density of laser energy. While the highest applicable laser energy density of 3.06 J $mm^{-2}$ removed three or four flowers on average, i.e. 50% of the flowers on the cluster.

To summarise, the application of laser radiation demonstrated that it can be considered as a feasible method for selective flower removal during the balloon and full bloom stages. The highest thinning efficacy is attained at the laser spot position from the front of the flower cluster (FFC), it may become a viable alternative method to achieve precise result of blossom thinning.

However, it must be stated that laser application for flower removal in apple farming is still challenging because of unsolved technical problems such as flower recognition and laser targeting. Consequences arise from potentially adverse effects of the laser radiation on fruit development and other nearby flowers as well as approval of the laser technology in the field with potentially harmful effects on animals and humans.

Further investigation and experimentation into the effect of laser radiation on the growth of apple trees are recommended due to the use of artificial apple flowers for samples in this

experiment. The effect of laser radiation on various cultivars of apple flowers is an important issue for future research as well. These expectations can be reached by studying apple flowers on potted trees before extending to the on-field experiment.

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## 9. List of publications

Netsawang, P., Damerow, L., Schulze Lammers, P. (2021a). "Use of laser radiaition as an alternative technique for selective blossom thinning in apple". In: *Proceedings of the 48th International Symposium Actual Tasks on Agricultural Engineering (ATAE)*. Zagreb, Croatia, pp. 141-149.

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