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Review

Managing Crop Load in European Pear (*Pyrus communis* L.)—A Review

Sally A. Bound

Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 98, Hobart, TAS 7001, Australia; sally.bound@utas.edu.au; Tel.: +61-3-6226-2958

Abstract: Reducing levels of fruit set is often desirable in many European pear (*Pyrus communis* L.) cultivars. With a negative linear relationship between crop load and fruit size, crop load management early in the season minimises wastage of tree carbohydrate resources and provides maximum benefits in terms of fruit size and quality. There are several tools available for managing crop load including hand thinning, chemical thinning, photosynthetic inhibition through shading or application of chemicals, mechanical thinning and pruning. While hand thinning is the most accurate method of reducing excessive crop loads, there are some major drawbacks. With awareness that the early thinning offered by chemical thinning provides distinct advantages with regard to fruit size and other quality parameters, chemical thinning is gaining increasing acceptance in pear production. Some chemicals are used worldwide for thinning, but there are differences between countries and growing regions on recommended application timing and concentrations. The risks involved in chemical thinning can be mitigated by use of a structured approach, using a sequential spray program with both bloom and post-bloom thinners. Knowledge of conditions that impact the carbon balance of the tree and the ability to make use of carbon-deficit conditions are likely to improve the predictability of chemical thinning. Mechanical thinning has potential as a thinning tool, with advantages over chemical thinning in that it is environmentally friendly, can be used in organic production and is not weather dependent. Although artificial bud extinction has not been trialled on pears to date, it has been shown to be economically viable in apple. As it is a precision crop load management method that minimises tree resource wastage, it should be given serious consideration. As growers require large annual yields of high-quality fruit, the aim of this review was to examine current and potential crop load management methods for European pear cultivars and provide a portfolio of available options that can be integrated into a systematic approach for managing crop load.

Keywords: annual crop; carbon balance; chemical thinning; fruit quality; hand thin; mechanical thinning; photosynthetic inhibition; spur extinction

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1. Introduction

Pears (*Pyrus* sp.) are grown in most temperate regions worldwide, with European pear (*Pyrus communis* L.) predominating in Africa, Australia, Europe and North and South America. Pears are grown on a range of rootstocks, with a trend towards more dwarfing rootstocks and denser plantings with training systems that allow for increased light efficiency [1]. In a recent review of *Pyrus*, *Cydonia* (quince) and *Amelanchier* rootstock selections, Einhorn [2] argues that rootstocks are "a critical factor affecting the precocity, efficiency and productivity of pear trees", and discusses their impact on yield efficiency and fruit size. With the move towards intensive production systems, desirable rootstocks are those that restrict tree vigour and are precocious and high yielding. Factors that reduce vigour, including rootstocks, lead to a change in partitioning of assimilates, nutrients and hormones between the various sinks within the scion tree and are likely to favour the production of floral primordia [3]; this often leads to increased fruit set and consequently imbalanced crop loads, especially when combined with productive cultivars such as

'Williams' and 'Conference' [4]. These orchards require good management to ensure good fruit size.

There is normally an inverse relationship between vegetative growth and flowering, and once young trees have filled their allocated space, it is important to maintain a balance between canopy volume and fruiting [2,5]. Once canopy fill is achieved, most European pear cultivars require some form of crop load management each year to ensure regular cropping and optimal fruit quality [6]. Some cultivars have low productivity and strategies need to be implemented to increase fruit set, but in many cultivars, crop load management is required to remove excess fruit that, if left on the tree, results in low-quality fruit and can push trees into a biennial bearing habit. This review will focus on crop load management for cultivars with excessive fruit set.

Crop load management is normally achieved through removal of excess or unwanted flowers and/or fruitlets from the tree (crop regulation or thinning), or by preventing flower initiation from occurring. There are several methods by which a reduction in flowers/fruitlets can be accomplished: (1) hand thinning; (2) application of plant bioregulators (PBRs) that either prevent fertilisation at flowering or result in abscission of flowers/fruitlets; (3) through shading (photosynthetic inhibition) of the tree; (4) physical removal by use of mechanical devices; or (5) through cultural practices such as pruning [6,7].

Considerable research has been undertaken on crop load management in apples worldwide, resulting in differing recommendations in each country/region [8]. However, there is limited information available for managing crop load in European pear cultivars, and even fewer studies focussing on the impact of crop load on pear fruit quality.

In an overview of factors influencing flowering and fruit set of European pears, Webster [3] indicated that reducing levels of fruit set is often desirable with pear cultivars. Similar to apples, the need for managing crop load in pears varies by region and cultivar. Sansavini et al. [9] indicated the need for increasing fruit retention in pear trees grown in European countries rather than reducing fruit number, while Williams and Edgerton [10] stated that in the USA, 'Bartlett' pear trees in Oregon and Washington require extensive thinning to attain acceptable market size, but in California they are seldom thinned. Schmidt et al. [11] noted that, although chemical thinning of pear was not common in the Pacific Northwest of the USA, there was increasing interest in the practice. Hand thinning of pear has become an important practice in Argentina due to the higher demand and better prices paid for larger fruit [12], while in Scandinavian countries, thinning of pears, either by hand or chemically is not a common practice [13–15]. A minority of Australian pear growers apply chemical thinners to manage crop load, but most pears are thinned by hand, which is a costly and time-consuming task [16].

Wertheim [16] suggests that flower thinning in pears has not become popular because fruit set in pear tends to be less reliable than in apple. It has been suggested that poor fruit set in pears can be the result of inadequate cross-pollination, too much tree vigour, infection by *Pseudomonas syringae* (pear blast), and in some cultivars a short effective pollination period [17]. As pears flower earlier than apples, they are also more at risk of spring frosts affecting fruit set [15], making growers cautious of thinning during the bloom period [3].

2. Advantages of Crop Load Management

A tendency towards biennial bearing is common in fruit trees. In many species, including pear, heavy crop loads prevent floral initiation—leading to no or poor return bloom the following year [6]. Once started, this alternate cropping (biennial bearing) cycle is usually self-perpetuating and is a major economic constraint for growers. Effective crop load management can eliminate biennial bearing, ensuring adequate return bloom each year with regular predictable yields. Fruit size and quality are also impacted by biennial bearing, with small, poorly coloured low-quality fruit in a heavy cropping ('on') year and large fruit that is susceptible to physiological disorders in a light ('off') year [18]. Hence, biennial bearing is undesirable and uneconomical.

The negative relationship between crop load and fruit size in apples is well known [6]. Studying unthinned 'Conference' pears, Maas et al. [19] demonstrated a clear negative linear relationship between crop load and fruit size; finding that for a crop load of 100 fruit per tree, average fruit weight was 200 g, and there was a 7 g reduction in fruit weight for every additional 10 fruits. This study demonstrates the importance of adequate thinning of high crop loads to obtain good fruit size. High crop loads can also have a negative effect on fruit firmness and sugar content [8]. In addition to increasing fruit size, appropriate management of crop load improves fruit colour and internal quality characteristics such as firmness (and thus post-harvest storage characteristics) and sugar content [6].

2.1. The Importance of Early Crop Load Management

An adequate supply of carbohydrates is required for developing fruit. The initial supply of carbohydrates in early spring is supplied from tree reserves and, once sufficient leaf area has developed, assimilates produced by spur and extension leaves are translocated to the developing fruitlets [3]. Growers need to manage competition for carbohydrates from competing sinks such as extension shoots and roots, while at the same ensuring that tree resources are directed into fruit that will remain on the tree through to harvest rather than into fruit that will be thinned later in the season. Jones et al. [20] strongly recommend that, to avoid wastage of carbohydrate resources and obtain maximum benefits in fruit size and quality, crop regulation practices should be performed early in the season before the completion of cell division; the longer the delay in removal of excess flowers/fruit the greater the potential loss in fruit size and firmness. These authors stress that crop load management early in the season minimises wastage of tree carbohydrate resources, providing maximum benefits in terms of fruit size and quality.

Another key reason for reducing crop load early in the season is to minimise biennial bearing in prone cultivars, as it results in a multitude of issues for the commercial grower, from fluctuations in orchard productivity, and hence profitability, through to potential tree damage and limb breakage as a result of excessive crop load.

In pears, there are three waves of natural fruit drop [21]. The first drop, usually going unnoticed, occurs soon after petal fall and is of non-fertilised flowers. The second drop is often the largest, particularly in trees with heavy crop loads, and occurs 6–8 weeks after bloom; this drop is known as the 'June' drop in the northern hemisphere, or 'December' drop in the southern hemisphere. The third drop occurs preharvest. In heavy bearing trees, the natural shedding that occurs in the first two drops is insufficient to achieve optimum crop loads, fruit size or quality, or to prevent biennial bearing [6]. Trees that are not carrying excessive crop loads tend to have either a very small or no second drop [6].

2.2. Economics of Crop Load Management

Optimum crop load for individual trees in terms of ensuring annual cropping varies with cultivar, but is related to tree size and structure. It is also affected by rootstock, geographic location, orchard aspect, soil type and climate. When considering crop loads in terms of yield per hectare (ha), high-density plantings should theoretically provide a greater yield per ha than low- or medium-density plantings simply on the basis of more trees. However, if low–medium-density trees are appropriately managed they can still achieve relatively high yields on a per hectare basis whilst retaining fruit quality.

The value of managing crop load is in attaining consistent production across the life of the orchard, protecting the tree from damage that may result from excessive crop load, and optimising fruit size and quality. However, in the majority of the research to date the economic consequences have received little attention, hence relatively little work has been performed to identify an optimal target for cropload following thinning or to compare distinct thinning treatments on an economic basis [22].

3. Techniques/Tools for Reducing Crop Load

As noted earlier, there are different techniques and tools available to orchardists to reduce crop load in heavy setting trees.

3.1. Hand Thinning

Hand thinning is the most accurate method of reducing excessive crop loads, and it is achieved by breaking off or cutting flowers/fruit with fingers, scissors or secateurs. Early hand thinning at blossom time is difficult to achieve accurately as it is not known which flowers will set fruit; retained flowers may not have been pollinated, resulting in later abscission [20]. In practice, hand thinning is normally commenced later in the season once growers can see what has set on the trees and the danger of spring frosts is over [7,20]. This timing makes fruitlet thinning by hand a low-risk strategy, particularly as it facilitates precision crop loading and can optimise fruit distribution on the tree [7].

There are, however, major drawbacks to relying solely on hand thinning for managing crop load. On a commercial scale, it is a high-cost strategy, being extremely time consuming and labour intensive [7,14,20]. Combined with the difficulty of completing hand thinning in a commercial orchard in a timely manner, this makes hand thinning impractical in countries where labour costs are high and/or there are shortages in labour supply. Additionally, to be fully effective, hand thinning is a skilled operation and not really suited to the itinerant labour force who normally undertake this task [20]. Hand thinning typically occurs later in the growing season, often after natural fruit drop when trees have already invested significant resources into fruitlets that will be discarded, resulting in considerable wastage of the tree's resources arising from the delay in achieving target fruit numbers. Apart from wastage of resources, not completing hand thinning before the end of the cell division period means that fruit size limits have already been set, as cell numbers within the fruit have been determined prior to hand thinning [3,20]. There can also be an adverse effect on return bloom for the following season—a heavy crop load during the period of flower initiation is likely to reduce the number of flowers initiated and/or result in weaker blossom as a result of competition for available resources [3,20].

Schmidt [23] recommends that growers of 'Bartlett' pear should adjust their crop load early in the season to avoid wasting of resources and to ultimately produce larger, better-quality fruit. This recommendation backs up earlier hand thinning studies on five pear cultivars in Norway by Meland [14], who found that hand thinning when the fruitlets were 10 mm in diameter proved most effective in optimising levels of fruit set while later thinning reduced fruit size and sugar content of all studied cultivars. Webster [7] also reported, albeit for 'Gala' apple, that hand thinning after petal fall but prior to 12 mm fruitlet diameter produced the highest yield in the desired larger size grades and later thinning was much less effective, with few fruits in the desired large size categories.

There is an established relationship between fruit size during the growing season and size at harvest [24]. According to Jones et al. [20], small fruit will never catch up in size to larger fruit and hence fruit size should be the basis for hand thinning. Bramardi et al. [12] suggested that, to improve hand thinning, it is necessary to know the fruit growth pattern for each cultivar, and provided seasonal growth charts for cultivars 'Bartlett' and 'Packham's Triumph' to enable prediction of fruit size distribution at harvest; these charts are used by Argentinian growers to aid selection of fruitlets for removal or retention at the time of hand thinning, in order to maximise the harvested yields of large-quality fruits.

3.2. Chemical Thinning

The standard industry practice for crop load management in many countries, predominantly for apples rather than pears, is based on chemical thinning, with PBRs applied during the bloom and/or post-bloom periods, followed up with hand thinning.

Chemical thinning uses caustic materials or synthetic hormonal growth regulators to reduce the number of flowers and/or fruit on the tree. Numerous factors can affect the degree of thinning and return bloom the following spring. These include species/cultivar, tree health, tree age, rootstock, vigour, blossom density, pollination, weather, chemicals used, and application method [13,20]. With many interacting factors influencing the thinning response of chemical thinning agents, responses to chemical thinning can be unpredictable, making optimal crop load management a difficult task. Under Australian conditions pears are more difficult to thin with chemicals than apples [25]. In particular, chemical thinning is very weather-dependent and there is considerable variation between cultivars in sensitivity to thinning chemicals [6,20,25]. Schmidt and Auvil [26] have also noted the sensitivity of some pear cultivars, such as D'Anjou, to chemical thinners; and Bonghi et al. [27] confirmed that pear cultivars differ in their sensitivity to chemicals.

Thinning chemicals can work in one of two ways:

- As *growth regulators* that mimic natural plant hormones, altering complex physiological processes in the tree, commonly through production of ethylene, or reducing the ability of fruitlets to compete for resources by stimulating abortion of seeds, inhibiting photosynthesis or through other poorly understood mechanisms [6,20]. Hormonal-type thinning agents can either be blossom or fruitlet (post-bloom) thinners.
- As *blossom desiccants*, also referred to as *blossom burners*. This group of chemicals acts by desiccating the style and stigma, thus preventing fertilisation. Desiccants do not thin pollinated blossom where fruit set has been achieved prior to spray application. Correct application timing of desiccants is critical as they need to be applied during blossom after sufficient flowers have set fruit [28]. As early opening flowers tend to produce the largest fruit, the aim is to allow these early flowers to pollinate and set fruit, then apply the desiccant to remove the later flowers—this usually means more than one application of the desiccant in cultivars or regions with an extended flowering period [8]. The mode of action of desiccants makes them less dependent on weather conditions for their effectiveness than hormonal-type blossom thinners. However, under conditions of high humidity or when rewetting occurs soon after application, they can be re-activated, in some cases causing severe burning, damaging buds, fruit and leaves [7].

Thinning chemicals vary in their optimal application time, some such as desiccants are only effective during the flowering period (blossom thinners) and others are more effective after petal fall (post-bloom thinners). Some chemicals are used worldwide, but there are differences between countries and growing regions on recommended application timing and concentrations. Some of these differences are due to fundamental differences in climate and culture in the various growing regions. Others, however, are the result of the differing degrees of uptake of new research and technology. High re-registration costs have also played a role in deregistration of some thinning chemicals in many countries, while others have been de-registered in several counties due to their negative effects on the environment [7]. Some chemicals, such as acetic acid, have shown good efficacy but have not been commercialised due to lack of proprietary exclusivity and cost of new chemical development [29].

The success of chemical thinning is dependent on the absorption of the thinning agent into the tree through the foliage, with less than half of the material applied to the leaves being absorbed [30]. To be absorbed into the plant, foliar applied chemicals must first penetrate the non-living cuticular membrane, then the cell wall and finally the plasmalemma [31]. Absorption is increased with higher temperatures during application [30,31] and humid conditions that increase drying time [30]. Absorption can also be increased by preconditioning the foliage with low light intensity and low temperature prior to application [30]. Other factors that can affect chemical absorption include spray formulation, addition of a wetting agent and hardness of the water [20,30] and pH of the spray solution [31].

The chemical thinning agents most commonly used for pome fruit are summarised in Table 1, but not all have been assessed for their efficacy in thinning European pears.

Table 1. Chemicals used worldwide for thinning of pome fruit (apple and pear).

Generic Name	Chemical Name	Trade Name	Type of Thinner	Crop
ABA	abscisic acid	Protone	Post-bloom	Apple, pear
ATS	ammonium thiosulphate	Thin-It, Culminate, Biothin	Blossom	Apple, pear
benzyladenine (BA)	N-(phenyl)-1H-purine 6-amine	MaxCel, Exilis, BAPSol, Abscission, Eurochem 6-BA	Post-bloom	Apple, pear
carbaryl	1-naphthyl (N)-methyl carbamate	Bugmaster [1], Carbaryl 500SC, Carbaryl 800 WP, Sevin [1,2], Thinsec [3]	Post-bloom	Apple
DNOC *	4,6-dinitro-ortho-cresol	Elgetol [2]	Blossom	Apple, pear
endothall	7, oxabicyclo (2,2,1) heptane—2-3 dicarboxylic acid	ThinRite [2]	Blossom	Apple
ethephon	2-chloroethyl phosphonic acid	Ethrel[1], Ethin, Promote	Blossom	Apple, pear
lime sulphur (LS)	polysulfide sulphur		Blossom	Apple, pear
metamitron	4-Amino-4,5-dihydro-3-methyl-6-phenyl-1,2,4-triazin-5-one	Brevis	Post-bloom	Apple
NAA	1-naphthalene acetic acid	NAA [1], NAA20, NAA Stop Drop [1] Rhodofix	Blossom	Apple, pear
NAD/NAAm	1-naphthalene acetamide	Amid-thin	Blossom, post-bloom	Apple, pear
pelargonic acid	nonanoic acid	Thinex [2]	Blossom	Apple
sulfcarbamide	1-aminomethanamide di-hydrogen tetraoxosulphate	Wilthin [2]	Blossom	Apple
Thiram	bis (dimethyl thio-carbomoyl) disulphide	TMTD	Post-bloom in conjunction with carbaryl	Apple

[1] Australia; [2] USA; [3] Europe, * not available since 1989.

3.2.1. Desiccants

As noted previously, desiccants act by burning or desiccating the style/stigma of the flower, inhibiting pollen tube growth and preventing fertilisation of the ovules, and the end result is abscission of the unfertilised flowers. However, for some desiccants, there may be additional modes of action. Discussing the use of scorching chemicals (desiccants) for increasing flower abscission, Wertheim [32] noted that extra ethylene may be formed by the injured flower parts, suggesting that this may contribute to abscission. McArtney [33] described research by Michael Schroder in Germany who showed that, in addition to the desiccating effect that prevented fertilisation, the blossom-thinning activity of ammonium thiosulphate (ATS) was also related to a transient reduction in leaf area (and therefore availability of carbohydrates) that indirectly caused drop of very young fruit and also a secondary thinning effect due to inhibition of auxin transport from young fruit that resulted in a slight increase in June drop (December drop in the southern hemisphere). Hence, in the case of ATS, it appears that there are three distinct mechanisms of action. Sulphur has been reported to reduce the rate of photosynthesis in apple—McArtney [33] reported that the effect of lime sulphur (LS) sprays on photosynthesis of spur leaves is additive, so photosynthetic rate may fall up to 50% and may remain suppressed for several weeks. So as well as preventing ovule fertilisation, the thinning activity of LS may also be related to a reduction in photosynthetic rate.

Discussing European studies examining a range of potential blossom thinners (ATS, urea, Armothin, pelargonic acid (Thinex), sulfcarbamide (Wilthin) and endothalic acid (Endothal)), Webster [7] reported that ATS proved to be the most reliable and least phytotoxic; however, he noted that flower thinning increased with increasing temperature at the time of spraying, but in humid slow drying conditions phytotoxicity to spur leaves increased. Schmidt and co-workers [11,26] also screened a range of potential bloom thinners for 'Bartlett' pears, including ATS, an organic magnesium/calcium brine (NC99), urea, LS, Crockers fish oil and combinations of horticultural oils with LS. Following several years of trials, they reported that while some products performed well in isolated cases, their effects were unreliable and they also concluded that ATS was more consistent in reducing fruit set than other products, and because of its consistency, relatively low cost and ease of handling, advised that it has now become the standard bloom thinning treatment in the course of their investigations.

Ammonium Thiosulphate

As discussed previously, both the concentration and time of application are important in ensuring the efficacy of ATS as a thinning agent. Examining rates of ATS from 0.5 to 2.0% on 'Packham's Triumph', Bound and Mitchell [34] reported that concentrations of 1.0 to 1.5% achieved sufficient damage to the reproductive organs to prevent fruit set without causing unacceptable phytotoxicity. A report on European studies comparing rates of 0.5% to 3.0%, also concluded that rates of 1.0–1.5% proved to be the most efficient [7]. In Scandinavian studies with the cultivar 'Clara Frijs', Bertelsen [15] reported that rates of 1–2% ATS reduced fruit set but resulted in pronounced unacceptable leaf damage. Despite the thinning effect in this study, Bertelsen [15] observed a lack of response in fruit size and concluded that this was likely a consequence of the severely damaged and dysfunctional spur leaves. In early studies of ATS on 'Elstar' apple in which rates of 2% showed a strong thinning effect but no increase in fruit size, Balkhoven-Baart and Wertheim [35] also concluded that the lack of response in fruit size was due to spur leaf damage. As noted above, several studies have reported good thinning results with ATS at rates of 1–1.5% without excessive phytotoxicity [7,28,34], so the severe phytotoxicity observed by Bertelsen [15] is likely due to a combination of the high humidity reported at application (85%) and the rewetting that occurred four hours after application.

In an Australian study examining time of application, 0.3% ATS reduced crop load in 'Winter Cole' pear when applied at 50% bloom and FB, but had no effect at 20% bloom, while rates of 1.5 and 4.0% thinned at all three application times [28], although there was a high degree of phytotoxicity following the 4% applications. This conflicts with the findings of Bound and Mitchell [34] who observed little thinning of 'Packham's Triumph' pear when ATS was applied at 80% bloom, irrespective of concentration, and recommended that to thin 'Packham's Triumph' effectively, ATS needs to be applied as early as the 20% bloom stage and follow up with a second application from 50% bloom is likely to enhance the thinning effect. This lack of effect with 80% bloom application is most likely due to a high fruit set already being achieved by this late stage of flowering. The work of Maas et al. [19] on 'Conference' pear in the Netherlands confirmed that two applications of ATS (1.2%) at 20% and 50% bloom was required to achieve a thinning effect. Bound [36] also concluded that two ATS applications were more effective than a single application.

Both concentration and time of application of desiccants such as ATS are critical in achieving a satisfactory level of thinning without causing excessive phytotoxicity [34]. Rewetting of leaves soon after ATS application can greatly increase leaf injury and thinning activity [33]. Webster [7] also noted that it is essential to adjust the spray concentration, volume and timing to suit the cultivar and the prevailing climatic conditions. Temperature at application can be important with many PGRs, and ATS has been noted to be effective at temperatures in the range 14–22 °C [15], a viable temperature range for changing spring conditions in most countries.

Desiccants can impact on fruit skin finish. An increase in fruit skin russet following application of ATS has been observed in cvs. 'Conference' [19] and 'Packham's Triumph' [36]. Chemically induced russet can be a serious problem, as russeted fruit is normally downgraded or discarded.

Other Desiccants

While a range of different caustic type chemicals have been screened for pome fruit thinning, very few have produced consistent results with minimal or no phytotoxicity [7,11,26]. Apart from ATS, the other potential desiccating chemical is LS, which is acceptable for use in organic production. Dussi et al. [37] reported that LS (10%) and sulphur (80%) applied at 80% full bloom had little effect on reducing fruit set of 'Williams' pears in Argentina and Oregon, USA. However, Garriz et al. [38] concluded that 7% LS applied at 30% bloom was an effective practice for thinning and enhancing fruit quality in 'Abbé Fetel' pears in Argentina, and Meland and Gjerde [13] reported that full bloom application of 5% LS will adequately thin cvs. 'Amanlis' and 'Moltke' in Norway.

3.2.2. Ethephon

Ethephon (2-chloroethyl phosphonic acid, sometimes abbreviated as CEPA) is successfully used in apples as a chemical thinner [20]. Ethephon thins over a long period, hence has been successfully applied as both a blossom and post-bloom thinning agent [32]. It acts by artificially raising ethylene levels, resulting in flower/fruitlet abscission.

Studies examining ethephon application to pear cultivars at both flowering and post-bloom have yielded variable results. In early work with ethephon on 'Williams Bon Chretien' pears, Selimi and Gibbs [39] reported 15% fruit removal with early sprays, but a week later the same application rate (300 mg/L) removed most of the fruit. Further work confirmed the thinning effect with rates of 300 mg/L but found that a lower rate of 150 mg/L had no thinning effect when applied later than 21 days after blossom [40]. McArtney and Wells [41] found that application of 400 mg/L ethephon at 15 days after full bloom (dAFB) resulted in a 51% increase in fruit set of 'Doyenne du Comice' pear, and a mild thinning effect was observed by Maas and van der Steeg [42] following application of 400 mg/L ethephon at 12–14 mm fruitlet diameter. Examining the effect of ethephon on 'Rosada' and 'Conference' pear in Italy, Bongi et al. [27] applied ethephon at 5 or 10 dAFB at the rate of 200–600 mg/L in the first year of study and 600–800 mg/L in the second year. They reported variability in the thinning effect and found that higher rates significantly reduced the unmarketable production without affecting the marketable yield or production of large fruits in 'Rosada', while in 'Conference' there was a negative effect on all cropping parameters, leading them to conclude that ethephon should be disregarded as a thinning agent for pear due to its negative effect on fruit growth and the huge variability of its thinning effect. In 'Winter Cole' pear, FB application of 100–400 mg/L ethephon has been shown to reduce crop load by more than half but later application at 11 dAFB was less effective [43]. Conversely, Bound [36] found that ethephon applied at FB had no thinning effect on 'Packham's Triumph' pear. Bound et al. [43] also reported that concentrations of 200–400 mg/L ethephon applied at 11 dAFB had an adverse effect on fruit growth of cv. 'Winter Cole'. Some of the variation in consistency of the results described above may be the result of a range of individual and interacting factors, including differences between cultivars in sensitivity to ethephon, application method and chemical coverage, tree vigour and blossom density, and preconditioning of leaves which is influenced by weather conditions before, during and immediately after application and can impact on the degree of absorption [13,20].

As ethephon is an effective thinner of apple at balloon blossom stage of flowering [20], it has been postulated that balloon blossom application of ethephon may be effective for thinning pears [43]. However, there are no reports of the effect of ethephon on pear cultivars at this early bloom stage.

3.2.3. NAA

Naphthalene acetic acid (NAA) is commonly used in apple along with its less potent form naphthalene acetamide (NAAm/NAD). According to Bound [8], while NAA can thin effectively between FB and 21 dAFB, the earlier it is applied, the better the response in fruit size. Australian recommendations for use of NAA in apples is as a blossom spray, preferably at FB but no later than 7 dAFB, as application later than 7 dAFB has been associated with pygmy fruit production [20]. However, in many countries NAA and NAAm are used as post-bloom thinners, being applied at petal fall or later [16,44]. Application of NAA causes a temporary check in tree growth and, according to Webster [7], fruit sizes at harvest are often less than anticipated. Studies with both NAA and NAAm in pear have produced variable results.

In the Australian state of Tasmania, NAA was recommended to thin European pears as late as 1980 [45]. However, the normal production at that time was of small fruit with much thinning performed by hand, and this is no longer economic. Menzies [25] reported that early attempts to thin pears with NAA in other regions of Australia were not successful. In studies on 'Williams' pear in Argentina, Dussi et al. [37] found that NAA applied at 20 mg/L at the 5 mm fruitlet diameter stage was ineffective as a thinner, and Vilardell et al. [46] reported that NAA applied at rates of 10 to 20 mg/L at 8–10 mm fruitlet diameter had no significant thinning effect on 'Conference' pears over three years of trials in Spain. In Slovenia, Hudina and Stampar [47] also observed a lack of thinning effect with NAA at rates ranging from 6 to 20 mg/L over three years of trials on 'Conference' pear; although there was no reduction in crop load, these authors observed an increase in fruit firmness in two out of the three years of the study. Application of 45 mg/L NAA at petal fall to cv 'Clara Frijs' had no thinning effect in Danish trials, but average fruit size and the amount of fruit larger than 65 mm were increased [15]. However, in a follow-up trial, there was no effect on fruit set or size with either full bloom or petal fall applications. The author suggested that the lack of effect was likely due to cool weather during the flowering period, suggesting that even a doubling of the standard concentration of 22.5 mg/L is not sufficient to compensate for adverse weather conditions.

In an Italian study, Bonghi et al. [27] found that NAA was totally ineffective on cv. 'Rosada' over two years of trials at rates of 5–40 mg/L applied at 5 or 10 dAFB, while on cv. 'Conference' at low concentration (5 mg/L) it acted as a setting agent in a low cropping year, and in the second year higher concentrations reduced the total and marketable yield. In a factorial study of rate of NAA (10, 15 or 20 mg/L) and time of application (10, 18 or 26 days after petal fall) on cvs. 'Winter Nelis' and 'Bartlett' in three Chilean orchards, Reginato and Gonzalez [48] found crop load was dependent on both rate and timing, but there was a difference in response between the two cultivars, with NAA tending to increase crop load in 'Bartlett' with later application times, but in 'Winter Nelis' all treatment combinations resulted in fruit thinning.

In Norway, successful thinning of four pear cultivars with petal fall applications of NAA was reported by Meland and Gjerde [13]; but they found differences in thinning effect with rate of NAA between the cultivars studied and recommended application rates of 10 mg/L for cv. 'Amanlis', 20 mg/L for 'Keiserinne' and 'Moltke' and 20–30 mg/L for 'Clara Frijs'. In Ontario, Canada, Cline et al. [49] reported thinning effects with 10 and 20 mg/L NAA applied at the 10 mm fruitlet stage in several trials on 'Bosc' and 'Cold Snap™' over three years, although they did find variation in the thinning response between the years and cultivars studied. Gonkeiwicz et al. [50] also observed a 33% reduction in crop load of 'Conference' pear with 20 mg/L NAA applied at the 12 mm fruitlet stage.

There are few reports of the efficacy of NAD as a pear thinner. Bonghi et al. [27] reported that NAD had a thinning effect at rates of 15 mg/L, particularly at 10 dAFB; the authors concluded that NAD may be a suitable chemical for regulating crop load and increasing fruit size on 'Conference' and 'Rosada' pear. In Poland, Gonkeiwicz et al. [50] found a 30% reduction in fruit set of 'Conference' pear following application of 80 mg/L NAAm A applied at 12 mm fruitlet diameter.

3.2.4. Carbaryl

The carbamate insecticide carbaryl (1-naphthyl (N)-methyl carbamate) is an effective fruitlet thinner on many apple cultivars but appears to work poorly or not at all on pears [7,25]. As well as being ineffective as a thinner in pears, carbaryl is a persistent pesticide that has been found in groundwater [28] and is toxic to bees and mammals [51]. As it has been withdrawn from use in many European countries [7], it is no longer a suitable chemical for further study.

3.2.5. 6-Benzyladenine

The synthetic cytokinin 6-benzyladenine (BA) [N-(phenylmethyl)-1H-purine-6-amine] is an effective post-bloom thinner for apples [52,53]. Application of BA to 'Winter Cole' pear after ethephon has shown some promise (Bound, unpublished data). In a factorial study of concentration of BA (50, 75, 100, 125, 150, 175 or 200 mg/L) and application timing (8, 11, 14, 17, 20, 23 or 26 dAFB) on 'Packham's Triumph' in two different climatic regions of Australia, Bound and Mitchell [54] found that concentrations of 100 to 150 mg/L BA were the most effective at application timings from 11 to 26 dAFB—all BA treatments were applied after ethephon at FB. Maas and van der Steeg [42] also reported that thinning of 'Conference' pear was achieved by application of 150 mg/L BA at 8–10 mm fruitlet diameter, and Dussi et al. [37] reported different levels of thinning according to rate and application time of BA on 'Williams' pear in Argentina, recommending doses equal to or higher than 150 mg/L. Further work by Dussi and Sugar [55] in both Argentina and USA confirmed the effectiveness of BA application rates of 100 and 125 mg/L on cv. 'Williams' in reducing crop load and increasing the yield per hectare of large fruit. Trials undertaken by Curetti et al. [56] on 'Williams' pear in Argentina confirmed that at 10–12 mm fruit size application rates of 50 mg/L BA were ineffective, 100 mg/L reduced fruit set by 10–20%, and 150 and 200 mg/L were most effective with a 20–40% reduction in crop load. Studies in South Africa applying BA to 'Early Bon Chrétien' at 8–12 mm fruit size also found a rate of 150 mg/L to be the most effective [57], and greater thinning was reported with 150 mg/L BA applied at 10–12 mm fruit size compared with a lower rate of 100 mg/L in Portuguese studies on cv. 'Rocha' [58]. While results varied between the three years of their study, Mauricio et al. [58] observed a 55% increase in the percentage of large fruit (>60 mm) and an 84% reduction in small fruit compared with hand-thinned trees in a heavy cropping year following application of 150 mg/L BA.

A Scandinavian study on cv. 'Clara Frijs' reported that application of 50 and 100 mg/L BA at 12 mm fruitlet size reduced crop load, increased average fruit size and increased return bloom compared with the untreated control [15]. Fruit size distribution was shifted in this study by both dose rates, but the effect was greater at the higher application rate of 100 mg/L with more fruit in the larger size categories and reduced numbers in the small size categories. Cline et al. [49] reported that in Ontario Canada, 150 mg/L BA at the 10 mm fruitlet stage was more consistent as a thinner of cvs. 'Bosc' and 'Cold Snap^{TM}' than 100 mg/L, but as crop load was not heavy, crop value was reduced compared with untreated trees due to a reduction in yield.

Time of application influences the efficacy of BA as a thinning agent. Studies on 'Williams' pear in Argentina examining timing of application of 150 mg/L BA from petal fall (PF) to 28 days after petal fall (dAPF) found significant fruit thinning between 4 and 16 dAPF when fruit diameters were between 9 and 19 mm [59]. These authors also reported that the largest commercial size was obtained following treatment at 12 dAFB, and in trials in Oregon, USA, where BA was applied at a lower rate of 125 mg/L, fruit size was increased between 10 and 15 dAPF when fruitlets were between 10 and 12 mm in diameter although there was no significant thinning [59]. These timing results are reasonably consistent with the timing window reported by Bound and Mitchell [54] for cv. 'Packham's Triumph'. However, Bound [36] reported an extended window of application for BA on 'Packham's Triumph' from 10 to 40 dAFB, with a greater thinning effect as applications moved further away from FB.

There is reasonable consistency between studies to confirm a rate of 150 mg/L as the most effective application rate for BA, but there are some discrepancies as to the timing window for application, and this is confused further by the different ways that application timing has been reported, from dAFB, dAPF to fruitlet size. Fruit growth rates will vary depending on both cultivar and climatic conditions, so this may partially explain these discrepancies. However, as with most other chemicals, there is likely to be a difference in sensitivity to BA, and thus thinning response, between cultivars. This difference in sensitivity was demonstrated clearly by Stern and Flaishman [60], who reported a heavy thinning effect in 'Coscia' and a light thinning response in 'Spadona' following application of 100 mg/L BA 2 weeks AFB.

Several authors have reported improved fruit size following BA application, regardless of its thinning effect [26,59,60]. This effect is most likely due to the fact that BA can also stimulate cell division, resulting in an increase in fruit size beyond the increase that would normally be observed as a result of thinning [61]. The russeting effect caused by ATS on 'Packham's Triumph' has been reported to be ameliorated by BA [36].

Multiple applications of the full rate of BA have shown no benefit over one application [36], nor have split applications of reduced rates of BA shown any benefit over single full rate applications [26]. Dussi et al. [37] suggested that BA is an effective thinner when used alone, but Schmidt and Auvil [26] recommended that, because chemical thinning is often confounded by poor weather or imprecise application timings, it is advantageous to make multiple applications using different materials to improve chances for success.

3.2.6. NAA/6-Benzyladenine Tank Mix

The practice of tank mixing of chemicals is becoming increasingly common. Schmidt and Auvil [25] reported that tank mixing of BA with other materials, including oil and carbaryl, did not produce clear benefits. However, mixes of BA and NAA have been found to be effective in some cases [19,42,62].

In a two-year study on 'Conference' and 'Blanquilla' pear, Asin et al. [62] reported better thinning effects with a combination of BA + NAA at the 8–10 mm fruitlet stage compared with either BA or NAA alone, reducing fruit set in both cultivars by approximately 50% with application of 150 mg/L BA plus NAA at either 20 or 40 mg/L. In spite of similar thinning levels they reported differences in final fruit yield between cultivars with a decrease of ~60% in 'Conference' and ~30% in 'Blanquilla', concluding that fruit size was directly related to crop load in 'Conference' but in 'Blanquilla' there was a tendency for fruit weight to increase with 6-BA. Maas et al. [19] also found that a tankmix of 150 mg/L BA and 20 mg/L NAA applied at 10–12 mm fruit size effectively reduced crop load of 'Conference' pear whereas neither chemical applied alone had a thinning effect, and Maas and van der Steeg [42] reported that a combined application of 150 mg/L BA + 10 mg/L NAA was more effective than BA alone in thinning 'Conference' pear at the 8–10 mm fruitlet diameter stage. In another trial, Maas et al. [19] found that application time influenced thinning effectiveness, with application at 8.8 mm average fruit size overthinning and the same treatments applied at 14.7 mm having a reduced thinning effect, even though weather conditions were relatively similar at both application times. These authors also reported that a reduction in fruit set by BA + NAA did not result in a proportional increase in the average fruit weight at harvest, and attributed this size-reducing effect to NAA, which as noted by Webster [7] causes a check in tree growth resulting in reduced fruit size.

In contrast, Vilardell et al. [46], Fernandes [63] and Mauricio et al. [58] found no additional benefit of tank mixing NAA and BA for cvs. 'Conference' and 'Rocha' compared with BA alone, and Gonkeiwicz et al. [50] observed the same level of thinning on cv. 'Conference' with 20 mg/L NAA and a mix of 37.5 mg/L BA + 7.5 mg/L NAA applied at 12 mm fruitlet diameter.

Theron et al. [64] and Maas and van der Steeg [42] reported good thinning effects with combinations of BA and NAA at fruitlet stages from 8 to 12 mm. However, they have not included either BA or NAA alone treatments in their studies so it is difficult to ascertain whether there is any benefit in combining the two chemicals as a tank mix.

3.2.7. Abscisic Acid (ABA)

Abscisic acid (ABA), a naturally occurring plant hormone, has been found to be quite an effective abscission-promoting compound on apples [65]. One of the plant physiological responses involving ABA is regulation of stomatal opening and closing, enabling plants to lower water loss by closing stomata when plants are exposed to stressful conditions [66]. Stomatal closure results in a decline in leaf photosynthesis [67], inducing carbohydrate stress [4] which can lead to fruit abscission.

In a study on 'Bartlett' pears, application of 500 mg/L ABA resulted in significant thinning at bloom, petal fall and 10 mm fruitlet diameter—effectiveness increased at the later development stages, with application at the 10 mm stage nearly defruiting the trees [68]. Greene [68] also demonstrated a quadratic dose response from 50 to 500 mg/L applied at 10 mm fruitlet diameter, with 500 mg/L being no different to the 250 mg/L application. In cv. 'Forelle', Theron et al. [64] found differing responses to ABA application between regions and years, and Cline et al. [49] reported inconsistent results over the three years of their study on cvs. 'Cold Snap^{TM}' and 'Bosc', but did find that 300 mg/L had a greater thinning effect than 150 mg/L. Evaluating the effect of ABA on 'Bartlett' pears over multiple years and sites, Arrington et al. [69] reported a dose response in thinning efficacy from applications of 50–500 mg/L at 10–12 mm fruitlet size. However, they found that the relative degree of thinning for a given dose was inconsistent among trials but trees treated with ABA had a higher proportion of blank and single-fruited spurs than the control. These authors reported that net photosynthesis (Pn) of single leaves was reduced 75% to 90% within one day of ABA application but gradually returned to 80% of control levels within 7 days and fully recovered by 14 days, observing a slightly greater and longer lasting Pn inhibition with increasing ABA dose. This finding supports the statement by Greene [68] that ABA has the potential to influence the carbohydrate status within a plant by closing stomates, thus reducing photosynthesis during the time the stomates are closed.

Both Greene [68] and Arrington et al. [69] reported increased fruit weight in cv. 'Bartlett' following application of ABA. According to Arrington et al. [69] fruit firmness, TSS content and titratable acidity were unaffected by ABA treatments, but Green [68] found an increase in flesh firmness and soluble solids. In their three-year study of 'Cold Snap^{TM}', and 'Bosc', Cline et al. [49] reported some improvement in fruit size but a decrease in yield and crop value which offset the increase in fruit size.

Extensive leaf yellowing and abscission were observed by Greene [68] with PF or later applications of 250 and 500 mg/L ABA, with no damage following bloom application. Arrington et al. [69] also reported severe defoliation with rates of 400 and 500 mg/L ABA and slight defoliation at 250 mg/L in some but not all trials, and Cline et al. [49] observed leaf yellowing and drop with application rates of 150 and 300 mg/L ABA. However, Fernandes [70] saw no negative effects on leaves or fruit following application of 300 mg/L ABA. Contemplating the inconsistent thinning response and variable effects on leaf abscission, Arrington et al. [69] suggested a potential interaction between ABA and environmental factors with rewetting and cloudy conditions in the days following application potentially enhancing ABA uptake and thus contributing to phytotoxic effects. Cultivar may also play a part as some cultivars are more sensitive to chemicals than others.

3.2.8. Metamitron

The latest post-bloom thinning chemical to be registered for use on apples is Brevis® (150 g/kg metamitron), a triazinone herbicide that acts by temporarily inhibiting photosynthesis through PSII inhibition via electron transport blockage, which reduces maximum potential quantum efficiency of PSII (Fv/Fm) [71]. Reporting the response of apples to metamitron, McArtney et al. [72] found that Fv/Fm declined 2 days after foliar application and remained suppressed for up to 11 days after treatment; they observed a negative linear response between metamitron concentration and fruit set and concluded that the transient carbohydrate deficit created through photosynthetic inhibition was severe enough to result in fruit abscission.

Although not yet registered for thinning of pears, several authors have reported thinning effects on pear following application of metamitron as a post-bloom spray. Maas and van der Steeg [42] observed increased thinning on 'Conference' pear with increasing concentration of Brevis® from 175 to 700 mg/L applied at the 10–12 mm fruitlet stage across three sites. In further trials, these authors found that desirable levels of thinning were obtained with single or repeated applications of 175 to 350 mg/L metamitron at the 8 to 12 mm fruitlet diameter stage. Evaluating the effect of metamitron on cv. 'Bartlett' in five separate trials over three years, Elsysy et al. [71] observed that photosynthesis and fruit set were reduced linearly with increasing metamitron rate (150–600 mg/L), but the effect varied by rate and year and may have been enhanced by high temperatures. They reported that photosynthesis was inhibited for a duration of 2 to 3 weeks, although longer persistence was observed in two trials. The work of Elsysy et al. [71] corroborates the results of Maas and van der Steeg [42], with both studies concluding that metamitron has good potential as a thinning agent for pear. Although Mass and van der Steeg [42] found a linear relationship between fruit abscission and rate of metamitron up to 700 mg/L, Elsysy et al. [71] reported that rates above ~300 mg/L did not induce additional thinning, suggesting that this difference may be due to cultivar and climatic differences.

Time of application also influences efficacy of metamitron as a thinner—Elsysy et al. [71] demonstrated that application between the 10 and 13 mm fruitlet stage thinned 'Bartlett' pears significantly, but earlier application at ~7 mm had little effect on fruit abscission. Maas and van der Steeg [42] also found that metamitron was more effective when applied at 10–12 mm fruitlet diameter compared with application at 6–8 mm. At the earlier fruit size of 6–7 mm, leaf expansion is only just beginning and hence there is minimal leaf area for chemical absorption [71], hence there is insufficient uptake of metamitron to induce a response.

Maas and van der Steeg [42] found that higher dosages were needed to thin well-pollinated trees compared to trees in orchards without pollinators. According to Yuda et al. [73], fruit with seeds are less prone to abscise than fruit without seeds because of growth regulators produced by the seeds; Maas and van der Steeg, [42] suggested that the presence of seeds enhances the sink activity of the fruit for assimilates making it more difficult to promote their abscission by the inhibition of photosynthesis.

Botton et al. [74] proposed that activation of the fruit abscission zone is triggered by a critical threshold level of carbohydrates within the fruit cortex, leading McArtney et al. [72] to suggest that the efficacy of metamitron as a fruit thinner will be dependent on a number of factors, including carbohydrate balance in the tree at the time of application, daily level of carbon assimilation, and allocation of assimilated carbohydrates between competing sinks such as shoots, fruit, and respiration. This assumption can be applied to all chemical thinners, particularly those with an hormonal effect.

Metamitron has also been combined in a sequential spray program with other chemical thinning agents. Fernandes [70] applied 150 mg/L BA, 300 mg/L ABA or a tank mix of 15 mg/L NAA + 150 mg/L BA to 'Coscia' pear 21 dAFB, following up with metamitron 37 dAFB and reported >80% reduction in crop load with all combinations at 121 dAFB compared with set at 21 dAFB on the same trees. In this study, Fernandes found that while metamitron alone thinned, a complementary hand thin was required to reach an acceptable crop load and this treatment had the lowest proportion of large sized fruit.

3.2.9. Potential Thinners

5-Aminolevulinic Acid

The natural amino acid 5-aminolevulinic acid (ALA) has gained attention in agriculture, livestock production and medicine [75]. In a world where chemicals used in agriculture are coming under increasing scrutiny, it has been described as a natural, non-toxic, biodegradable, environmentally-friendly plant bioregulator [27] and is present in microbe, plant and animal cells [75,76] acting as an essential biosynthetic precursor of all organic heterocyclic tetrapyrrole molecules, including chlorophyll, heme and vitamin B12 [76].

The efficacy of ALA as a pear thinner has been demonstrated by An et al. [77]. These authors reported that rates of 100 and 200 mg/L ALA applied at 75% bloom significantly reduced fruit set by 88–89%, but 50 mg/L ALA had no thinning effect. In further studies to determine the optimal time of application they concluded, that while application at 25% bloom showed a thinning effect, application at 50–75% bloom was more effective, leading to a recommendation that application of 100 mg/L ALA at 50–75% bloom was effective for thinning pear. Both in vivo and in vitro studies across several pear cultivars demonstrated that the mechanism by which ALA thinned was inhibition of pollen germination and tube growth via Ca^{2+} efflux by activating Ca^{2+}-ATPase [77], thus thinning fruits by preventing fertilisation. As ALA is a non-toxic biodegradable amino acid present in living cells it is likely to meet modern environmental and food quality guidelines and thus has considerable potential as a chemical thinning agent, particularly if used at low concentrations. An efficient method of production of ALA has been described by Chen et al. [75].

1-Aminocyclopropane-1-Carboxylic Acid

Recently, the bioregulator 1-aminocyclopropane-1-carboxylic acid (ACC) has gained attention as a potential chemical thinning agent. It is a precursor to ethylene metabolism and is involved in fruit abscission and ripening [49].

Theron et al. [64] found some thinning effect in cv. 'Forelle' following application of ACC at the 8–10 mm fruitlet stage in one out of four trials, reporting a 50% reduction in crop load with a dose rate of 300 mg/L and an increase in fruit weight. Similarly, Cline et al. [49] reported that ACC at a concentration of 300 mg/L markedly reduced the crop load of cv. 'Bosc' in two out of three years, but observed no thinning effect for cv. 'Cold Snap™' compared with the untreated control.

Although there is minimal information on the efficacy of ACC, Cline et al. [49] suggested that, given its positive response, further research is worthwhile to determine optimal concentrations for pears and to test other application timings.

3.2.10. The Future of Chemical Thinning

With numerous interacting factors affecting the thinning response to chemical thinning agents, it can be difficult to determine why a chemical causes flower/fruitlet abscission in some situations but not others. The wide variation in efficacy of the chemicals discussed above may be explained partly by the different sensitivities between cultivars and the different climatic conditions. Weather conditions before, during and after application can influence chemical absorbance, and thus efficacy; Botton and Costa [78] stress that the action of chemical thinning agents is strongly related to meteorological conditions at application as well as to the physiological state of the tree. However, many papers did not report weather conditions during their studies. Following application of chemical thinning agents, a higher level of fruit abscission is observed with weather conditions that favour reduced carbohydrate levels in the tree, in particular low light levels and elevated temperature after treatment [79,80]. Lack of untreated controls in trials [58,70] can lead to difficulties in interpreting trial results as the background crop load level is unknown.

In spite of the variations in thinning response of most chemicals and the negative impacts that chemical thinners can have on fruit size, shape and skin finish [8], chemical thinning is gaining increasing acceptance in pear production with awareness that the early thinning offered by chemical thinners provides distinct advantages with regard to fruit size and other quality parameters such as firmness. Comparing hand thinning cost with chemical alternatives, Mauricio et al. [58] reported a cost reduction of approximately 40% with the advantage of fewer smaller fruits in an on year with chemical thinning. The risks involved in chemical thinning can be mitigated by use of a structured approach [8,20], commencing a thinning program early at flowering and using a sequential spray program with both blossom and post-bloom thinners. This approach has been confirmed by Schmidt and Auvil [26] who recommended that it is advantageous to make multiple applications using different materials to improve chances for success, and Wertheim [16] who noted that combination sprays of two different thinning agents and sequential sprays may cause more thinning than compounds used separately. Dussi [80] also noted that for effective thinning, it is important to consider different "thinning programs" appropriate to the cultivar, integrating diverse products, doses and timings. Awareness of the impact of weather conditions before, during and after application on chemical absorbance and efficacy can also reduce unpredictability. The production of carbon assimilates through photosynthesis, which is also influenced by weather conditions, is critical for fruit retention in the early stages of fruit development [81]. When a tree is in carbon-deficit fruitlet abscission is more likely, making thinners more effective, whereas in carbon excess conditions fruitlets are retained more strongly and thinners are less effective [82]. Use of a carbon balance model such as Malusim, the dynamic simulation model of apple tree carbohydrate supply and demand balance developed by Lakso and Robinson [83], would allow more precise prediction of thinner response under specific environmental and physiological conditions.

Traditionally, Australia is one of the few countries where growers have relied on blossom-thinning sprays as the first stage of their thinning program for pome fruit. However, blossom thinners are increasingly being integrated into crop load management strategies worldwide. McArtney [33] noted that blossom thinners have been more readily accepted in drier regions where there is a low frost risk during the bloom period. In regions prone to frosts during and shortly after flowering, growers are reluctant to apply blossom thinners as the risk of losing their crop can increase and hence post-bloom thinners are more likely to be used in these regions as they allow the period of greatest frost incidence to pass before the application of thinning chemicals [37]. McArtney [33] has also observed that there is a reluctance to use blossom thinners in regions where higher humidity and longer drying times increase the potential for fruit russet, but even post-bloom thinners can cause russet when applied in slow-drying conditions [20].

Costa [44] sums up the value of plant bioregulators as an important tool, noting that they should be considered as part of a larger portfolio of options to be integrated into a whole sustainable, systematic approach program for controlling vigour and improving cropping. To maximise the benefits of chemical thinning, an understanding of the physiological mechanisms involved for each active ingredient is beneficial along with knowledge of optimal application timing, dose rates and impact of weather conditions before, during and after application. Knowledge of the factors affecting the tree carbon balance can also be used to optimise thinning outcomes (Table 2). The best conditions for thinning are warm temperatures with low light which results in high demand for carbohydrates but low supply.

Table 2. Factors affecting tree carbon balance during fruit development.

	High Carbon Supply (Hard to Thin)	**Low Carbon Supply (Easy to Thin)**
Water availability	Adequate water supply	Water stress resulting in tree shutdown
Vegetative growth	Low vegetative growth	Vigorous growth competing for C
Canopy development	Full canopy, leaves attained full photosynthetic potential	Leaves still developing
Crop load	Low crop load—high leaf:fruit ratio	High crop load—reduced leaf:fruit ratio
Solar radiation	Clear sunny days—increased light interception increases photosynthesis	Overcast conditions—low light interception reduces photosynthesis
Day temperature	Cool: fruit growth slowed so C demand reduced	Hot: encourages stomatal closure, reducing photosynthesis
Night temperature	Low temperatures reduce respiration	High temperatures increase respiration, thus increasing C demand

Sources: Jones et al. [20]; Darbyshire et al. [82]; Lakso [84]; Fischer et al. [85].

3.3. Shading/Photosynthetic Inhibition

Greene et al. [65] describes several studies by other authors showing that fruit can be thinned by shading trees or by applying photosynthetic inhibitors (such as metamitron), both of which decrease carbohydrate availability to the competing sinks; these authors state that the 8 to 15 mm fruit size is the stage when developing fruit are easily thinned because carbohydrate demand by developing fruit and other sinks often exceeds the supply provided by photosynthesis. Byers et al. [86] suggested that cloudy periods as short as three days, or even less, may greatly affect apple fruit set under natural conditions, since photosynthetic inhibitors or short periods of shading can dramatically reduce set. Although most shading studies have been on apple, the results should also be applicable to pears.

Apple trees can be almost completely defruited by shading of whole trees from 25 to 35 dAFB [86]. Timing of shading can affect fruit set. Byers et al. [87] reported a 7–17% reduction in fruit set when trees were shaded with 92% shade cloth for 2–3 days at 14, 21 and 28 dAFB, but 2–3 days of artificial shade applied 8, 35 or 42 dAFB had no influence on fruit drop. Shading the whole tree for three days when fruit were 20 mm in diameter caused 98% fruit abscission. Bertschinger et al. [88] observed total fruit drop in two apple cultivars with 100% shading at 28 dAFB, but 100% shading for five days starting at 14 dAFB resulted in an ideal level of fruit set equivalent to hand thinning after June drop. Low light from three-four consecutive days of cloudy periods has been calculated as being equivalent to two-three days of 92% artificial shade [87]. It also appears that a tree is able to compensate for partial shading. Byers et al. [87] found that if a limb was left in the sun 70% of its fruit were retained on that limb whilst a shaded limb on the shaded part of the tree retained only 5% of its fruit; and shading only one limb for three days caused 45% fruit abscission on that limb without affecting the fruit set on the rest of the tree.

Studies by Zibordi et al. [89] support the hypothesis that C-starvation may induce fruit abscission at approx. 30 dAFB when fruitlets are approximately 20 mm in diameter, but they concluded that the duration of shading required to be effective remains difficult to define. Shading can also affect fruit size, the severe shading apparent within canopies of poorly pruned and vigorous trees may well contribute to poor fruit size at harvest because shading of trees reduces photosynthesis and hence total assimilate supply [90,91]. Specific physiological responses can be triggered in fruit trees by use of photoselective coloured nets, including better crop yields and improved fruit quality [92].

Shading is applicable in organic orchards and may provide a mechanism to reduce the use of chemicals in conventional orchards that use chemical thinning. However, more work is required to determine the length of the period of shading and the optimal timing for each cultivar, bearing in mind that this may also be influenced by seasonal weather conditions.

3.4. Mechanical Thinning

Greater awareness of the environmental impact of chemicals combined with increasing labour costs has opened the door for mechanical thinning. Mechanical thinning can be achieved in various ways—shaking the tree, use of stiff bristled brushes to sweep the tree, flailing the tree with ropes or switches, or use of high pressure water or air to remove flowers or fruitlets. According to Webster [7], attempts at mechanical thinning of fruitlets have focussed on trying to comb or shake a proportion of the fruitlets from trees; however, these methods have caused considerable damage to trees and tend to remove the larger fruit, leaving the smaller less desirable fruit.

A range of mechanical systems are described by Jacobus de Villiers [93] and Wouters [94]. Trunk shakers have been effective on peaches trained to a V or regular vase system, but they preferentially remove the larger fruit from the upper canopy and leave clusters of fruit. Lopes et al. [95] noted several clear disadvantages of trunk shakers including excessive fruitlet removal, reduction in marketable grade fruit, irregular thinning pattern—particularly near the top of the tree, loss of larger fruitlets, an inability to remove fruitlet clusters and significant leaf removal which negatively affects fruit growth. Limb shakers with lower vibration frequency were also reported to cause excess removal of high-quality fruit from the top of the tree [96]. While trunk or limb shakers have been successfully used in stone fruit, they are not recommended for pome fruit because fruit is easily bruised [97].

Spiked drum shakers use rotating drums consisting of whorls of rigid nylon rods that revolve around a vertical axis [94]; both the axis angle and working height can be changed to adapt to the canopy shape. However, they remove more fruit from the outside of the canopy than the inside and create an uneven fruit distribution [94]. Other systems described include rope curtains [93], water jet thinning [94], hot air blowers [94] and string thinners [93,94]. Timing of use of the different mechanical devices varies between bloom and fruitlet stages of growth. The majority of studies with mechanical thinning devices have been undertaken on peach and other stone fruit, with very few studies in pome fruit. The timing of thinning for the most commonly studied devices is described in Table 3.

Table 3. Application time for different mechanical thinning devices.

Flower Stage	Fruitlet Stage
Rope curtain Darwin string thinner Baum string thinner Compressed air pulses	Limb/trunk shakers Spiked drum shakers

Trials on several fruit species have shown the potential of the tractor mounted Darwin string thinner developed by H. Gesseler, an organic apple grower in Germany [93] and the BAUM device developed by the University of Bonn, Germany [44,93]. Originally called a wire-machine, the Darwin thinner uses flexible strings/cords rotating around a vertical spindle and thinning intensity can be adjusted by changing the rotational speed of the spindle, the speed of the tractor or the arrangement of the cords; it can be used from pink stage in apples (white bud in pears) through to petal fall and has been shown to reduce the time required for hand thinning by up to 50% [93]. The BAUM device consists of a 3 m vertical spindle with three horizontal rotors, which can be set independently of each other [93]. According to Damerow and Blanke [98], precise control over the number of flowers removed can be achieved by choosing between a selection of brush type, rotor speed, rotor position and tractor speed. Because the rotors can be swung individually out of the tree row, the device provides flexibility for selective thinning of one side of a tree row and different canopy sections (lower or higher, inner or outer part of the tree) [98]. In terms of thinning efficacy, speed, and ability to control damage, string thinners are probably the most feasible mechanised thinning solution [94,99,100].

Using a BAUM mechanical thinner, Basak et al. [101] reported varying effects between years with 'Conference' pear at rotor speeds of 360 and 420 rpm; in the first year they observed no thinning effect, while in the second year mechanical thinning at the lower rotor speed reduced fruit set by 12% and the higher rotor speed resulted in a 27% reduction. There was no mechanical injury observed and mechanical thinning did not affect return bloom in either trial. Working with 'Conference' and 'Lucas' pear trees trained as super spindles, Seehuber et al. [102] was able to remove 25–33% of flowers by selecting a range of rotor speeds (300–450 rpm) and tractor speeds (4–8 km/hr). Damerow and Blanke [98] reported that rotor speeds between 300 and 420 rpm at tractor speeds of 5–7 km/hr showed the best efficacy of flower thinning on slender spindle trained trees, removing 50% of flowers; rotor speeds in excess of 500 rpm led to high leaf and branch damage. As well as removing flowers on the periphery of the tree, the BAUM also removes flowers in the centre of the tree close to the trunk where fruit is normally of lower quality due to shading [93].

Tree architecture is important to the success of mechanical thinning; it is unlikely to succeed in voluminous three-dimensional canopies which are likely to impede machine access to blossom clusters [7,69]. Bertschinger et al. [88] concluded that tree architecture needs to be adapted to the thinning machine, recommending slender cylindrical trees with short branches. Tree training methods that are suited to mechanical thinning include spindle, solaxe, vertical axis and central leader [102].

Fruit morphology can also play a role in the success of mechanical thinning. Menzies [103] reported that 'Williams', 'Josephine' and, to a lesser extent, 'Beurré Bosc' could be mechanically thinned successfully, but found that the long flexible peduncle of 'Packham's Triumph' was a major limitation in mechanically thinning this cultivar. However, Seehuber et al. [102] attributed successful mechanical thinning of 'Conference' and 'Alexander Lucas' cultivars partly to the steep upright long peduncles, particularly when compared with the shorter flower stalks of apples.

Mechanical and hand thinning have been reported to be equally effective in reducing the proportion of small fruit in 'Williams' pears [103]. One advantage of mechanical thinning is the saving in hand-thinning labour costs, the cost of mechanical thinning has been reported to be half that of hand thinning based on 20 ha and 10 years depreciation of the mechanical thinner [102].

Both the Darwin and BAUM units are limited in that they are unable to account for the thinning requirements of individual trees—in this respect, they are no different to current chemical thinning practices where orchard blocks are treated as one unit, each tree receiving the same amount of chemical. Additionally, they do not discriminate between flowers, hence are non-selective and can also cause damage to leaves and bark, providing an entry point for disease such as fire blight (*Erwinia amylovora*) and canker (*Nectria gallingea*) [94]. Ngugi and Schupp [104] reported a 3.8 fold increase in fire blight infection of apple trees following mechanical thinning with a Darwin 300 rotating string thinner. To avoid infection, these authors recommend that string thinners should be limited to orchards with no history of disease within the last three years and they should only be used when predicted weather is not suitable for infection by *E. amylovora*. An increase in aphid (*Eriosoma lanigerum*) populations in plots thinned with a Darwin style thinner has also been observed [88].

Flowering in stone fruit occurs before leaf development, but pome fruit can have a substantial leaf area at bloom and this presents a challenge for flower thinning with mechanical thinners as leaf damage to fruiting trees early in the season can negatively affect fruit size as well as fruit set. Spur leaves have been shown to have an important localised influence on fruit set [105], particularly early in the season as developing fruit are unable to receive photosynthate from elsewhere in the tree, but the degree of dependence on spur leaves appears to vary with cultivar [106]. In a defoliation study on apple trees, Bound [107] demonstrated that trees are able to tolerate light to moderate spur leaf damage throughout the season with no significant effect on fruit set, but loss of 75% or more of the leaf surface will reduce both fruit set and quality.

The development of a system aimed at adapting thinning intensity individually to each tree was described by Gebbers et al. [108]. This system combined a stereo camera with software for real-time determination of flower density with a mobile geographic information system with a decision support tool to calculate optimum thinning intensity based on current flower density and a mechanical thinning unit controlled in real time. A vision system that estimates blossom density and adjusts spindle rotational speed is now commercially available (SmaArt; Fruit-Tec, Markdorf, Germany) [29].

To overcome the issues of non-selectivity and tree damage, Wouters [94] set out to develop a novel mechatronic device that offered a high degree of selectivity with minimal tree damage. His objectives were to develop a sensor capable of detecting floral buds and to investigate a new non-contact way of thinning using pulses of compressed air. Because pre-bloom recognition of green floral buds amongst green leaves is hard to realise with standard cameras, Wouters designed a dedicated multispectral sensor, achieving 95.14% correct pixel classification under laboratory conditions and adapted his algorithms to achieve 87% recognition of unoccluded buds in the orchard. Working initially with a single pneumatic nozzle to determine the effects of air pressure, nozzle type, distance and phenology on the attainable removal efficiency, he achieved thinning grades as high as 93.13% and 74.52% during a dry and a wet season, respectively, with little damage as the floral buds were removed at their natural attachment point. Further work with a multiple nozzle prototype in one season achieved a maximum success rate of 36.59%. Following integration of the detection sensor and the pneumatic thinning technique, it was concluded that such a mechatronic system can realize precision thinning by choosing the required settings of the pneumatic thinning device based on the measured floral bud distribution. Additionally, after the thinning operation, a second bud detection and counting procedure can be used to assess the effectiveness of the procedure and to adjust the machine settings if required. Initial tests of this concept have been conducted in the orchard with positive results. A cost analysis has indicated that pneumatic thinning can be an economically feasible alternative to traditional hand thinning [94].

The current commercially available mechanical thinning devices suffer from several serious drawbacks. The string thinners are non-selective, often making for uneven fruit distribution within the tree. The same machine settings are used for whole rows/blocks, hence do not account for variation in floral bud distribution between trees within a block, or even within a tree. Damage levels to bark, shoots, leaves and fruitlets can be high, providing entry points for disease and impacting on fruit size/quality. Tree architecture of many existing orchards is not suited to mechanical thinning, as mechanical devices require a two-dimensional hedgerow canopy. However, in spite of the drawbacks of currently available devices, there are several advantages to mechanical thinning: (1) they are not weather dependent; (2) thinning can be undertaken early in the flowering period as soon as flowers can be identified on the tree; (3) the thinning effect can be observed immediately after treatment, allowing additional thinning measures to be undertaken more rapidly if required; and (4) they provide a low environmental impact method for crop load management and are a good fit for organic orchards.

With most new plantings moving towards two-dimensional tree architecture the problems encountered with mechanical thinning of three-dimensional canopies are removed. There is work in progress to overcome the problems of non-selectivity and tree damage and a move towards mechatronics, and if these systems can be proven to be economical there is potential for mechanical thinning to provide an environmentally friendly, efficient means of managing crop load.

3.5. Pruning

The primary function of pruning is to control tree size and improve light distribution within the canopy, but it can also be used to manage floral bud numbers [99] and is recommended as the first stage of any thinning program [20]. The strategy of reducing floral bud numbers through pruning has several benefits: (1) it can be achieved during routine winter pruning; (2) it reduces competition for assimilates between flowers/fruitlets thus providing maximum benefit in terms of assimilate distribution; and (3) it is an environmentally friendly method of reducing crop load. Pruning is used to maintain balance between vegetative and reproductive activity [1].

Webster [7] suggests that unless winter pruning of floral buds is left until late spring, this method lacks precision in terms of relative numbers of flowers removed and left on the tree, and notes that it can be a high-risk strategy in frost prone areas. However, despite these drawbacks, Webster recommends that growers need to give this technique serious consideration as it can be a valuable aid in reducing flower abundance and reducing the cost of subsequent thinning operations.

The concept of spur or bud extinction was first introduced by Lauri and Lespinasse [109,110] after observing that regular bearing cultivars have high natural spur extinction and the remaining floral structures bear fruit and produce bourse shoots that flower the following season [111,112]. Laurie and Lespinasse [109] reported that by reducing the number of axillary shoots along the branches cultivars characterised by alternate bearing can be encouraged to produce more regularly. Artificial spur (or bud) extinction (ASE/ABE) imitates natural bud extinction by reducing bud density through manual removal of floral buds during late winter or early spring. It is a precision crop load management technique as it precisely defines both how much fruit is set on the tree and where it is positioned. Tustin et al. [113] suggested that ASE could replace chemical thinning as a crop load management tool, and Bound [114] demonstrated that ASE is indeed a feasible alternative to chemical thinning for managing crop load in apple with the added advantages that it is not weather dependent and removes the risk of negative impacts that chemical thinners can have on fruit size, shape and skin finish. In terms of costs, implementation of ASE is comparable to managing crop load through chemical thinning programs, but has the advantage that costs reduce in subsequent years after the initial tree set-up [114].

Although ASE has not yet been trialled in European pear cultivars, it is likely to have potential as a crop load management tool.

3.6. Inhibition of Flower Initiation

As flower initiation in pome fruit is favoured by low levels of gibberellins [115], gibberellins can suppress flower initiation if present in high concentrations during the critical stages of floral initiation [7]. Chan and Cain [116] demonstrated that when seeded fruit were present on apple spurs, the following year flowers developed on only 13% of spurs but when the fruit were seedless 90% of spurs flowered, demonstrating a strong relationship between the seed content of fruit in one year and the proportion of flowering spurs the next.

Seeds of pome fruit trees produce high levels of endogenous gibberellins that stimulate growth and diminish flower initiation [115], thus playing a significant role in triggering biennial bearing [7,117]. Biennial bearing has traditionally been managed through application of chemical thinning agents in the 'on' year of the biennial bearing cycle. However, as application of exogenous gibberellins has been shown to inhibit floral bud initiation (FBI) in woody perennial plants [118], this provides a potential tool to inhibit excessive return bloom when applied during the flower induction period in the 'off' year.

Many PBRs can induce different responses depending on the application time and rate used [44,80]. The gibberellins GA_3 and GA_{4+7} are used as setting agents on some cultivars with low fruit set [44]. However, McArtney and Li [119] discuss the suppression of flowering with gibberellins GA_3, GA_4, GA_7 and GA_{4+7}, and have ranked them as GA_4 being least inhibitory and GA_7 most inhibitory, with GA_3 and GA_{4+7} being intermediate in their ability to inhibit flowering.

According to Einhorn [4], the time of FBI in pears varies from 30 to 77 days after full bloom, depending on cultivar, and is often associated with cessation of shoot growth. The sequence of FBI in pears has been described by Webster [3] as being firstly on the terminals of short or medium length shoots, then on spurs formed on the branches of wood $\geq$ two years old, and axillary buds on current season growth formed later in the summer months.

When GA was applied to spurs later than six weeks after bloom, there was no response in return bloom [119], but inhibition of flowering on 1-year-old wood was observed. This suggests that the response to GA on FBI is largely controlled by time of application, and thus this may be a useful method of controlling FBI on different parts of the tree, particularly on 1-year-old wood which often produces inferior fruit. However, there is still a need for a better understanding of the floral induction process in order to be able to reliably manipulate this process with PBRs [80]. Webster [7] has suggested that although application of gibberellins when flowers are initiating or in the early stages of development is successful in peach, a similar strategy is not viable for use with pears as it is difficult to control the degree of flower bud inhibition achieved and the quality of flower buds produced in the subsequent season may be reduced.

4. Conclusions

Although the need for managing crop load in European pears varies by cultivar and region, reducing levels of fruit set is desirable in many pear cultivars to optimise fruit size and quality. Hand thinning is effective, but sole reliance on hand thinning is a costly exercise as it is time consuming and labour intensive. As hand thinning is normally performed after natural fruit drop, there is considerable wastage of the tree's resources arising from the delay in achieving target fruit numbers, hence fruit are unable to attain their optimum size.

With awareness that the early thinning offered by chemical thinners provides distinct advantages with regard to fruit size and other quality parameters such as firmness, chemical thinning is becoming more common in pear production. However, there are limited registered chemicals available for use on pear, and the wide variation in the response of thinning chemicals on different cultivars and under different climatic conditions can make chemical thinning unpredictable. Knowledge of conditions that impact the carbon balance of the tree and the ability to make use of carbon-deficit conditions are likely to improve the predictability of chemical thinning. In addition, understanding the physiological mechanisms involved for each active ingredient along with knowledge of optimal application timing and dose rates for each chemical thinning agent will maximise the benefits of chemical thinning. Use of a sequential thinning program, commencing with winter pruning to reduce floral bud numbers and following up with blossom and post-bloom thinners applied under optimal conditions will improve thinning efficacy. A sequential spray program also spreads the risk in seasons where it is difficult to find a window with suitable application conditions.

With the move towards two-dimensional architecture for new plantings, mechanical thinning has potential as a thinning tool. Mechanical thinning has advantages in that it is an environmentally friendly tool, it can be used in organic production and it is not weather dependent. Like chemical thinning, mechanical thinning can be undertaken early in the flowering period but current technology does not account for the thinning requirements of individual trees. A major drawback of string style thinners is the lack of selectivity and the potential tree damage. However, research to overcome these problems is in progress and it is likely that mechatronic devices will solve the problems that occur with current technology.

Pruning has long been recommended as the first stage of any thinning program, but artificial bud extinction has potential to maximise tree resources while enabling precision crop load management. Although bud extinction has not been trialled on pears to date, it should be given serious consideration as it is suitable for use in organic production systems, its efficacy is not weather dependent and it can potentially replace chemical thinning, thus removing the risk of negative impacts that chemical thinners can have on fruit size, shape and skin finish, and it has been demonstrated to be economically feasible.

In economic terms, an increase in overall fruit size does not always compensate for the reduction in fruit number, at times leading to a reduction in yield per hectare. The value of the crop is dependent on the yield of fruit in, and market value for, each size category and the costs of producing the crop. Each of the thinning tools discussed can be considered as part of a portfolio of available options that can be integrated into a systematic approach for managing crop load. Whatever strategies are implemented, the statement by Davis et al. [22] that "*achieving optimal crop value is not merely a matter of maximizing fruit size, but rather of identifying crop loads that balance the tradeoff between yield and fruit size*" should be remembered.

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